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A hybrid approach based on SERVQUAL and fuzzy TOPSIS for evaluating transportation service quality

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A B S T R A C T

Managing service quality is vital to retain customer satisfaction and augment revenues for any business organization. Often it is difficult to assess service quality due to lack of quantifiable measures and limited data. In this paper, we present a hybrid approach based on SERVQUAL and fuzzy TOPSIS for evaluating service quality of urban transportation systems. The proposed approach consists of three steps. The first step involves development of a SERVQUAL based questionnaire to collect data for measuring transportation service quality. The participants provide linguistic assessments to rate the service quality criteria and the alternatives. In step 2, the linguistic ratings are combined through fuzzy TOPSIS to generate an overall performance score for each alternative. The alternative with the highest score is finally chosen. In step 3, sensitivity analysis is conducted to evaluate the influence of criteria weights on the decision making process.

The strength of the proposed approach is its practical applicability and ability to provide solution under partial or lack of quantitative information. An application of the proposed approach for evaluation of service quality of metro in Montreal is provided.

1. Introduction

Evaluation of service quality of urban transportation systems is vital to improve productivity, gain profits and increase customer satisfaction. All transportation organizations carry evaluation of their service quality on a regular basis. This involves assessment of various parameters related to service quality for example, efficiency, reliability, safety, comfort, etc. against their desired target values by the decision makers. The evaluation can be done by customers, service personnel, transportation experts, etc. for important time intervals related to service for example, weekdays vs weekends, peak vs off-peak hours, etc. The goal of all organizations is to achieve high customer satisfaction by providing high quality service at all times to all customers.

1.1. Existing state of the art

The problem of evaluating service quality of urban transportation systems has been investigated by several researchers (Apostolopoulou, Nellas, Ganoudis, & Marinaki, 2000; DuPlessis, 1984; Iseki & Taylor, 2008; Miller, 1995; Pullen, 1993; Said, 2002; TRB, 1999). The commonly used approaches can be classified into:

- Survey studies and Interviews.
- Statistical analysis of collected data.
- Multicriteria decision making.

The first category of techniques is based on survey studies and interviews. The survey studies involve introducing a questionnaire to participants to seek their opinion on service quality attributes. In interviews, the participants are questioned face to get answers. One of the most commonly used survey instrument for evaluating service quality is SERVQUAL (Parasuraman, Zeithaml, & Berry, 1988). SERVQUAL is based on 22 items related to measuring five dimensions of service quality namely tangibles, reliability, responsiveness, assurance and empathy. Cavana Robert, Corbett Lawrence, and Lo (2007) extend SERVQUAL instrument to evaluate passenger rail service quality in Wellington, New Zealand by adding three more dimensions namely comfort, connection, and convenience. Fick and Ritchie (1991) use SERVQUAL to measure service quality in the travel and tourism industry. Tripp and Drea (2002) conducted a survey study of Amtrak riders, and found that

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the core service elements of on-board conditions, cafe car conditions, and on-time performance were most strongly related to attitude toward the service. Paquette, Cordeau, and Laporte (2009) classifies three principal approaches to define quality service quality in dial-a-ride operations: the customer-based approach (customer perceptions), the technical approach (specifications), and the philosophical approach (excellence).

The second category of techniques is based on statistical analysis of data for evaluating service quality. These involve regression models (Agarwal, 2008), logit models (Hensher, Stopher, & Bullock, 2003; Tyrinopoulos & Antoniou, 2008), structural equation modeling, stated preference method (Eboli & Mazzulla, 2008; Swanson, Ampt, & Jones, 1997), etc. Regression and logit models are used to study the causal relationship between the dependent variable (service quality) and the independent variables (service quality attributes like reliability, comfort, security, etc.). In regression models, it is assumed that the relationship exists between the dependent and the independent models while in logit models, uncertainty exists. Agarwal (2008) used factor and regression analysis to identify the effect of customers' perception about the quality of performance of various factors on customer satisfaction and found that employee behavior has the maximum effect on satisfaction level of customers with Indian Railways as a whole. Tyrinopoulos and Antoniou (2008) use factor analysis and ordered logit models to evaluate public transit user satisfaction. In stated preference techniques, individual respondents' statements about their preferences in a set of transport options are collected to estimate utility functions. The options are typically descriptions of transport situations or contexts constructed by the researcher (Kroes & Sheldon, 1988). A stated preference experiment for measuring transit service quality can be found in Eboli and Mazzulla (2008).

