

Sustainable transport fleet appraisal using a hybrid multi-objective decision making approach

Chunguang Bai¹ · Behnam Fahimnia² · Joseph Sarkis³

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Abstract One of the most critical operational practices influencing the environmental sustainability of organizations and their supply chains is the transport of materials, products and people. The carbon footprints, materials depletion, and general pollution emissions from transport vehicles makes their environmental burdens significant. Thus, identifying, selecting and implementing more environmentally conscious transportation vehicles can be of paramount importance for the development and management of greener supply chains. Given the relative importance of this issue, it is surprising that research on transport fleet evaluation, especially from an environmental sustainability perspective, has been rather limited. A primary challenge in this context is the broad range of influencing factors that need to be considered, many of which are not fully and easily measurable. This paper aims to (1) develop a holistic framework for sustainable transport fleet appraisal incorporating various vehicle performance, economic and environmental criteria, (2) introduce a novel hybrid approach for sustainable transportation vehicle evaluation and selection by combining a three-parameter interval grey number with a rough set theory and VIKOR method, (3) investigate the application of the proposed approach in a case example where empirical data is collected from industry experts, (4) evaluate the robustness of the methodology through sensitivity analysis experiments, and (5) provide practical insights and directions for future research in this area.

✉ Chunguang Bai
chunguang.bai@dufe.edu.cn

Behnam Fahimnia
behnam.fahimnia@sydney.edu.au

Joseph Sarkis
jsarkis@wpi.edu

¹ School of Management Science and Engineering, Dongbei University of Finance and Economics, Dalian, China

² Institute of Transport and Logistics Studies, The University of Sydney Business School, Sydney, Australia

³ Foisie School of Business, Worcester Polytechnic Institute, Worcester, MA 01609-2280, USA

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1 Introduction

Demand for transportation and logistics operations has increased rapidly as organizations focus more on their core competencies and outsource distribution operations. Industrial vehicle usage has increased in response to this growing need for transportation between supply chain nodes. Increase in commercial vehicle use has become one of the major sources of fossil-fuel consumption and air pollutants emission (Takeshita 2012; Yan and Crookes 2010). Eco-efficient transport fleet decision-making can help address some these concerns facing organizations, stakeholders and governments.

Many transportation and logistics providers have started adopting alternative-fuel vehicles. Practical and investment concerns associated with greening transportation fleets have occurred with UPS and FedEx, who are experimenting with all-electric vehicles with a range of over 50 miles (King 2013). In addition to the logistics industry, companies in the retail industry (e.g. Wal-Mart), telecommunications and utilities industry (e.g. AT&T and Verizon), beverage industry (e.g. Coca-Cola and Pepsi), and even forestry and banking industries have planned for sustainable transportation fleet strategies (Bae et al. 2011). The decisions to lower carbon emissions from transportation fleets are evidenced by a number of companies in their annual sustainability reports. For example, utility companies such as Pacific Gas and Electric (PGE) are concerned with greening corporate vehicles used by employees.¹ Third party (rental) providers of transportation vehicles have also been involved in helping them and their clients to justify alternative energy vehicles. One such company is Penske that was awarded a clean technology award by the US environmental protection agency in 2015.² Penske was recognized for its collaborations with its customer to analyze and determine where natural gas is operationally, financially, and organizationally compatible for organizations seeking to rent greener fleets and vehicles.

Most sustainable transportation vehicles rely on alternative fuel sources such as electricity, solar, wind, bio-fuels, and compressed natural gas (Capasso and Veneri 2014; Rose et al. 2013; Mabit and Fosgerau 2011; Arsie et al. 2010). Depending on the type of alternative fuel, every transportation vehicle type (e.g. full electric vehicles, hydrogen/fuel cell vehicles, and internal combustion/electric hybrids) has its operational, environmental, and economic strengths and weaknesses. Therefore, organizations need to evaluate the transport fleet requirements given their internal economic goals and sustainability strategies.

Research on adoption of alternative-fuel vehicles is well grounded. Studies have focused on the adoption of alternative-fuel buses for public transportation (Tzeng et al. 2005; Yedla and Shrestha 2003), preferences of clean-fuel vehicles for individual customers (Ewing and Sarigöllü 2000), promoting the adoption of alternative-fuel vehicles (Zhang et al. 2011; Yeh 2007; Byrne and Polonsky 2001), and barriers to widespread adoption of alternative-fuel vehicles (Egbue and Long 2012; Browne et al. 2012). Yet, research on transport fleet evaluation has been rather limited and studies focusing on sustainable vehicle evaluation and selection are virtually non-existent.

Transportation vehicle evaluation and selection becomes more challenging when sustainability considerations are added to the traditional economic-oriented models. An initial step

¹ <http://www.pge.com/myhome/environment/pge/fleets/>.

² <http://www.epa.gov/oar/cleanairawards/winners-current.html>.

is to identify and evaluate the related sustainability attributes. Exploring a balance between economic and environmental objectives is a next step. Although there has been some effort to identify the attributes of alternative-fuel vehicles selection (Hsu et al. 2014; Awasthi et al. 2011; Tzeng et al. 2005), a holistic framework does not exist. The adoption of alternative-fuel vehicles requires a holistic consideration of economic, environmental and social dimensions when making important purchasing decisions (Byrne and Polonsky 2001).

Decision support tools and methodologies can help organizations make more effective and informed supply chain and transportation fleet decisions (Fahimnia et al. 2013b, 2015e). To help advance this area of research and further integrate sustainability discussions into the transportation vehicle fleet selection and evaluation management, we introduce a multi-criteria decision-making (MCDM) model that integrates rough set theory and the VIKOR method with three-parameter interval grey numbers. VIKOR is a valuable tool to help solve MCDM problems with conflicting and non-commensurable (different units) criteria (Opricovic and Tzeng 2007). Some researchers have developed hybrid MCDM models by combining VIKOR with other methods (Ou Yang et al. 2013). In this paper, we used rough set theory and three-parameter interval grey number to overcome the limitations of the VIKOR method to develop a novel MCDM model considering decision makers' (DM) judgments. Rough set theory is used to identify the weight of attributes of vehicles to overcome the defect of a VIKOR method that needs additional information about criterion weights. Rough set theory also is helpful in narrowing the initial attributes of vehicles, and reduces the complexity and difficulty of the evaluation, which tends to occur with these types of strategic and multidimensional sustainability issues (Varsei et al. 2014). The three-parameter interval grey number is more appropriate to model decision makers' linguistic values to extend the VIKOR method overcome uncertainty and qualitative factors (Luo et al. 2013). The dominance probability degree based on the three-parameter interval grey number is introduced in this study to provide flexibility and reliability of the VIKOR ranking results. This is the first time these three methods are integrated to arrive at a ranking result including a possibility degree.

The proposed hybrid MCDM method is used to identify and prioritize performance-, economic- and sustainability-related attributes in an empirical case example where real data is collected from company experts and transportation professionals. The contribution of this work is an expansion on the knowledge and tools available for organizational transportation fleet management, especially from a sustainability perspective, and to help validate these new tools.

The next section provides some background information on sustainability-based corporate transportation fleet evaluation and selection. The novel hybrid MCDM model is then introduced. To help practically validate the model, an Australian case study illustration is presented. A sensitivity analysis to examine the robustness of the approach follows. Insights, implications, limitations and future research directions are discussed in the concluding section.

2 Literature on sustainability-based transportation vehicle fleet selection

Sustainability initiatives can be undertaken in various organizational and planning levels (Bai et al. 2015). These may include sustainable supplier selection (Bai and Sarkis 2014a), sustainable supply chain management (Fahimnia et al. 2013a, 2015d), sustainable manufacturing and service provision (Fahimnia et al. 2015c; Gunasekaran and Spalanzani 2012), and

sustainable information technology (Dao et al. 2011; Bai and Sarkis 2013a). Our focus in this paper is on the sustainable transportation vehicle fleet evaluation and selection or more generally “sustainable transportation vehicle management”. The topic is emergent and our study is an early attempt in this area.

The foundation of sustainability decisions is the use of a triple bottom-line approach that seeks to balance economic, environmental, and social dimensions of sustainability (Norman and MacDonald 2004). Economic, or business, sustainability may include whether a transportation vehicle meets the basic needs of transportation on cost, time, and quality. Environmental sustainability may include whether a transportation vehicle meets national and regional environmental regulations, limits emissions and waste, minimizes consumption of non-renewable resources, and facilitates the recovery of scrap (or have a closed-loop material capturing support system). Social sustainability may include whether a transportation vehicle meets transportation security and is consistent with human health concerns. These are just initial examples of factors and other criteria or factors in each of the categories may be included. A comprehensive listing of sustainability factors from a variety of perspectives do exist and can be integrated. Additional attributes for consideration are introduced in the next section.

2.1 Attributes for transportation vehicle selection

Conventional transportation vehicle selection practices have ignored the systematic inclusion of sustainability attributes (Bai et al. 2012). The literature on sustainable transportation vehicle fleet management is rather limited. This section aims to develop a framework for sustainable evaluation and selection of vehicle types using the existing literature and expert opinions. For this purpose, we review some of the major attributes from a sustainability perspective including sustainable transportation systems, transportation modes, and alternative-fuel vehicle characteristics (Do et al. 2014; Bai and Sarkis 2013b; Litman 2013; Bae et al. 2011; Awasthi et al. 2011; Yan and Crookes 2010; Gehin et al. 2008; Zhao and Melaina 2006; Litman and Burwell 2006; Litman 2005; Byrne and Polonsky 2001; Deakin 2001). We also take into consideration experts’ opinions including professionals from logistics, food and beverage, and discrete part manufacturing industries.