The third category of approaches involve multicriteria decision making. The commonly used multicriteria decision making approaches for service quality assessment of public transit systems are based on weighted scoring. In multicriteria decision making approaches, the alternative is evaluated against multiple weighted criteria and an aggregate performance score is determined. If the alternative performs above a pre-defined threshold limit, the service quality is deemed to be good. In case of multiple alternatives, the alternative with the highest score is chosen as the best alternative. Yeh, Deng, and Chang (2000) present a fuzzy multicriteria analysis approach for performance evaluation of bus companies. Yedla and Shrestha (2003) propose a multi-criteria approach based on AHP (Saaty, 1980) for the selection of alternative options for environmentally sustainable transport system in Delhi. Yeh and Kuo (2003) present a fuzzy multiattribute decision making approach for evaluating passenger service quality of 14 major Asia–Pacific international airports. Nathanail (2008) proposed a multicriteria evaluation framework for measuring the quality of service for passengers on the Hellenic railways. The criteria chosen were itinerary accuracy, system safety, cleanness, passenger comfort, servicing, and passenger information. Hensher et al. (2003) propose a service quality index in the provision of commercial bus contracts. Eboli and Mazzulla (2009) proposed an index based on customer perspective for evaluating transit service quality.

1.2. Motivation for this research

Managing service quality is vital to retain customer satisfaction and improve business profitability. Despite implementation of sound service quality initiatives, it is often difficult to measure their performance due to lack of quantifiable measures and limited data. In realistic situations, customers may not provide quantitative or numerical evaluations. Rather, they may be comfortable providing qualitative assessments such as good, very good, poor, very poor, etc. The reasons can be many including no prior experience with similar products, higher comfort level with qualitative ratings than discrete numbers, etc. Besides, the criteria used for judging service quality should not be only limited to quantitative ones since some of the service quality dimensions such as responsiveness, empathy, assurance cannot be measured quantitatively. Most of the existing studies in service quality literature rely on numerical data which may not often be practically available. Therefore, studies that are able to treat both qualitative and quantitative criteria and extract maximum information out of limited numerical data are required for improving service quality.

In this paper, we present a hybrid approach integrating SERVQUAL and fuzzy TOPSIS for evaluation of service quality of urban transportation systems. Fuzzy set theory is used to model vagueness and uncertainty in decision making processes arising due to lack of quantitative information (Zadeh, 1965). For example, it is much easier to represent the quality of service in organizations in linguistic terms such as good, very good, poor, very poor, etc. than in numbers. In fuzzy set theory, linguistic terms are used to represent decision maker preferences. This is the reason why we have used linguistics terms in seeking questionnaire responses from respondents.

The rest of the paper is organized as follows. In section 2, we present preliminaries of fuzzy set theory and fuzzy TOPSIS. In section 3, we present our solution approach for evaluating service quality of urban transportation systems. Section 4 presents an application of our approach on evaluation of service quality for metro service in Montreal. In the fifth and the last section, we present the conclusions and future work.

2. Preliminaries of fuzzy set theory

Some related definitions of fuzzy set theory adapted from (Buckley, 1985; Dubois & Prade, 1982; Kaufmann & Gupta, 1991; Klir & Yuan, 1995; Pedrycz, 1994; Zadeh, 1965; Zimmermann, 2001) are presented as follows.

Definition 1. A fuzzy set $\tilde{a}$ in a universe of discourse X is characterized by a membership function $\mu_{\tilde{a}}(x)$ that maps each element x in X to a real number in the interval $[0, 1]$. The function value $\mu_{\tilde{a}}(x)$ is termed the grade of membership of x in $\tilde{a}$ (Kaufmann and Gupta). The nearer the value of $\mu_{\tilde{a}}x$ to unity, the higher the grade of membership of x in $\tilde{a}$.

Definition 2. A triangular fuzzy number (Fig. 1) is represented as a triplet $\tilde{a} = (a_1, a_2, a_3)$. Due to their conceptual and computation simplicity, triangular fuzzy numbers are very commonly used in practical applications (Klir & Yuan, 1995; Pedrycz, 1994). The membership function of $\mu_{\tilde{a}}x$ triangular fuzzy number is given by:

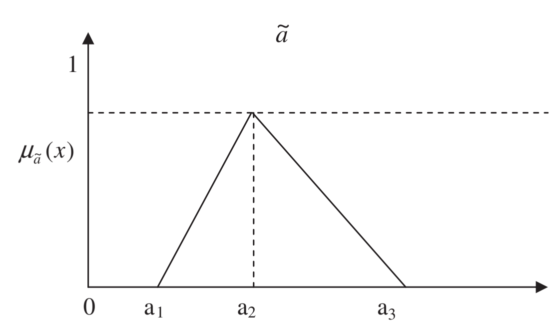

Fig. 1. Triangular fuzzy number $\tilde{a}$.

$$\mu_{\tilde{a}}(x) = \begin{cases} 0, & x \leqslant a_1, \\ \frac{x-a_1}{a_2-a_1}, & a_1 \leqslant x \leqslant a_2, \\ \frac{a_3-x}{a_3-a_2}, & a_2 \leqslant x \leqslant a_3, \\ 0, & x > a_3 \end{cases} \tag{1}$$

where a_1, a_2, a_3 are real numbers and $a_1 < a_2 < a_3$. The value of x at a_2 gives the maximal grade of $\mu_{\tilde{a}}(x)$ i.e., $\mu_{\tilde{a}}(x) = 1$; it is the most probable value of the evaluation data. The value of x at a_1 gives the minimal grade of $\mu_{\tilde{a}}x$, i.e., $\mu_{\tilde{a}}(x) = 0$; it is the least probable value of the evaluation data. Constants a_1 and a_3 are the lower and upper bounds of the available area for the evaluation data. These constants reflect the fuzziness of the evaluation data (Liang, 1999). The narrower the interval $[a_1,a_3]$, the lower is the fuzziness of the evaluation data.

2.1. Linguistic variables and fuzzy set theory

In fuzzy set theory, conversion scales are applied to transform the linguistic terms into fuzzy numbers. In this paper, we will use a scale of 1–9 to rate the criteria and the alternatives. Table 2 presents the linguistic variables and fuzzy ratings used for the alternatives and Table 3 presents the linguistic variables and fuzzy ratings used for the criteria.

2.2. Fuzzy TOPSIS

The fuzzy TOPSIS approach involves fuzzy assessments of criteria and alternatives in TOPSIS (Hwang and Yoon, 1981). The TOPSIS approach chooses alternative that is closest to the positive ideal solution and farthest from the negative ideal solution. A positive ideal solution is composed of the best performance values for each criterion whereas the negative ideal solution consists of the worst performance values. The various steps of Fuzzy TOPSIS are presented as follows:

Step 1: Assignment of ratings to the criteria and the alternatives.
Let us assume there are J possible candidates called $A = \{A_1,A_2,A_j\}$ which are to evaluated against m criteria, $C = \{C_1,C_2,C_m\}$. The criteria weights are denoted by w_i $(i = 1,2,\ldots,m)$. The performance ratings of each decision maker D_k $(k = 1,2,\ldots,K)$ for each alternative $A_j(j = 1,2,\ldots,n)$ with respect to criteria $C_i(i = 1,2,\ldots,m)$ are denoted by $\widetilde{R}_k = \tilde{x}_{ijk}(i = 1,2,\ldots,m; j = 1,2,\ldots,n; k = 1,2,\ldots,K)$ with membership function $\mu_{\widetilde{R}_k}(x)$.