The attributes are clustered into distinct categories which show the multi-faceted nature of sustainable transportation fleets. Although there are no ready-made classifications, some of the past studies have investigated sustainable transportation measures and attributes from different aspects. For example, some studies classify sustainable transportation indicators into three main categories: environmental indicators: reductions pollution and energy savings; economic indicators: impacts of vehicles characteristics and other system elements (infrastructure, resources or fuels); and social indicators: safety and health, control training, and quality of life (Mihyeon Jeon and Amekudzi 2005; Shifan et al. 2003). Alternatively, Byrne and Polonsky (2001) believe that there are a number of impediments to consumer adoption of alternative fuel vehicles, including regulatory barriers, resources, infrastructure and vehicle characteristics themselves, which can also represent categories. In addition, recycling is currently a common practice in the automotive vehicle industry, and the European Union’s End-of-Life Vehicle (ELV) Directive aims to increase recovery of ELVs in order to reduce wastes and improve the environmental performance of vehicles (Gehin et al. 2008). In a sustainable transportation system, vehicles should increase scalability to overcome some risks, such as reducing accident likelihood (Abkowitz 2002). Using this variety of literature, we classify the identified attributes into eight categories including vehicle characteristics, policies and regulations, pollution emissions, resources consumption, infrastructure, recy-

cling scrap, employees, and scalability. A total of 51 attributes and measures are considered under these categories. Table 1 summarizes the results and the related literature support for each attribute. Brief descriptions of each category are given below:

1. *Vehicle characteristics*: These are the most popular business attributes in conventional vehicle selection practices and include, but are not limited to, price of the vehicle, operational performance, cost of maintenance, safety, and technology (Lane and Potter 2007; Byrne and Polonsky 2001).
2. *Policies and regulations*: One primary trigger for adoption of greener vehicles is the response to tighter environmental regulatory policies (Bae et al. 2011; Fahimnia et al. 2015b). Some of the major regulations that have influenced the adoption and utilization of sustainable transportation fleets include the fuel economy standards, pollution standards and associated public economic incentives (Yeh 2007). The fuel standards and pollution standards are important as significant reductions in resource consumptions and pollution emissions may be achieved through the selection of greener vehicles (Ewing and Sarigöllü 2000). Organizations may improve sustainability of their transportation vehicles to compliance with environmental regulation standards and avoid governmental fines and penalties (Bae et al. 2011). Another reason for the adoption of sustainable vehicles could be the reputational issues and potential competitive advantages (Zakeri et al. 2015).
3. *Pollution emissions*: Vehicle emissions are major sources of air pollution such as carbon monoxide (CO₂ and CO), nitrogen oxide (NO_x), volatile organic compounds (VOC) [or hydrocarbons (HC)], particulate matter (PM), and smoke that can cause environmental issues including smog, haze, acid rain, and climate change (Yan and Crookes 2010; Calef and Goble 2007; Orsato and Wells 2007). Countries face great challenges to meet greenhouse gas (GHG) emission reduction goals, with road transportation being responsible for most of those emissions (Reichmuth et al. 2013; Safaei Mohamadabadi et al. 2009). Solid and water waste generation are related to vehicle manufacturing and maintenance.
4. *Resources consumption*: Resource use in vehicle operations is the largest operational expense for logistics and transportation industries. Most of these resources are petroleum-based which has turned into a major concern due to the petroleum crisis, rapidly increasing fuel prices, and uncertainties in fuel availability (Meng and Bentley 2008). Alternative-fuel vehicles have strengths and weaknesses on various dimensions. The availability, efficiency and environmental impact of fuel resources play a critical role in this aspect (Bae et al. 2011).
5. *Infrastructure*: The market demand for the use of sustainable vehicles may be highly reliant on the available infrastructure (Byrne and Polonsky 2001). This may include, but is not limited to, the availability of sustainable transportation vehicles, availability of sufficient fuels, availability of fuel delivery outlets, availability of maintenance services, support monetary policy, and appropriate transportation easements. This requires the commitment of stakeholders (government, market distributors, energy suppliers, infrastructure providers, and indeed the entire supply chain) for widespread adoption of sustainable transport fleets.
6. *Recycling*: The European Union's ELV Directive, which came into force in September 2000, aims to increase recovery of ELVs in order to reduce waste from ELV and improve environmental performance (Vermeulen et al. 2011). It is designed to promote collection, reuse and recycling of these vehicles. The directive states that vehicle manufacturers and material and equipment manufacturers must meet a number of objectives including reducing the use of hazardous substances, facilitating the dismantling reuse, recovery

Table 1 Attributes for sustainable vehicle evaluation and selection

Category	Attributes	Related literature
Vehicle characteristics	Vehicle price	Zhao and Melaina (2006)
	Maintenance costs	Zhao and Melaina (2006)
	Running costs	Awasthi et al. (2011)
	Travelling speed range	Litman and Burwell (2006)
	Driving range (e.g. high-speed roads, hills)	Litman and Burwell (2006)
	Traffic safety	Litman (2005)
	Quality of service (e.g. breakdown rate)	Litman (2013)
	Loading capacity	Litman (2013)
	Requirements for goods specifications (e.g. size, shape)	Litman (2013)
	Information technology (e.g. routing or scheduling systems)	Deakin (2001)
Policies and regulations	Technical innovation for improved efficiency	Litman and Burwell (2006)
	Compliance with energy-base government regulations	Byrne and Polonsky (2001)
	Compliance with emission-based government requirements	Byrne and Polonsky (2001)
	The use of hazardous substances (RoHS)	Gehin et al. (2008)
	The use of volatile organic compounds (VOCs)	Do et al. (2014)
	Tax relief benefits	Byrne and Polonsky (2001)
	Fuel subsidies	Byrne and Polonsky (2001)
Pollution emissions	Governments subsidies or incentives	Zhao and Melaina (2006)
	CO ₂ emissions rate	Awasthi et al. (2011)
	GHG emissions rate	Awasthi et al. (2011)
	Noise pollution rate	Awasthi et al. (2011)
	Solid or water waste generation	Litman and Burwell (2006)
	Other air pollutants (e.g. NOx, VOCs, CO, particulates, toxics)	Awasthi et al. (2011)
	Resources	Unit fuel cost
Sufficient fuel supply		Byrne and Polonsky (2001)
Alternative fuels		Byrne and Polonsky (2001)
Energy saving		Awasthi et al. (2011)
Fossil fuel usage rate		Awasthi et al. (2011)
Renewable energy use		Awasthi et al. (2011)
Fuel efficiency		Litman and Burwell (2006)
Clean technologies		Zhao and Melaina (2006)
Fuel safety		Awasthi et al. (2011)
Infrastructure	Market availability of the vehicle	Byrne and Polonsky (2001)
	Availability of fuels	Byrne and Polonsky (2001)
	Availability of fuel delivery outlets	Byrne and Polonsky (2001)

Table 1 continued

Category	Attributes	Related literature
	Availability of maintenance services	Byrne and Polonsky (2001)
	Financing and lending policies	Zhao and Melaina (2006)
	Transportation easements (e.g. lower transportation tolls)	Byrne and Polonsky (2001)
Recycling	Vehicle compliance with ELVs	Gehin et al. (2008)
	Vehicle compliance with WEEE	Gehin et al. (2008)
	Waste from ELV or used tires	Gehin et al. (2008)
	Recycling costs	Gehin et al. (2008)
	Recyclability rate	Gehin et al. (2008)
	Dismantling and reuse possibility	Gehin et al. (2008)
	Recycled materials usage	Gehin et al. (2008)
Employees	Health and safety	Litman and Burwell (2006)
	Comfort of use (e.g. comfortable seats, accessories)	Tzeng et al. (2005)
	Personnel training	Russo and Comi (2010)
	Availability of technical support staff	Russo and Comi (2010)
Scalability	The impact of weather changes on vehicle operations	Abkowitz (2002)
	The impact of road conditions on vehicle operations	Litman and Burwell (2006)
	Vehicle operation in disasters	Abkowitz (2002)

and recycling of ELVs; increasing the use of recycled materials in vehicle manufacture, and ensuring that components of vehicles are free of mercury, hexavalent chromium, cadmium or lead.

7. *Employees*: The previous concerns of economic and environmental aspects in sustainable vehicles selection need to be expanded into social concerns, the third pillar of a triple bottom-line approach. Social attributes may include employee health and safety, personnel training, and the availability of technical support staff.
8. *Scalability*: To reduce the impact of sudden environmental disasters, manufacturers may develop and use various techniques to improve the operational performance of vehicles and reduce the risks when facing natural and man-made disasters.

2.2 Vehicle evaluation and selection models

A range of approaches have been adopted for sustainability evaluation of transportation vehicles. Some of these approaches include life cycle analysis (LCA) (Wang et al. 2013; Nanaki and Koroneos 2012), cost-benefit analysis (CBA) (Damart and Roy 2009), cost-effectiveness analysis (CEA) (Wood 2003), environmental impact assessment (EIA) (Canter et al. 1977), optimization and mathematical programming models (Mula et al. 2010; Shah et al. 2012), system dynamics models (Wang et al. 2008), assessment indicator models (Phillis and Andriantiatsaholainaina 2001), game theoretic models (Bai and Sarkis 2014b; Bae et al. 2011) and multi-criteria decision analysis (MCDA) methods (Awasthi et al. 2011).

A number of combined approaches have been recently developed to overcome the weaknesses of individual approaches. For example, Yedla and Shrestha (2003) rank alternative

transport options by means of analytic hierarchy process (AHP) using weighted arithmetic mean method (WAMM) for group aggregation. Tzeng et al. (2005) apply TOPSIS and VIKOR to find the best compromise alternative-fuel bus with the relative weights of evaluation criteria determined by AHP. Combining MCDA with grey theory (Pai et al. 2007; Deng 1989) has also resulted in the development of new methods like grey TOPSIS (Lin et al. 2008).

Interestingly, given the importance of greening corporate fleets, none of the above methods have been used for sustainability evaluation of transportation vehicles as fleets. We introduce in this paper a new methodology that can be used to evaluate the sustainability performance of vehicles using the attributes defined in Sect. 2.1. This approach involves the integration of rough set theory, the VIKOR method and grey system theory to evaluate the importance of sustainability attributes of vehicles. Our study is an early attempt in introducing three-parameter interval grey number into rough set theory and the VIKOR method. The proposed approach (1) is able to work with no preliminary information, such as probability data or the weight of attributes, (2) can effectively deal with data ambiguity and incomplete information, and (3) provides a possible range for the ranking results, instead of firm numbers.