Step 2: Compute aggregate fuzzy ratings for the criteria and the alternatives.
If the fuzzy ratings of all decision makers is described as triangular fuzzy number $\widetilde{R}_k = (a_k, b_k, c_k), k = 1,2,\ldots,K$, then the aggregated fuzzy rating is given by $\widetilde{R} = (a,b,c), k = 1,2,\ldots,K$ where;

$$a = \min_k\{a_k\}, \quad b = \frac{1}{K}\sum_{k=1}^{K} b_k, \quad c = \max_k\{c_k\}$$

If the fuzzy rating and importance weight of the kth decision maker are $\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk})$ and $\tilde{w}_{ijk} = (w_{jk1}, w_{jk2}, w_{jk3}), i = 1,2,\ldots,m, j = 1,2,\ldots,n$ respectively, then the aggregated fuzzy ratings $(\tilde{x}_{ij})$ of alternatives with respect to each criteria are given by $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ where

$$a_{ij} = \min_k\{a_{ijk}\}, b_{ij} = \frac{1}{K}\sum_{k=1}^{K} b_{ijk}, \quad c_{ij} = \max_k\{c_{ijk}\} \tag{2}$$

The aggregated fuzzy weights $(\tilde{w}_{ij})$ of each criterion are calculated as $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$ where

$$w_{j1} = \min_k\{w_{jk1}\}, w_{j2} = \frac{1}{K}\sum_{k=1}^{K} w_{jk2}, \quad w_{j3} = \max_k\{c_{jk3}\} \tag{3}$$

Step 3: Compute the fuzzy decision matrix.
The fuzzy decision matrix for the alternatives $(\widetilde{D})$ and the criteria $(\widetilde{W})$ is constructed as follows:

$$\widetilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{array}\!\!\begin{array}{c} \begin{array}{cccc} C_1 & C_2 & & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \ldots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \ldots & \tilde{x}_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \ldots & \tilde{x}_{mn} \end{bmatrix} \end{array}, \quad i = 1,2,\ldots,m; j = 1,2,\ldots,n \tag{4}$$

$$\widetilde{W} = (\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_n) \tag{5}$$

Step 4: Normalize the fuzzy decision matrix.
The raw data are normalized using linear scale transformation to bring the various criteria scales into a comparable scale. The normalized fuzzy decision matrix $\widetilde{R}$ is given by:

$$\widetilde{R} = [\tilde{r}_{ij}]_{mxn}, \quad i = 1,2,\ldots,m; \quad j = 1,2,\ldots,n \tag{6}$$

where:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \text{ and } c_j^* = \max_i c_{ij} \text{ (benefit criteria)} \tag{7}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \text{ and } a_j^- = \min_i a_{ij} \text{ (cost criteria)} \tag{8}$$

Step 5: Compute the weighted normalized matrix
The weighted normalized matrix $\widetilde{V}$ for criteria is computed by multiplying the weights $(\tilde{w}_j)$ of evaluation criteria with the normalized fuzzy decision matrix $\tilde{r}_{ij}$.

$$\widetilde{V} = [\tilde{v}_{ij}]_{mxn}, \quad i = 1,2,\ldots,m; \\ j = 1,2,\ldots,n \quad \text{where } \tilde{v}_{ij} = \tilde{r}_{ij}(.)\tilde{w}_j \tag{9}$$

Step 6: Compute the fuzzy ideal solution (FPIS) and fuzzy negative ideal solution (FNIS)
The FPIS and FNIS of the alternatives is computed as follows:

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*) \quad \text{where } \tilde{v}_j^* = \max_i\{v_{ij3}\}, \\ i = 1,2,\ldots,m; \quad j = 1,2,\ldots,n \tag{10}$$

$$A^- = (\tilde{v}_1, \tilde{v}_2, \ldots, \tilde{v}_n) \quad \text{where } \tilde{v}_j^- = \min_i\{v_{ij1}\}, \\ i = 1,2,\ldots,m; \quad j = 1,2,\ldots,n \tag{11}$$