To help place the methodology proposed here within the broader methodology literature we do a high level comparative analysis. Table 2 provides a comparative analysis of various evaluation and selection techniques, some of which were mentioned above. The table also places and summarizes the relationship of the technique introduced in this paper (at the bottom of Table 2) to other existing approaches. Given that it is an optimization approach, it has similarities to other discrete alternative MCDM approaches such as AHP and Outranking, but includes some additional stages and complexity. However, the goals of the technique, as described previously in the paper and further detailed below, are different from other approaches in the filtration and ranking processes.

3 A hybrid MCDM approach

In this section, the foundational elements for the hybrid MCDM approach will be presented. Background on the various mathematical developments and notation are also introduced. The three major elements of the proposed approach include interval grey numbers, rough set theory, and the VIKOR method.

3.1 Three-parameter interval grey number

Grey system theory can be used to deal with uncertain data and incomplete information (Deng 1989). The major advantage is that it can generate outcomes with a relatively small amount of data or when great variability exists in attributes (Li et al. 1997). Grey system theory has been extensively applied in various fields of decision making, such as evaluating transportation effects on air quality trends (Pai et al. 2007) and sustainable supply chain and operations management (Bai and Sarkis 2010a, b). The traditional interval grey number only considers the upper and lower limit with an equivalent probability occurrence of the values between the upper and lower limits. This characteristic of an interval grey number makes it unsuitable for real situations and may produce some erroneous results (Luo et al. 2013). Grey system theory uses linguistic terms to represent decision maker preferences. For example, the probability that it will rain on Monday can be represented in linguistic terms as very high, high, low, etc. We use grey system theory to model the vehicle selection decision-making as several model parameters cannot be analytically and objectively determined and require

Table 2 Summary of multiple criteria evaluation technique characteristics H = high, M = medium, L = low (adapted from Sarkis and Sundarraj 2000)

Evaluation technique	Cost of implementation	Data requirements	Ease of sensitivity	Economic rigor	Decision maker involvement	Management understanding	Mathematical complexity	Parameter mixing-flexibility
Scoring models	L	L	L	L	H	H	L	H
AHP	M	M	L	L	H	M	L	H
Outranking	M	M	L	M	H	L	M	M
MAUT	H	H	M	M	H	M	M	H
DEA	M	M	L	M	L	L	H	M
Goal program	M	M	M	H	M	L	H	L
Simulation	H	H	H	H	L	H	H	M
Expert systems	H	H	L	H	M	M	H	H
Grey VIKOR rough set	M	M	L	L-M	M-H	L-M	M	H

expert judgments. The three-parameter interval grey number system is then integrated with rough set theory and the VIKOR method.

Definition 1 A three-parameter interval grey number $\otimes x$ can be expressed by a triplet $(\underline{x}, \tilde{x}, \bar{x})$. The three-parameter interval grey number is based on a three-value judgment: the minimum possible value \underline{x} , the most likely value \tilde{x} (also known as the center of gravity), and the maximum possible value \bar{x} .

When the center of gravity is unknown, the three-parameter interval grey number is the common interval grey number. Obviously, if $\underline{x} = \tilde{x} = \bar{x}$ then the three-parameter interval grey number $\otimes x$ is reduced to a real number. Conversely, real numbers may be easily rewritten as three-parameter interval grey numbers.

Definition 2 Let $\otimes x = (\underline{x}, \tilde{x}, \bar{x})$ and $\otimes y = (\underline{y}, \tilde{y}, \bar{y})$ be two three-parameter interval grey numbers. Mathematical operations of the three-parameter interval grey number are defined as Luo and Wang (2012):

$$\otimes x \oplus \otimes y = (\underline{x} + \underline{y}, \tilde{x} + \tilde{y}, \bar{x} + \bar{y}) \tag{1}$$

$$\otimes x \times \otimes y = [\min(\underline{x}\underline{y}, \underline{x}\tilde{y}, \tilde{x}\underline{y}, \tilde{x}\tilde{y}), \tilde{x} \times \tilde{y}, \max(\underline{x}\underline{y}, \underline{x}\tilde{y}, \tilde{x}\underline{y}, \tilde{x}\tilde{y})] \tag{2}$$

$$\otimes x_1 \div \otimes x_2 = [\min(\underline{x}/\underline{y}, \underline{x}/\tilde{y}, \tilde{x}/\underline{y}, \tilde{x}/\tilde{y}), \tilde{x}/\tilde{y} \max(\underline{x}/\underline{y}, \underline{x}/\tilde{y}, \tilde{x}/\underline{y}, \tilde{x}/\tilde{y})] \tag{3}$$

Definition 3 Let $\otimes x = (\underline{x}, \tilde{x}, \bar{x})$ and $\otimes y = (\underline{y}, \tilde{y}, \bar{y})$ be two three-parameter interval grey numbers, with $l(\otimes x) = \bar{x} - \underline{x}$, and $l(\otimes y) = \bar{y} - \underline{y}$. The possible degree, largest value, of two interval grey numbers has previously been defined (Nakahara et al. 1992). We now define the possible degrees for a three-parameter interval grey numbers as:

$$P(\otimes x \geq \otimes y) = \begin{cases} 1 & \underline{x} \geq \bar{y} \\ \frac{\bar{x} - \underline{y} + \tilde{x} - \tilde{y}}{l(\otimes x) + l(\otimes y)} & \underline{x} > \underline{y} \wedge \tilde{x} < \bar{y} \\ 0 & \bar{x} \leq \underline{y} \end{cases} \tag{4}$$

where $P(\otimes x \geq \otimes y)$ means that the possible value of three-parameter interval grey number $\otimes x$ is bigger than three-parameter interval grey number $\otimes y$, shown as a percentage.

Definition 4 Let $\otimes x = (\underline{x}, \tilde{x}, \bar{x})$ and $\otimes y = (\underline{y}, \tilde{y}, \bar{y})$ be two three-parameter interval grey numbers. We also introduce a new distance measure for both three-parameter interval grey numbers which are represented by expression (5).

$$d(\otimes x, \otimes y) = \alpha \sqrt{(\underline{x} - \underline{y})^2} + \beta \sqrt{(\tilde{x} - \tilde{y})^2} + (1 - \alpha - \beta) \sqrt{(\bar{x} - \bar{y})^2} \tag{5}$$

where α, β are weight parameters, $0 \leq \alpha \leq 0.5; 0.5 \leq \beta \leq 1; \alpha + \beta \leq 1$.

The two interval number distance measures represent a new area of study and utilize the Minkowski space distance (Bai and Sarkis 2010b). Although these types of distance formula could take into account the main features of the interval number: upper limit, lower limits, and center of gravity, they do not reflect the importance of the center of gravity. The new distance formulae treat the center of gravity as important as the traditional upper and lower limit values of grey numbers. Expression (5) provides a distance measure allowing for a different weighting system for upper and lower limits, and the center of gravity. The differential weighting system can incorporate issues such as decision makers’ experience, expertise, and risk propensity.

Definition 5 Let $\otimes x = (\underline{x}, \tilde{x}, \bar{x})$ and $\otimes y = (\underline{y}, \tilde{y}, \bar{y})$ be two three-parameter interval grey numbers, and let $\otimes z = (\underline{z}, \tilde{z}, \bar{z})$ be an ideal three-parameter interval grey number. Then the dominance relation of two three-parameter interval grey numbers is represented by expression (6).

$$d(\otimes x, \otimes z) < or = or > d(\otimes y, \otimes z) \tag{6}$$

where $d(\otimes x, \otimes z) < d(\otimes y, \otimes z)$ indicates that the three-parameter interval grey number $\otimes x$ dominates $\otimes y$, denoted as $\otimes x \succ \otimes y$. The small distance measure of a three-parameter interval grey number from the ideal three-parameter interval grey number will be the more dominant degree in decision-making and why a smaller distance value is more dominant.

Definition 6 Let $x = \{\otimes x_1, \otimes x_2, \dots, \otimes x_n\}$ and $y = \{\otimes y_1, \otimes y_2, \dots, \otimes y_n\}$ be a decision sequence consisting of three-parameter interval grey numbers, and let $z = \{\otimes z_1, \otimes z_2, \dots, \otimes z_n\}$ be the ideal sequence consisting of the ideal three-parameter interval grey number. Then the dominance relation of a two decision sequence is represented by expression (7).

$$\sum_{j=1}^n d(x, z) < or = or > \sum_{j=1}^n d(y, z) \tag{7}$$

where $\sum_{j=1}^n d(x, z) < \sum_{j=1}^n d(y, z)$ represents decision sequence x as more dominant than y . Denoted $x \succ y$.

These relationships will be utilized to advance the traditional VIKOR method.

3.2 Rough set theory

Rough set theory (Pawlak 1982), is an analytical approach for managing vagueness and ambiguity. The method classifies objects into similarity classes (clusters) containing objects that are indiscernible with respect to previous occurrences and knowledge. These similarity classes are then employed to determine various patterns within the data. Rough set theory has been utilized for such diverse applications as technical diagnostics for a fleet of vehicles (Sawicki and Žak 2009), credit risk for financial information (Ong et al. 2005) and more recently for sustainable supply chain and operations management concerns (Bai and Sarkis 2010a, b; 2014b). Some particulars of rough set theory, for later integration, are now introduced with notation and definitions.

Definition 7 Let $S = (U, R)$ be an approximation space, where U is a non-empty finite universe and R is an equivalence relation on U . An approximation space $S = (U, R)$ can be regarded as a knowledge base about U .

The equivalence relation R can be defined that two objects are equivalent if and only if they have the same value on every attribute based on a set of attributes (Pawlak 1982). The equivalence class, which are called elemental information granules in the approximation space, contain an object $x(x \in U)$ defined as $[x]_R = \{y \mid y \in U, x R y\}$.