Step 7: Compute the distance of each alternative from FPIS and FNIS:
The distance (d_i^*, d_i^-) of each weighted alternative $i = 1, 2, \ldots, m$ from the FPIS and the FNIS is computed as follows:

$$d_i^* = \sum_{j=1}^{n} d_v\left(\tilde{v}_{ij}, \tilde{v}_j^*\right), \quad i = 1,2,\ldots,m \tag{12}$$

$$d_i^- = \sum_{j=1}^{n} d_v\left(\tilde{v}_{ij}, \tilde{v}_j^-\right), \quad i = 1,2,\ldots,m \tag{13}$$

Where $d_v(\tilde{a}, \tilde{b})$ is the distance measurement between two fuzzy numbers $\tilde{a}$ and $\tilde{b}$ and $d_v(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}[(a_1-b_1)^2 + (a_2-b_2)^2 + (a_3-b_3)^2]}$

Table 1
Criteria for evaluating quality of transportation service.

Criteria	Questionnaire item (rate the importance on the following scales)					Category	Criteria Id
	Very high	High	Medium	Low	Very low		
Responsiveness	Staff service for customer requests (charging cards, schedule sheet,...)					B	C1
	Availability of service staff when needed					B	C2
Reliability	Arrival performance of metro with respect to schedules					B	C3
	Costliness of metro ticket					C	C4
	Waiting times for metro before departure					B	C5
	Security at metro stations					B	C6
	Security inside metro					B	C7
Tangibles	Usage of modern equipments in metro services (Train, Schedule, Screen)					B	C8
	Cleanliness of metro stations					B	C9
	Politeness and appearance (well dressed) of metro employees					B	C10
	Well being facilities at metro stations (washroom, store, public telephone...)					B	C11
Assurance	Adherence to quality standards in metro (seating space, standing space, quality of heating, etc.)					B	C12
	Safety during travel by metro					B	C13
Empathy	Understanding of customer needs in metro service					B	C14

*Benefit (The higher the response, the better) Cost (The lower the response, the better).

Step 8: Compute the closeness coefficient (CC_i) of each alternative. The closeness coefficient represents the distances to the fuzzy positive ideal solution (A*) and the fuzzy negative ideal solution (A-) simultaneously. The closeness coefficient of each alternative is calculated as:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}, \quad i = 1, 2, \ldots, m \tag{14}$$

Step 9: Rank the alternatives
In step 9, the different alternatives are ranked according to the closeness coefficient (CC_i) in decreasing order. The best alternative is closest to the FPIS and farthest from the FNIS.

3. Solution approach

The proposed framework for evaluation of service quality of urban transportation systems under uncertainty consists of three steps.

1. Development of a SERVQUAL based questionnaire for collecting data for measuring service quality.
2. Aggregation of survey responses using fuzzy TOPSIS and selection of best alternative.
3. Performing sensitivity analysis to determine the influence of criteria weights on decision making.

These steps are presented in detail as follows:

3.1. Development of SERVQUAL based questionnaire for collecting data on service quality

The first step involves development of a questionnaire survey for measuring service quality. The questions were framed using the service quality criteria proposed in SERVQUAL (Parasuraman et al., 1988). SERVQUAL is a useful instrument for performing gaps analysis where a gap is measured as the difference between the customer expectations and customer perceptions. SERVQUAL measures service quality on five dimensions namely Tangibles, Service Reliability, Responsiveness, Assurance and Empathy. These dimensions are defined as follows:

- Tangibles include the physical appearance of the service facility, the equipment, the personnel, and the communication materials. For example, appearance of stations, lighting, etc.
- Service reliability relates to the ability of the service provider to perform the promised service dependably and accurately. For example, arrival of trains at the right time.
- Responsiveness is the willingness of the service provider to be helpful and prompt in providing service. For example, response of customer queries by railway personnel.
- Assurance refers to the knowledge and courtesy of employees and their ability to inspire trust and confidence. For example, knowledge staff at information desks.
- Empathy refers to caring, individualized attention to customers. For example, helping old age customers with ticket reservation at kiosks.