Definition 8 Given any equivalence relation R and any subset $X \in U$, we can define a lower approximation of X in U and an upper approximation of X in U by the following expressions:

$$\underline{R}X = \{x \in U \mid [x]_R \subseteq X\} \tag{8}$$

and

$$\bar{R}X = \{x \in U \mid [x]_R \cap X \neq \emptyset\} \tag{9}$$

Approximation vagueness is usually defined by precise values of lower and upper approximations. Lower approximations $POS_R(X) = \underline{R}X$ describe the object domain that definitely belongs to the subset of interest. Upper approximations describe objects which may possibly belong to the subset of interest. The difference between the upper and the lower approximations constitutes a boundary region $BNDR(X) = \overline{R}X - \underline{R}X$ for the vague set. Hence, rough set theory expresses vagueness by employing a boundary region of a set. If the boundary region of a set is empty, $BNDR(X) = 0$, the set is crisp; otherwise, the set is rough (inexact).

3.3 VIKOR method

The VIKOR method was developed for multi-criteria optimization and compromise solutions of complex systems and has been used in some areas of transportation evaluation (Opricovic and Tzeng 2002, 2004; Tzeng et al. 2005). It is a discrete alternative multiple criteria ranking and selection approach based on a particular measure of proximity to an ideal solution. VIKOR focuses on ranking of solutions in the presence of conflicting criteria helping decision-makers select the “best” compromise solution (Opricovic and Tzeng 2007). Compromise solutions can aid decision makers reach improved final decisions and solve discrete decision problems with non-commensurable and conflicting criteria (Ou Yang et al. 2013).

The multi-criteria measure for compromise ranking is developed from the L_p -metric used as an aggregating function in a compromise programming method (Yu 1973). Let $i = 1, 2, \dots, m$ and F_1, F_2, \dots, F_m denote the m alternatives facing a decision-maker. Let $j = 1, 2, \dots, n$, with n being the number of criteria. Then the performance score for alternative F_i with respect to the j th criterion is denoted by f_{ij} . Let w_j be the weight on the j th criterion which expresses the relative importance of that criterion. Development of the VIKOR method starts with the following form of the L_p -metric:

$$L_{p,i} = \left\{ \sum_{j=1}^n \left[w_j \left(|f_j^+ - f_{ij}| \right) / \left(|f_j^+ - f_j^-| \right) \right]^p \right\}^{1/p}, \quad 1 \leq p \leq \infty; i = 1, \dots, m \tag{10}$$

where f_j^+ represents the highest performance score with respect to the j th criterion among all alternatives. Likewise, f_j^- represents the lowest performance score with respect to the j th criterion. $L_{1,i}$ (as S_i) and $L_{\infty,i}$ (as Q_i) are used to formulate ranking measures.

$$S_i = L_{p=1,i} = \sum_{j=1}^n \left[w_j \left(|f_j^+ - f_{ij}| \right) / \left(|f_j^+ - f_j^-| \right) \right] \tag{11}$$

$$Q_i = L_{p=\infty,i} = \max_j \left[w_j \left(|f_j^+ - f_{ij}| \right) / \left(|f_j^+ - f_j^-| \right) \right] \tag{12}$$

VIKOR ranks the alternatives by sorting the values of S_i , Q_i and R_i , for $i = 1, 2, \dots, m$, in decreasing order.

$$R_i = v(S_i - S^+) / (S^- - S^+) + (1 - v)(Q_i - Q^+) / (Q^- - Q^+) \tag{13}$$

where $S^+ = \min_i S_i$, $S^- = \max_i S_i$, $Q^+ = \min_i Q_i$, $Q^- = \max_i Q_i$ and v is introduced as a weight on the strategy of maximum group utility (average gap in scale normalization), whereas $1 - v$ is the weight of the individual regret (maximal gap in special criterion for priority improvement).

[Opricovic and Tzeng \(2004\)](#) propose a compromise solution, for a transportation vehicle in this case, $A(1)$, which is ranked by the measure R (minimum) when the following two conditions are satisfied:

C1. Acceptable advantage:

$$R(A(2)) - R(A(1)) \geq 1/(m - 1), \quad (14)$$

where $A(2)$ is the alternative positioned second in the ranking list by R and m is the number of alternatives.

C2. Acceptable stability in decision making:

The alternative $A(1)$ must also be the best ranked by S and/or Q . This compromise solution is stable within a decision making process, which could be the strategy of maximum group utility (when $v > 0.5$ is needed), or “by consensus” $v \approx 0.5$, or “with veto” ($v < 0.5$). Here, v is the weight of the decision making strategy of maximum group utility.

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

- Alternatives $A(1)$ and $A(2)$ if only the condition C2 is not satisfied, or
- Alternatives $A(1), A(2), \dots, A(M)$ if the condition C1 is not satisfied; $A(M)$ is determined by the relation $R(A(M)) - R(A(1)) < 1/(m - 1)$ for maximum M (the positions of these alternatives are “in closeness”).

4 An empirical case study

We now illustrate the application of the proposed hybrid methodology for evaluation and selection of sustainable transportation vehicles using actual case study data. Decision-making data and estimations were provided by a panel of experts comprised of three industry professionals from three different sectors. The experts, including three Australian professionals with senior fleet management roles in logistics, food and beverage, and discrete part manufacturing industries, were nominated by two of the leading industries in each sector.

Step 1: Construct the original decision system

To start evaluating and ranking transportation vehicles based on various sustainability metrics, a decision table is constructed for the potential alternatives (see Table 3). This decision table is defined by $T = (U, C, V, f)$, where $U = \{F_1, F_2, \dots, F_m\}$ is a set of m alternative transportation vehicles called the universe. $C = \{c_1, c_2, \dots, c_n\}$ is a set of n sustainability attributes. Where f is a function used to define the value V .

In this case, a total of 10 potential vehicle alternatives, $U = \{F_i, i = 1, 2, \dots, 10\}$ is considered. The performance of each vehicle alternative is weighted against 18 attributes $C = \{c_j, j = 1, 2, 3, \dots, 18\}$. The attributes outlined in Table 1 were used as the starting point and were further refined and reduced by the expert panel to reflect the current transport vehicle fleet selection practice in three major industrial sectors, logistics, food and beverage, and discrete part manufacturing. The resulting attributes include five vehicle characteristic attributes including price, unit fuel cost, speed range, safety, and information technology; three pollution emissions attributes including CO₂ emissions, noise pollution, and other air pollutants; two policies and regulations attributes including compliant with environmental regulations and governments subsidies and incentives; two resources attributes including alternative fuels and energy consumption rate; two infrastructure attributes including the availability of fuels and maintenance services; two recycling attributes including compliance

with ELV and recycling costs; and two scalability attributes including the impacts of weather change and vehicle operation in disasters.

Step 2: Determine the performance of each vehicles against the sustainability attributes
 The panel of experts was asked to evaluate the performance of each vehicle against the identified attributes. Some of this data is related to actual values (such as the vehicle price), and others are scaled in linguistic perceptual scores such as very poor, medium/average, good and very good. The collected data and expert opinions are shown in Table 3. No data was available for recycling costs and the impacts of weather change on vehicle operation. A “not available” (N/A) notation is used in the table and the two attributes are discarded from the evaluation process.

Step 3: Normalize the information decision system
 For consistency in evaluations, a normalization procedure is introduced such that sustainability attributes and all the later calculations, such as distance measures, use similar scales. Note that some of these raw values are in crisp (regular) form and some are based on qualitative judgments. This normalization will adjust all the sustainability attribute values for each alternative (f_{ij}) to be $(0, 0, 0) \leq \otimes f_{ij} \leq (1, 1, 1)$.

Step 3.1: Transform values into three-parameter interval grey numbers
 All values are transformed into a three parameter interval grey number $\otimes f$. For the crisp form, the transformation is given as: $f_{ij} = \otimes f_{ij} = (\underline{f}_{ij} = f_{ij}, \tilde{f}_{ij} = f_{ij}, \bar{f}_{ij} = f_{ij})$. Price is an example of a crisp valued attribute, for which the transformation to a three parameter interval grey number for vehicle 01 is given as $F_{01Price} = 84000 = (\underline{f}_{01Price} = 84000, \tilde{f}_{01Price} = 84000, \bar{f}_{01Price} = 84000)$. For the linguistic or qualitative form, we introduce a three parameter interval grey numerical scale table that would correspond to the qualitative values given by the decision makers. Seven linguistic variables, namely “very good”, “good”, “medium good”, “medium”, “medium poor”, “poor” and “very poor”, are used to assess the level of the performance criteria. This seven-level scale is shown in Table 4. The qualitative variables and natural language variables are transformed into three parameter interval grey numbers. Identical scales are used for all decision attributes.

Safety is an example of a qualitatively valued attribute, for which the transformation to a triangular grey number for vehicle 01 is given as: $F_{01Safety} = VG = (0.9, 1.0, 1.0)$.

Step 3.2: Normalize the numeric variables by membership function
 All the three parameter interval grey numeric values are now normalized. Each decision attribute has a different maximum and minimum value. The three parameter interval grey numbers cannot be normalized using a traditional normalization procedure. To address this issue a membership function, expressions (15) and (16) are introduced. Normalization of the incremental (beneficial) value of the three parameter interval grey number is completed using the membership function in expression (15).

$$\otimes v_{ij} = (v_{ij}, \tilde{v}_{ij}, \bar{v}_{ij}) = \left(v_{ij} = \frac{\underline{f}_{ij} - Lower_j}{Upper_j - Lower_j}, \tilde{v}_{ij} = \frac{\tilde{f}_{ij} - Lower_j}{Upper_j - Lower_j}, \bar{v}_{ij} = \frac{\bar{f}_{ij} - Lower_j}{Upper_j - Lower_j} \right) \tag{15}$$

where $(\underline{f}_{ij}, \tilde{f}_{ij}, \bar{f}_{ij})$ is the initial specific evaluation value, $(v_{ij}, \tilde{v}_{ij}, \bar{v}_{ij})$ is the normalized evaluation value and $0 \leq v_{ij}, \tilde{v}_{ij}, \bar{v}_{ij} \leq 1$. $Lower_j$ is the minimum historical value for a

Table 3 Information system table: the performance of each vehicle against the identified sustainability attributes