Our questionnaire survey addressed these five dimensions of SERVQUAL. The questionnaire contains 14 questions (Column 2, Table 1) related to the following aspects of urban transportation services:

- Metro contains modern equipments.
- Metro services are on schedule.
- Cleanliness of metro stations.
- Appearance of metro employees.
- Well-being facilities at metro stations (washroom, store, public telephone, etc.).
- Waiting times (before train departure).
- Reasonable ticket price.
- Security of metro stations.

Table 2
Linguistic terms for alternatives ratings.

Linguistic term	Membership function
Very poor (VP)	(1,1,3)
Poor (P)	(1,3,5)
Fair (F)	(3,5,7)
Good (G)	(5,7,9)
Very Good (VG)	(7,9,9)

Table 3
Linguistic terms for criteria ratings.

Linguistic term	Membership function
Very Low	(1,1,3)
Low	(1,3,5)
Medium	(3,5,7)
High	(5,7,9)
Very High	(7,9,9)

- Prompt and easy service for customer requests (charging card, schedule sheet, etc.).
- Employee's knowledge to answer questions.
- Safety during travel by metro.
- Adherence to standards.
- Etc.

The respondents were asked to provide linguistic assessments to the criteria and to the alternatives using rating scales of Tables 2 and 3 respectively. The linguistic responses were transformed into triangular fuzzy numbers and then aggregated to obtain an overall response.

3.2. Alternatives evaluation and selection using fuzzy TOPSIS

The second step involves application of fuzzy TOPSIS (Section 2.2) on the aggregated criteria and alternative ratings obtained from step 1. The fuzzy TOPSIS generates an overall performance score for assessing the service quality of the alternatives (urban transportation systems). The alternative with the highest score is deemed as one with highest service quality and finally chosen.

Fig. 2. Metro map of Montreal. (Source: STM (2009))

Table 4
Service timings for the four metro lines. (Source: STM, 2009)

Lines 1 – green & 2 – orange	
Weekdays	5:30 a.m. (first departure) to 12:35 a.m. (last departure)
Saturday	5:30 a.m. (first departure) to 1:00 a.m. (last departure)
Sunday	5:30 a.m. (first departure) to 12:30 a.m. (last departure)
Line 4 – yellow	
Weekdays	5:30 a.m. (first departure) to 12:50 a.m. (last departure)
Saturday	5:30 a.m. (first departure) to 1:30 a.m. (last departure)
Sunday	5:30 a.m. (first departure) to 1:00 a.m. (last departure)
Line 5 – blue	
Weekdays	5:30 a.m. (first departure) to 12:15 a.m. (last departure)
Saturday	5:30 a.m. (first departure) to 12:15 a.m. (last departure)
Sunday	5:30 a.m. (first departure) to 12:15 a.m. (last departure)

3.3. Sensitivity analysis

The third step involves conducting the sensitivity analysis. Sensitivity analysis addresses the question, "How sensitive is the overall decision to small changes in the individual weights assigned during the pair-wise comparison process?". This question can be answered by varying slightly the values of the weights and observing the effects on the decision. This is useful in situations where uncertainties exist in the definition of the importance of different factors. In our case, we will conduct sensitivity analysis in order to see the importance of criteria weights in selecting the transportation system with highest quality of service.

4. Application to metro service of Montreal

The metro service in Montreal is run and managed by Society of Transport (STM). Currently, there are four metro lines operational in Montreal: Orange Line, Blue Line, Yellow Line and Green Line. These four lines serve 71 km of tracks and 68 stations. The Orange Line is operational between Cote-Vertu and Montmorency stations, the Green Line between Angrignon and Honore Beaugrand stations, the Yellow Line between Berri UQAM and the Universite de sherbrooke Longueil stations, and the Blue Line between Snowdon and Saint Michel stations. Fig. 2 shows the map of these four metro lines in Montreal.