Vehicles type	Vehicle characteristics				Pollution emissions				Policies and regulations		
	Vehicle price	Unit fuel cost	Travelling speed range	Safety features	Information technology	CO ₂ emissions rate	Noise pollution rate	Other air pollutants	Compliance with government regulations	Government subsidies/incentives	
Vehicle 01	\$84,000	(\$1.54, \$1.56, \$1.58)	(60, 70, 80)	VG	VG	VG	VG	M	VG	\$2,000	
Vehicle 02	\$80,000	(\$1.54, \$1.56, \$1.58)	(60, 70, 80)	VG	VG	G	VG	M	VG	\$2,000	
Vehicle 03	\$74,000	(\$1.54, \$1.56, \$1.58)	(60, 70, 80)	G	G	MG	VG	M	VG	\$0	
Vehicle 04	\$70,000	(\$1.54, \$1.56, \$1.58)	(60, 70, 80)	MG	M	M	G	M	VG	\$0	
Vehicle 05	\$68,000	(\$1.54, \$1.56, \$1.58)	(60, 70, 80)	M	M	M	G	M	VG	\$0	
Vehicle 06	\$65,000	(\$1.54, \$1.56, \$1.58)	(60, 70, 80)	M	M	MP	G	M	VG	\$0	
Vehicle 07	\$62,000	(\$1.54, \$1.56, \$1.58)	(60, 70, 80)	MP	M	P	G	M	VG	\$0	
Vehicle 08	\$60,000	(\$1.54, \$1.56, \$1.58)	(60, 70, 80)	MP	M	P	G	M	G	\$0	
Vehicle 09	\$57,000	(\$1.54, \$1.56, \$1.58)	(60, 70, 80)	P	M	VP	MG	M	G	\$0	
Vehicle 10	\$52,000	(\$1.54, \$1.56, \$1.58)	(60, 70, 80)	P	M	VP	MG	M	G	\$0	

Table 3 continued

Vehicles type	Resources		Infrastructure		Recycling		Scalability	
	Alternative fuel	Energy consumption rate	Availability of fuels	Availability of maintenance services	Vehicle compliance with ELV	Recycling costs	The impact of weather changes	Vehicle operation in disasters
Vehicle 01	VP	VG	VG	MG	G	N/A	N/A	VG
Vehicle 02	VP	VG	VG	VG	G	N/A	N/A	VG
Vehicle 03	VP	G	VG	VG	G	N/A	N/A	M
Vehicle 04	VP	G	VG	M	G	N/A	N/A	M
Vehicle 05	VP	MG	VG	M	G	N/A	N/A	VP
Vehicle 06	VP	M	VG	M	G	N/A	N/A	VP
Vehicle 07	VP	MP	VG	M	G	N/A	N/A	VP
Vehicle 08	VP	MP	VG	M	G	N/A	N/A	VP
Vehicle 09	VP	MP	VG	M	G	N/A	N/A	VP
Vehicle 10	VP	P	VG	M	G	N/A	N/A	VP

Table 4 The linguistic variables and their corresponding three-parameter interval grey numbers

Linguistic variables	Three-parameter interval grey numbers
Very poor (VP)	(0, 0, 0.1)
Poor (P)	(0, 0.1, 0.3)
Medium poor (MP)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
Medium good (MG)	(0.5, 0.7, 0.9)
Good (G)	(0.7, 0.9, 1.0)
Very good (VG)	(0.9, 1.0, 1.0)

factor j , and $Upper_j$ is the maximum historical value for a factor j . If \underline{v}_{ij} or \tilde{v}_{ij} or $\bar{v}_{ij} < 0$, we set \underline{v}_{ij} or \tilde{v}_{ij} or $\bar{v}_{ij} = 0$, If \underline{v}_{ij} or \tilde{v}_{ij} or $\bar{v}_{ij} > 1$, we set \underline{v}_{ij} or \tilde{v}_{ij} or $\bar{v}_{ij} = 1$,

The negative (decreasing) membership value of the three parameter interval grey number is determined using the membership function in expression (16):

$$\otimes v_{ij} = (\underline{v}_{ij}, \tilde{v}_{ij}, \bar{v}_{ij}) = \left(\underline{v}_{ij} = \frac{Upper_j - \tilde{f}_{ij}}{Upper_j - Lower_j}, \right. \\ \left. \tilde{v}_{ij} = \frac{Upper_j - \tilde{f}_{ij}}{Upper_j - Lower_j}, \bar{v}_{ij} = \frac{Upper_j - \underline{f}_{ij}}{Upper_j - Lower_j} \right) \tag{16}$$

For the vehicle price attribute (smaller is better) of vehicle 01 which was exemplified in step 3.1, the normalization using expression (16) is as follows:

$$F_{01Price} = 84000 = (\underline{f}_{ij} = 84000, \tilde{f}_{ij} = 84000, \bar{f}_{ij} = 84000), \text{ and} \\ Upper_{Price} = 84000, Lower_{Price} = 52000 \\ \underline{v}_{01Price} = \frac{|Upper_{Price} - \tilde{f}_{01Price}|}{|Upper_{Price} - Lower_{Price}|} = \frac{|84000 - 84000|}{|84000 - 52000|} = 0; \\ \tilde{v}_{01Price} = \frac{|Upper_{Price} - \tilde{f}_{01Price}|}{|Upper_{Price} - Lower_{Price}|} = \frac{|84000 - 84000|}{|84000 - 52000|} = 0; \\ \bar{v}_{01Price} = \frac{|Upper_{Price} - f_{01Price}|}{|Upper_{Price} - Lower_{Price}|} = \frac{|84000 - 84000|}{|84000 - 52000|} = 0$$

Thus, the normalized value of the three-parameter interval grey number for vehicle price attribute of vehicle 01 would be $F_{01Price} = \otimes v_{ij} = (\underline{v}_{01Price} = 0, \tilde{v}_{01Price} = 0, \bar{v}_{01Price} = 0)$. We arrive at a normalized matrix $\otimes v_{ij}$ from the original matrix f_{ij} with expressions identified in this step 3.2. The normalization process alters all normalized decision attributes to have increasing values representing better sustainability attributes. The resulting normalized values are shown in Table 5. Note that these transformed three parameter interval grey number values for qualitative variables and natural language variables are already normalized. These type of variable values do not need a normalization process.

Step 4: Determine information content of each attribute

In the following steps we focus on the use of rough set theory to determine the importance (weight) of each attribute. The goal is to determine the various ‘conditional attribute elementary sets’ (X) for each vehicle. First, expression (17) is used to determine the level of information content across the conditional attributes (c) (Liang et al. 2006).

Table 5 Normalized values of all sustainability attributes

Vehicle type	Vehicle price	Unit fuel cost	Travelling speed range	Safety features	Information technology	CO ₂ emissions rate	Noise pollution rate	Other air pollutants	Compliance with government regulations
Vehicle 01	(0, 0, 0)	(0, 0.5, 1)	(0, 0.5, 1)	(0.9, 1, 1)	(0.9, 1, 1)	(0.9, 1, 1)	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.9, 1, 1)
Vehicle 02	(0.125, 0.125, 0.125)	(0, 0.5, 1)	(0, 0.5, 1)	(0.9, 1, 1)	(0.9, 1, 1)	(0.7, 0.9, 1)	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.9, 1, 1)
Vehicle 03	(0.313, 0.313, 0.313)	(0, 0.5, 1)	(0, 0.5, 1)	(0.7, 0.9, 1)	(0.7, 0.9, 1)	(0.5, 0.7, 0.9)	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.9, 1, 1)
Vehicle 04	(0.438, 0.438, 0.438)	(0, 0.5, 1)	(0, 0.5, 1)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)	(0.9, 1, 1)
Vehicle 05	(0.5, 0.5, 0.5)	(0, 0.5, 1)	(0, 0.5, 1)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)	(0.9, 1, 1)
Vehicle 06	(0.594, 0.594, 0.594)	(0, 0.5, 1)	(0, 0.5, 1)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.1, 0.3, 0.5)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)	(0.9, 1, 1)
Vehicle 07	(0.688, 0.688, 0.688)	(0, 0.5, 1)	(0, 0.5, 1)	(0.1, 0.3, 0.5)	(0.3, 0.5, 0.7)	(0, 0.1, 0.3)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)	(0.9, 1, 1)
Vehicle 08	(0.75, 0.75, 0.75)	(0, 0.5, 1)	(0, 0.5, 1)	(0.1, 0.3, 0.5)	(0.3, 0.5, 0.7)	(0, 0.1, 0.3)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)
Vehicle 09	(0.844, 0.844, 0.844)	(0, 0.5, 1)	(0, 0.5, 1)	(0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0, 0, 0.1)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)
Vehicle 10	(1, 1, 1)	(0, 0.5, 1)	(0, 0.5, 1)	(0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0, 0, 0.1)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)
Ideal vehicle	(1, 1, 1)			(0.9, 1, 1)	(0.9, 1, 1)	(0.9, 1, 1)	(0.9, 1, 1)		

Table 5 continued

Vehicle type	Governments subsidies/incentives	Alternative fuel	Energy consumption rate	Availability of fuels	Availability of maintenance services	Vehicle compliance with ELV	Vehicle operation in disasters
Vehicle 01	(1, 1, 1)	(0, 0, 0.1)	(0.9, 1, 1)	(0.9, 1, 1)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)	(0.9, 1, 1)
Vehicle 02	(1, 1, 1)	(0, 0, 0.1)	(0.9, 1, 1)	(0.9, 1, 1)	(0.9, 1, 1)	(0.7, 0.9, 1)	(0.9, 1, 1)
Vehicle 03	(0, 0, 0)	(0, 0, 0.1)	(0.7, 0.9, 1)	(0.9, 1, 1)	(0.9, 1, 1)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)
Vehicle 04	(0, 0, 0)	(0, 0, 0.1)	(0.7, 0.9, 1)	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)
Vehicle 05	(0, 0, 0)	(0, 0, 0.1)	(0.5, 0.7, 0.9)	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)	(0, 0, 0.1)
Vehicle 06	(0, 0, 0)	(0, 0, 0.1)	(0.3, 0.5, 0.7)	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)	(0, 0, 0.1)
Vehicle 07	(0, 0, 0)	(0, 0, 0.1)	(0.1, 0.3, 0.5)	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)	(0, 0, 0.1)
Vehicle 08	(0, 0, 0)	(0, 0, 0.1)	(0.1, 0.3, 0.5)	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)	(0, 0, 0.1)
Vehicle 09	(0, 0, 0)	(0, 0, 0.1)	(0.1, 0.3, 0.5)	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)	(0, 0, 0.1)
Vehicle 10	(0, 0, 0)	(0, 0, 0.1)	(0, 0.1, 0.3)	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)	(0, 0, 0.1)
Ideal vehicle	(1, 1, 1)		(0.9, 1, 1)		(0.9, 1, 1)		(0.9, 1, 1)

The ideal vehicle is defined by selecting the maximum value for the attributes using expression (20)

Table 6 Elementary sets for vehicle price attribute

Elementary set type	Members in elementary set type	Number in set ($ X_i^{\text{Price}} $)
TYPE1	Vehicle 01	1
TYPE2	Vehicle 02	1
TYPE3	Vehicle 03	1
TYPE4	Vehicle 04 Vehicle 05	2
TYPE5	Vehicle 04 Vehicle 05 Vehicle 06	3
TYPE6	Vehicle 05 Vehicle 06 Vehicle 07	3
TYPE7	Vehicle 06 Vehicle 07 Vehicle 08	3
TYPE8	Vehicle 08 Vehicle 09	2
TYPE9	Vehicle 09	1
TYPE10	Vehicle 10	1

$$I(c) = 1 - \frac{1}{|U|^2} \sum_{i=1}^{|U|} |X_i^c| \tag{17}$$

where $I(c)$ is the information content³ for each conditional attribute, in the case of this study, it is each of the sustainability attributes. $|U|$ is the cardinality of the universe of vehicles. $|X_i^c|$ is the number of vehicles with similar attributes levels across the conditional attribute c for vehicle i . It is also defined as the number of members within the conditional attribute c for vehicle i .

Given lower approximation \underline{RX} of a rough set from Definition 8, a lower approximation of X for attribute c with a three parameter interval grey number can be determined using expression (18):

$$X_i^c = \{x_j \in U | d_c(x_i, x_j) \leq \delta\}, \tag{18}$$

where δ is the inclusion threshold value and $0 \leq \delta \leq 0.5$. In this case study, $\delta = 0.1$. That is, two vehicles i and j are members of the same set only if $d_c(x_i, x_j) \leq \delta$ for $c \in C$, where $d_c(x_i, x_j)$ denotes the distance measure of two transportation vehicle i and j for the value of attribute $c \in C$.

Take for example, the distance measure $d_{\text{Price}}(x_{05}, x_{04}) = 0.063$ between transportation vehicle 5 and 4 is less than 0.1. The distance measure $d_{\text{Price}}(x_{05}, x_{06}) = 0.094$ between vehicles 5 and 6 is also less than 0.1. Overall, $|X_{05}^{\text{Price}}| = 3$. Table 6 shows the listing of vehicle price attribute elementary set types and respective $|X_i^{\text{Price}}|$ values for each vehicle within that set. The various ‘conditional attribute elementary set types’ (X_i^c) for the vehicles are determined for the vehicle set when they have similar attributes levels across the conditional attribute c for a vehicle i .

Using expression (17) and data in Table 6, the information content for the vehicle price attributes will be:

$$I(\text{vehicle price}) = 1 - \left(\frac{1}{|10|^2} (1 + 1 + \dots + 1) \right) = 1 - \frac{20}{100} = 0.8.$$

³ This term has also been defined as information entropy of a system (Liang and Shi 2004).

Table 7 Information content and importance for each sustainability attribute

Category	Attributes	Information content	Weight
Vehicle characteristics	Vehicle price	0.8	0.156
	Unit fuel cost	0	0.000
	Travelling speed range	0	0.000
	Safety features	0.78	0.152
	Information Technology	0.42	0.082
Pollution emissions	CO ₂ emissions rate	0.74	0.145
	Noise pollution rate	0.32	0.063
	Other air pollutants	0	0.000
Policies and regulations	Compliance with government regulations	0	0.000
	Governments subsidies/incentives	0.32	0.063
Resources	Alternative fuel	0	0.000
	Energy consumption rate	0.72	0.141
Infrastructure	Availability of fuels	0	0.000
	Availability of maintenance services	0.46	0.090
Recycling scrap	Vehicle compliance with ELV	0	0.000
	Recycling costs	0	0.000
Scalability	The impact of weather changes	0	0.000
	Vehicle operation in disasters	0.56	0.109

An analogous approach is used to calculate the information content for the remaining vehicle attributes. The results are shown in Table 7. The information content will be valuable input to help identify the relative importance weight of each attribute, which is described in step 5.

Step 5: Determine the importance (weight) of each attribute

Expression (19) is a normalization equation used to identify the information significance (weight) of each attribute.

$$w(c_j) = \frac{I(c_j)}{\sum_{j=1}^n I(c_j)} \tag{19}$$

where aggregated weight values meet the condition $\sum_{j=1}^n w_j = 1$.

The cumulative information content of all attributes is equal to $\sum_{j=1}^n I(c_j) = 5.12$. The information content for vehicle price attributes is 0.8. Then the normalized weight for vehicle price attribute is $w(\text{vehicle price}) = \frac{0.8}{5.12} = 0.156$. The calculated weights of all attributes are shown in Table 7. For some attributes, the weight is equal to zero. According to the original rough set approach these attributes do not provide useful information in distinguishing the sustainability performance of different vehicles, they are excluded from subsequent analyses.

Table 8 The index values for each vehicle type

Vehicle type	S_i	Ranking	Q_i	Ranking	R_i	Ranking
Vehicle 01	0.181	2	0.156	10	0.530	6
Vehicle 02	0.151	1	0.137	7	0.357	3
Vehicle 03	0.299	3	0.107	4	0.291	2
Vehicle 04	0.415	4	0.088	1	0.263	1
Vehicle 05	0.512	5	0.104	2	0.478	4
Vehicle 06	0.554	6	0.104	3	0.520	5
Vehicle 07	0.624	7	0.123	6	0.728	8
Vehicle 08	0.614	8	0.123	5	0.718	7
Vehicle 09	0.651	9	0.137	8	0.861	9
Vehicle 10	0.652	10	0.137	9	0.861	10

Step 6: Determine the ideal vehicle/solution

The most ‘ideal’ vehicle F^* is defined by selecting the maximum value for the attributes using expression (20).

$$F^+ = \{v_1^+, \dots, v_n^+\} = \{(\max_i v_{ij})\} \tag{20}$$

Using expressions (20), we arrive at: $F^+ = \{(1, 1, 1), (0.9, 1, 1), (0.9, 1, 1), (0.9, 1, 1), (0.9, 1, 1), (1, 1, 1), (0.9, 1, 1), (0.9, 1, 1), (0.9, 1, 1), (0.9, 1, 1)\}$.

Step 7: Calculate the group utility S_i and the maximal regret Q_i

The values of S_i and Q_i are calculated based on the distance measure expression (5). The center of gravity is set by decision makers, tapping into their experience, is set equal to 0.5. The importance of the upper limit and lower limit are set at 0.25 each. For the vehicle price attribute of vehicle 01, the distance measure is calculated as $w_{Price}d(v_{01Price}, v_{Price}^*) = 0.156 * (0.25|0 - 1| + 0.5|0 - 1| + 0.25|0 - 1|) = 0.156$. The results for other attributes are 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.025, 0, and 0 respectively. The value of S_i for vehicle 01 is the sum of the above values, which will be equal to 0.181. The value of Q_i for vehicle 01 is the max of above values, i.e. 0.156.

Step 8: Compute the index values (R_i)

R_i is a compromise solution for a vehicle which is the highest ranked when considering the maximum group utility and the individual regret jointly. We set parameter v equal to 0.5 implying that the weights on the strategy of maximum group utility would be equal the weight of the individual regret. Then, we get $S^+ = \min_i S_i = 0.151$, $S^- = \max_i S_i = 0.652$, $Q^+ = \min_i Q_i = 0.088$, and $Q^- = \max_i Q_i = 0.156$. The value of R_1 for vehicle 01 would be $R_i = v(S_i - S^+) / (S^- - S^+) + (1 - v)(Q_i - Q^+) / (Q^- - Q^+) = 0.5 * (0.181 - 0.151) / (0.652 - 0.151) + 0.5 * (0.156 - 0.088) / (0.156 - 0.088) = 0.530$. The values of S_i , Q_i , and R_i for other vehicles are shown in Table 8.

The compromise solutions for vehicles, which are ranked as better by the measure R_i , where smaller values are better, must satisfy the C1 and C2 conditions. For the acceptable advantage condition (C1), we have $R_5 - R_2 = 0.121 \geq 0.111$ where $R_2 = 0.357$ and $R_5 = 0.478$ and $\frac{1}{m-1} = \frac{1}{10-1} = 0.111$ shown in the Table 8. For the acceptable stability in decision making condition (C2), vehicles F_4 , F_3 and F_2 are the compromise solutions. These are compromise solutions due to the advantages between them not being significant or obvious, that is, $R_4 - R_3$ and $R_3 - R_2$ are smaller than $\frac{1}{m-1}$.

Step 9: Compute the dominance probability

VIKOR can rank the transportation vehicles, but it cannot determine the dominance probability value for each vehicle when compared to other vehicles. We introduce this important extension to the method at this time. The VIKOR methodology is enhanced since the initial data is based on decision makers’ subjective judgment, the ranking result contains some probability degrees. The dominance probability degree is now determined by establishing a dominance matrix. First Definition 9 is introduced to help us construct the dominance matrix.