The first departure of the four metro lines takes place at 5:30 am and the service terminates between 12:15–12:30 in the night. On weekdays, the frequency of metro is higher than on weekends (Table 4). The regular fare for a one way metro trip is $2.75 CAD (2009). The details of ridership evolution over the years 2006–2008 is presented in Table 5.

The SERVQUAL based questionnaire (appendix A) was administered to 60 participants in city of Montreal to evaluate the service quality of the four metro lines. These participants were regular users of the metro service in Montreal. 60 responses were received (100% response rate). The participants provide linguistic assessments (Tables 1, 2) to rate the fourteen criteria (Table 3) and the four alternatives (Yellow Line (A1), Green Line (A2), Orange Line (A3), Blue Line (A4)).These linguistics assessments were then transformed to fuzzy triangular numbers and aggregated using Eqs. (2, 3). The aggregate fuzzy ratings for the criteria are presented in Table 6 and the four alternatives in Table 7 respectively.

Table 6
Aggregate fuzzy criteria weights (based on 60 responses from SERVQUAL).

Criteria	Aggregate fuzzy weight
C1	(1,5.67,9)
C2	(1,5,9)
C3	(1,6.33,9)
C4	(1,5,9)
C5	(5,7.67,9)
C6	(1,7,9)
C7	(1,6.33,9)
C8	(1,6.33,9)
C9	(1,3,9)
C10	(5,7,9)
C11	(1,5,9)
C12	(1,5,9)
C13	(1,4.33,9)
C14	(3,6.33,9)

Table 7
Aggregate fuzzy decision matrix (based on 60 responses from SERVQUAL).

Criteria	Alternatives			
	A1	A2	A3	A4
C1	(3,6.33,9)	(1,5,9)	(1,3.67,9)	(1,5,9)
C2	(1,5.67,9)	(1,5.67,9)	(1,1.67,5)	(3,7,9)
C3	(1,4.33,9)	(1,2.33,7)	(1,7,9)	(1,3,7)
C4	(3,5.67,9)	(3,7,9)	(1,1,3)	(1,5.67,9)
C5	(1,2.33,5)	(1,7,9)	(1,5.67,9)	(1,5,9)
C6	(1,5,9)	(5,7,9)	(1,5.67,9)	(1,5,9)
C7	(1,5,9)	(5,7,9)	(1,5,9)	(1,5,9)
C8	(3,6.33,9)	(1,3,7)	(1,3.67,9)	(1,3.67,9)
C9	(1,3,7)	(1,3.67,9)	(1,3,9)	(3,6.33,9)
C10	(1,4.33,9)	(1,5,9)	(1,5,9)	(1,5,9)
C11	(1,5.67,9)	(3,7,9)	(1,3.67,9)	(1,2.33,5)
C12	(1,2.33,7)	(3,6.33,9)	(1,3.67,7)	(1,5.67,9)
C13	(1,5.67,9)	(5,7,9)	(1,4.33,9)	(1,5,9)
C14	(5,7,9)	(1,2.33,5)	(1,5.67,9)	(1,5,9)

In the next step, we perform normalization of the fuzzy decision matrix of alternatives using Eqs. (6)–(8). For example, the normalized rating for alternative A1 for criteria C1 (Category B) is given by:

$$c_j^* = \max_i(9,9,9,9) = 9$$

$$\tilde{r}_{ij} = \left(\frac{3}{9}, \frac{6.333}{9}, \frac{9}{9}\right) = (0.33, 0.704, 1)$$

For criteria C4 (category cost), the normalized rating for alternative A1 is:

$$a_j^- = \min_i(3,3,1,1) = 1$$

$$\tilde{r}_{ij} = \left(\frac{1}{9}, \frac{1}{5.667}, \frac{1}{3}\right) = (0.111, 0.176, 0.333)$$

Likewise, we compute the normalized values of the alternatives for the remaining criteria. The normalized fuzzy decision matrix for the four alternatives is presented in Table 8.