Definition 9 Let $x = \{\otimes x_1, \otimes x_2, \dots, \otimes x_n\}$ and $y = \{\otimes y_1, \otimes y_2, \dots, \otimes y_n\}$ be a transportation vehicle decision sequence consisting of the various attributes represented by three parameter interval grey numbers, and let w_j be the importance weight of attribute j . Then the dominance probability degree of two alternative vehicles based on the VIKOR theory is obtained from expression (21).

$$\begin{aligned}
 p(x \succ y) &= p \left(\left(\frac{1}{n} v \left(\sum_{j=1}^n w_j x_j \right) + (1 - v)(w_k x_k) \right) \right. \\
 &\quad \left. \geq \left(\frac{1}{n} v \left(\sum_{j=1}^n w_j y_j \right) + (1 - v)(w_g y_g) \right) \right) \quad k, g \in Q \quad (21)
 \end{aligned}$$

where the expression “ $p(x \succ y)$ ” represents the probability that transportation vehicle x is better than transportation vehicle y . The variable v is identical to that within VIKOR. The indices k and g represent the attributes (factors) with the greatest individual regret in VIKOR for transportation vehicles x and y , respectively [see expression (12)]. According to the dominance probability degree, the dominance probability matrix is developed using expression (22):

$$P_{n \times n} = p(x_j \geq x_k)_{n \times n} \quad (22)$$

For example, the performance level of vehicle 04 is calculated, using portions of expression (21), as $(\frac{1}{n} v (\sum_{j=1}^n w_j x_j) + (1 - v)(w_k x_k)) = (0.114, 0.132, 0.147)$, where attribute 01 for vehicle 04 ($k =$ attribute 01) is the greatest individual regret attribute from the above VIKOR method process in step 7. The performance level of vehicle 03 is $(0.110, 0.126, 0.136)$, where attribute 01 for vehicle 03 ($k =$ attribute 01) has the greatest individual regret attribute from the above VIKOR method process. Then the probability measure that vehicle 04 is better than vehicle 03 is $p(F_{04} \succ F_{03}) = \frac{0.147 - 0.11 + 0.132 - 0.126}{0.261 + 0.246} = 73\%$. The complete dominance matrix is show in Table 9.

Thus, with a score of 0.263 for the relative closeness, vehicle 04 is the most preferred transportation vehicle among all vehicles in the original set. Vehicle 04 has a 73 % probability that it is better than the second preferred alternative, vehicle 03. The relative closeness rank with the index values (R_i) of vehicles are:

$$F_{04} \underset{73\%}{\succ} F_{03} \underset{100\%}{\succ} F_{02} \underset{100\%}{\succ} F_{05} \underset{61\%}{\succ} F_{06} \underset{0\%}{\succ} F_{01} \underset{100\%}{\succ} F_{08} \underset{52\%}{\succ} F_{07} \underset{82\%}{\succ} F_{09} \underset{50\%}{\succ} F_{10}$$

where the expression “ $F_{04} \underset{73\%}{\succ} F_{03}$ ” represents a 73 % probability that transportation vehicle 04 is better than transportation vehicle 03. $F_{04} \succ F_{03}$ means that vehicle 04 is better than vehicle 03 according the relative closeness rank; 73 % means that vehicle 04 is 73 % likely to be better than vehicle 03 (a probability degree).

A general rank for vehicles with the index values (R_i) from the VIKOR method now exists. Also pairwise comparisons with a probability value (degree) exist. The probability

Table 9 The dominance probability matrix

Vehicles	Vehicle 01 (%)	Vehicle 02 (%)	Vehicle 03 (%)	Vehicle 04 (%)	Vehicle 05 (%)	Vehicle 06 (%)	Vehicle 07 (%)	Vehicle 08 (%)	Vehicle 09 (%)	Vehicle 10 (%)
Vehicle 01	50.00	0.00	0.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00
Vehicle 02	100.00	50.00	0.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00
Vehicle 03	100.00	100.00	50.00	27.00	100.00	100.00	100.00	100.00	100.00	100.00
Vehicle 04	100.00	100.00	73.00	50.00	100.00	100.00	100.00	100.00	100.00	100.00
Vehicle 05	0.00	0.00	0.00	0.00	50.00	61.40	44.80	42.90	86.30	87.10
Vehicle 06	0.00	0.00	0.00	0.00	38.60	50.00	36.50	34.60	74.60	75.20
Vehicle 07	0.00	0.00	0.00	0.00	55.20	63.50	50.00	48.50	81.50	82.00
Vehicle 08	0.00	0.00	0.00	0.00	57.10	65.40	51.50	50.00	83.50	84.00
Vehicle 09	0.00	0.00	0.00	0.00	13.70	25.40	18.50	16.50	50.00	50.10
Vehicle 10	0.00	0.00	0.00	0.00	12.90	24.80	18.00	16.00	49.90	50.00

degree can be used evaluate the quality of the VIKOR method rank. From the dominance probability matrix, vehicle 01 has a 100 percent probability of being better than vehicle types 05 and 06. But from Table 8, vehicle 01 is ranked lower, using the R_i value, than vehicles 05 and 06. Additionally, we can also adjust ranks by considering dominance probability degrees for vehicles with more than 50% dominance. In this situation, vehicle 01, vehicle 08 and vehicle 07 are ranked fourth, fifth, and sixth, respectively.

$$F_{04} \underset{73\%}{>} F_{03} \underset{100\%}{>} F_{02} \underset{100\%}{>} F_{01} \underset{100\%}{>} F_{08} \underset{52\%}{>} F_{07} \underset{55\%}{>} F_{05} \underset{61\%}{>} F_{06} \underset{75\%}{>} F_{09} \underset{50\%}{>} F_{10}$$

The reason for different results produced by the VIKOR distance measure and the dominance probability degree is that the distance measure calculates the relationship with the ideal vehicle, while the dominance probability degree measures the relationship between two vehicles in a pairwise comparison.

5 Sensitivity analysis

In this section we alter the basic values and assumptions associated with the initial case study example to determine the robustness of the results. The distance measure for the three parameter interval grey number was set using values of α and β equal to 0.25 and 0.5, respectively. $\delta = 0.1$ was set as the lower approximation using rough set, and $v = 0.5$ for the weights on the strategy of maximum group utility within VIKOR. These initial results showed the effective application of the proposed methodology for evaluating and ranking the performance of vehicles. However, management may not be quite aware of how to set these parameters due to limited knowledge and understanding of the methodology, or personal subjectivity. To address this issue, a sensitivity analysis is completed to determine the impact of changing some of these parameters on the final results.

5.1 Varying parameters α and β

This section aims to determine the solution robustness when varying parameters α and β . β is varied over the range of $0.5 \leq \beta \leq 1.0$, in increments of 0.1 and $\alpha = \frac{(1-\beta)}{2}$ for the relative closeness rank implying that the upper and lower limits are of identical importance. The results of the sensitivity analysis are shown in Fig. 1. We observe that the vehicle ranking results are relatively robust for changes in α and β values. This indicates the limited impact of the weight of α and β on the relative closeness rank. These values can be determined by decision makers according to the certainty of the center of gravity for each attribute.

5.2 Varying parameter δ

We complete another analysis to determine the sensitivity of the weight of each attribute when varying the value of δ . The results are shown in Fig. 2 for δ values over the range of $0.1 \leq \delta \leq 0.5$ in increments of 0.1. The first general observation of these results is that the weight for each sustainability attribute does change. If we were completing a rough set analysis at $\delta = 0.5$, then the weight of information technology, noise pollution and availability of maintenance services attributes would be equal to zero. This result may reduce the sustainability performance measurement (attribute) to a large degree such that significant information could be lost. We observe that the weight for noise pollution attribute would be equal to zero when $\delta = 0.3$. When $\delta = 0$, the rough set model reduces to the basic rough set model and the equivalence relation will become very strict. Two objects with

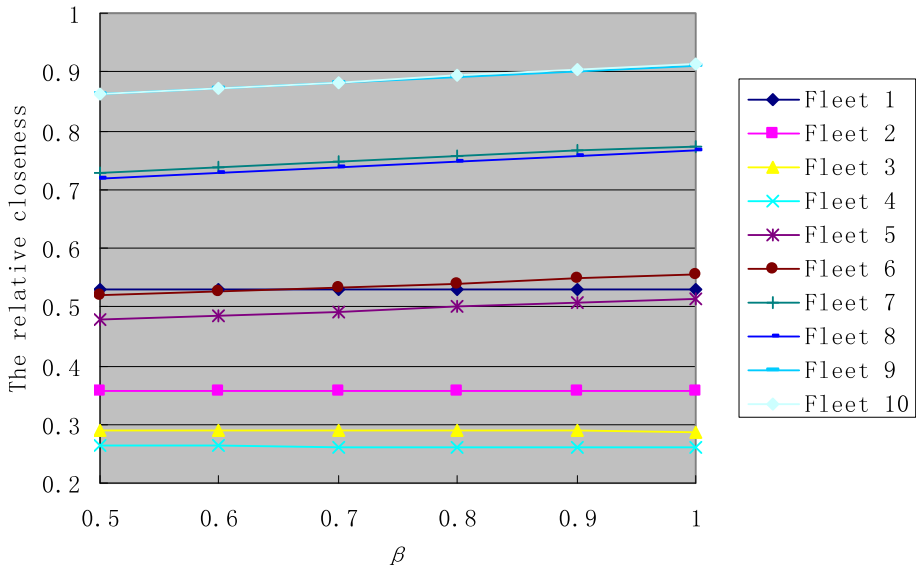


Fig. 1 The relative closeness rank for different values of β

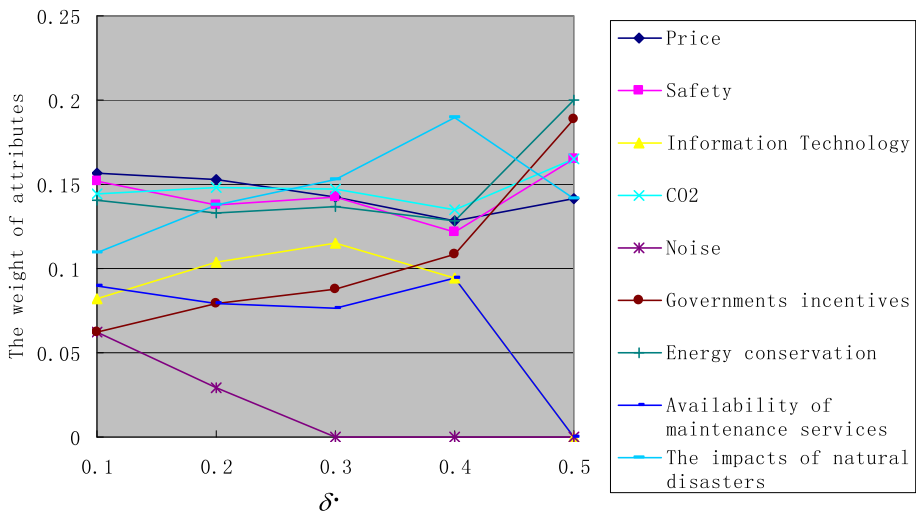


Fig. 2 The weight of attributes for different δ values

the equivalent relation R must have the same value on every attribute. This is not applicable for the three parameter interval grey number. For example, two different vehicles may receive dissimilar values under each attribute, like data for the vehicle price attribute. Then all attributes will have a same weight for $\delta = 0$. The importance of attributes will be difficult to distinguish among attributes. Therefore, a better rang for the inclusion threshold δ is $[0.1, 0.2]$.

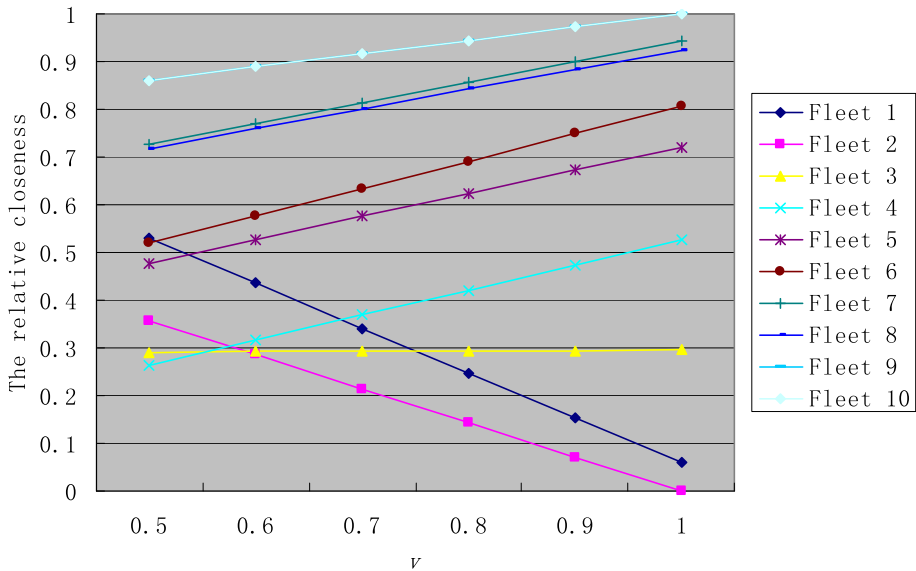


Fig. 3 The relative closeness rank for different v values

5.3 Varying parameter v

A sensitivity analysis can also be completed to determine the robustness of the solution using the weight for the strategy of maximum group utility of VIKOR. We do this over the range of $0.5 \leq v \leq 1.0$ in increments of 0.1 for VIKOR. The results are shown in Fig. 3. It can be observed that the vehicle ranking results do change and sometimes rather significantly. Vehicle 2, for example, is the third best vehicle when $v = 0.5$ and becomes the best alternative when $v > 0.6$. The effect on the relative closeness rank of VIKOR increases as v becomes larger. The ranking performance for vehicles 2 and 1 improves as v increases.

To determine an appropriate value for v, the dominance probability degree between vehicles for every value of v can be helpful. The results are as follows:

$$\begin{aligned}
 v = 0.6 : & F_{02} \succ_{33\%} F_{03} \succ_{49\%} F_{04} \succ_{100\%} F_{01} \succ_{100\%} F_{05} \succ_{63\%} F_{06} \succ_{42\%} F_{08} \succ_{52\%} F_{07} \succ_{78\%} F_{09} \succ_{50\%} F_{10} \\
 & T = 5.67 \\
 v = 0.7 : & F_{02} \succ_{71\%} F_{03} \succ_{92\%} F_{01} \succ_{35\%} F_{04} \succ_{100\%} F_{05} \succ_{63\%} F_{06} \succ_{50\%} F_{08} \succ_{52\%} F_{07} \succ_{74\%} F_{09} \succ_{50\%} F_{10} \\
 & T = 5.87 \\
 v = 0.8 : & F_{02} \succ_{100\%} F_{01} \succ_{55\%} F_{03} \succ_{78\%} F_{04} \succ_{100\%} F_{05} \succ_{64\%} F_{06} \succ_{58\%} F_{08} \succ_{53\%} F_{07} \succ_{70\%} F_{09} \succ_{50\%} F_{10} \\
 & T = 6.28 \\
 v = 0.9 : & F_{02} \succ_{97\%} F_{01} \succ_{91\%} F_{03} \succ_{87\%} F_{04} \succ_{100\%} F_{05} \succ_{65\%} F_{06} \succ_{65\%} F_{08} \succ_{53\%} F_{07} \succ_{66\%} F_{09} \succ_{50\%} F_{10} \\
 & T = 6.74 \\
 v = 1.0 : & F_{02} \succ_{78\%} F_{01} \succ_{100\%} F_{03} \succ_{94\%} F_{04} \succ_{84\%} F_{05} \succ_{66\%} F_{06} \succ_{72\%} F_{08} \succ_{54\%} F_{07} \succ_{62\%} F_{09} \succ_{50\%} F_{10} \\
 & T = 6.6
 \end{aligned}$$

where T is the sum of probability degree for the ranked transportation vehicles.

The greater the value of T , the higher the overall probability that the rank order is correct. For example, the highest value if all the order probabilities were exactly 100 % would mean a total value of $T=10$. At $v = 0.9$, the dominance probability degree sums to 6.74. Therefore, $v = 0.9$ results in the most likely, based on probabilities, ordering.

5.4 Discussion

The results of this study show that the approach can be useful for managers seeking to identify the type of vehicles and vehicle fleets to select using various performance and sustainability criteria. Practical validity of the approach occurred because managers saw value in this approach and provided realistic inputs. The introduction of new factors and decision metrics for sustainable transportation vehicles, rough set analysis, and a probability analysis of the rank order are valuable in providing a more realistic evaluation of the situation. Also, it addresses some concerns related to inconsistencies of the VIKOR method and providing an alternative evaluation with VIKOR as a core technique.

The further development and refinement of the approach is valuable in advancing logical and rigorous application of various discrete alternative MCDM tools. This refinement may be needed by developing a seamless linkage of the techniques through development of a decision support tool. Currently, the process involved various software tools and steps, which were opaque to management. The question of whether providing additional transparency will aid in acceptance or confuse managers is a concern. Management may be unwilling to accept approaches without some idea of the inner workings of a technique and not a 'black-box'. A simplified explanation, rather than mathematical symbolism, is needed.

We also show that this technique is sensitive to parameter selection. This sensitivity may be viewed as a weakness since some of the solutions vary significantly. But, the sensitivity can also be considered a methodological strength. A sensitive solution allows managers to be more discriminate and careful in their selection of parameter values. A sensitive solution can result in additional discussion. It can also show that the technique is 'fairer' in that not one solution is always viewed as the best and that a more balanced set of results can be incorporated. Management may be more accepting of this situation since it allows them to manipulate and argue for a particular choice and incorporate their own implicit factors and considerations. Even though the technique started with a narrowing down of factors, sometimes consensus factors are selected which may leave out some factors that individual managers view as critical outside the final consensus factor set.

Overall, the technique helps model a relatively complex sustainable transportation vehicle fleet decision environment and simplify it somewhat through rough set approaches. The use of VIKOR and probability estimations of the correctness of the rankings is an advance to enhance the reliability of the solutions and even adjust as necessary. Overall, these two additions help in providing further support for these tools by simplifying the procedure and providing more reliable results.

6 Conclusions

Given the critical significance of the environmental burdens of transportation activities (Fahimnia et al. 2015a), the need for the development of decision support tools for evaluation and selection of environmentally conscious transportation fleets is evident. This paper contributed to this area by introducing a novel 9-step methodology integrating rough set theory and the VIKOR method with three-parameter interval grey numbers. These three

approaches allow for consideration of intangibility and ambiguity from expert judgment amongst the attributes and help reduce the number of most pertinent factors and attributes to consider. Providing the factors and attributes for environmentally sustainable vehicles in a tabular framework is another contribution of this work. To help provide an analysis of the reliability of the VIKOR ranking results a new dominance probability degree (valuation) approach was introduced. The methodology was evaluated using real data collected from industry experts in related logistics industry organizations.

Sensitivity analysis experiments were used to investigate value determination and effects of the parameters. The examination focused on the impact of varying these parameters on vehicle ranking results. The methodology was found to be sensitive to parametric perturbations. Thus, managerial input and care is still required to determine effective ranges of the parameters. Within a smaller parametric range, a core set of candidate preferred transportation vehicles can be found. The final decision will also be sensitive to the attributes that are used in the evaluation process, as shown by the rough set analysis variations.

Although the novel methodology can prove valuable for evaluating the environmental sustainability of transportation fleets by organizations, certain limitations do exist. First, the methodology requires development and filtering of factors and attributes to be initially included. A technique, other than asking for expert opinions, may be helpful in narrowing down the initial factors. Rough set approaches can do this, but data must be collected for all factors for rough set to work. To save on data gathering, priori factor selection process is needed. Second, the multi-stage and three-parameter interval grey number characteristics of the technique may not be readily understood by management. This complexity may make it more difficult for managerial acceptance of the technique. Clear, transparent, and easy-to-understand directions and support systems will be required. Third, a comparative analysis of the proposed methodology to other MCDM approaches will still be needed. The difficulty is that even if other techniques provide varying results, the comparison can only be truly made on factors such as relative cost to implement, ease of understanding by management, and involvement by decision makers (Sarkis and Sundarraj 2000). Variations on the technique such as using different numbering approaches (e.g. not just grey, but other number types), alternative calculations for the ‘probabilities’, and integration of other discrete alternative approaches such as TOPSIS, can provide additional insights for this tool.

This paper provided a powerful tool for researchers and practitioners for complex multi-criteria transportation vehicle fleet decision making, whether it is for sustainability or business purposes. We believe that the findings and limitations of this study suggest new directions for future research in this important research area.

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