Then, the fuzzy weighted decision matrix for the three alternatives is constructed using Eq. (14). The $\tilde{r}_{ij}$ values from Table 8 and

Table 5
Characteristics of the metro line. (Source: STM, 2008)

Service characteristics	Unit	2006	2007	2008	Variation 2006–2008 (%)
Métro offer of service	Thousands of km travelled	59,839	64,792	75,715	26.5
Number of trips (ridership)	Millions	363.3	367.5	382.5	5.3
Passenger-kilometers	Millions	2820	2852	2969	5.3

Table 8
Normalized fuzzy decision matrix for alternatives.

Criteria	Alternatives			
	A1	A2	A3	A4
C1	(0.33,0.703,1)	(0.11,0.556,1)	(0.11,0.407,1)	(0.11,0.556,1)
C2	(0.11,0.629,1)	(0.11,0.629,1)	(0.11,0.185,0.556)	(0.33,0.778,1)
C3	(0.11,0.481,1)	(0.11,0.259,0.778)	(0.11,0.778,1)	(0.11,0.33,0.778)
C4	(0.11,0.176,0.333)	(0.11,0.142,0.333)	(0.33,1,1)	(0.11,0.176,1)
C5	(0.11,0.259,0.556)	(0.11,0.778,1)	(0.11,0.629,1)	(0.11,0.556,1)
C6	(0.11,0.55,1)	(0.556,0.778,1)	(0.11,0.629,1)	(0.11,0.556,1)
C7	(0.11,0.55,1)	(0.556,0.778,1)	(0.11,0.556,1)	(0.11,0.556,1)
C8	(0.33,0.703,1)	(0.11,0.333,0.778)	(0.11,0.407,1)	(0.11,0.407,1)
C9	(0.11,0.11,0.778)	(0.11,0.407,1)	(0.11,0.333,1)	(0.33,0.703,1)
C10	(0.11,0.481,1)	(0.11,0.556,1)	(0.11,0.556,1)	(0.11,0.556,1)
C11	(0.11,0.629,1)	(0.33,0.778,1)	(0.11,0.407,1)	(0.11,0.259,0.556)
C12	(0.11,0.259,0.778)	(0.33,0.703,1)	(0.11,0.407,0.778)	(0.11,0.629,1)
C13	(0.11,0.629,1)	(0.556,0.778,1)	(0.11,0.481,1)	(0.11,0.556,1)
C14	(0.55,0.77,1)	(0.11,0.259,0.556)	(0.11,0.629,1)	(0.11,0.556,1)

Table 9
Weighted normalized alternatives, FPIS and FNIS.

Criteria	Alternatives				FNIS (A-)	FPIS (A∗)
	A1	A2	A3	A4		
C1	(0.33,3.98,9)	(0.11,3.148,9)	(0.11,2.3,9)	(0.11,3.14,9)	0.111	9
C2	(0.11,3.14,9)	(0.11,3.148,9)	(0.11,0.92,5)	(0.33,3.89,9)	0.111	9
C3	(0.11,3.04,9)	(0.11,1.641,7)	(0.11,4.92,9)	(0.11,2.11,7)	0.111	9
C4	(0.11,0.88,3)	(0.11,0.714,3)	(0.33,5,9)	(0.11,0.88,9)	0.111	9
C5	(0.56,1.98,5)	(0.556,5.96,9)	(0.56,4.82,9)	(0.56,4.25,9)	0.556	9
C6	(0.11,3.88,9)	(0.556,5.44,9)	(0.11,4.40,9)	(0.11,3.89,9)	0.111	9
C7	(0.11,3.51,9)	(0.556,4.92,9)	(0.11,3.51,9)	(0.11,3.51,9)	0.111	9
C8	(0.33,4.45,9)	(0.11,2.11,7)	(0.11,2.58,9)	(0.11,2.58,9)	0.111	9
C9	(0.11,1,7)	(0.11,1.22,9)	(0.11,1,9)	(0.33,2.11,9)	0.111	9
C10	(0.56,3.37,9)	(0.556,3.89,9)	(0.56,3.89,9)	(0.56,3.89,9)	0.556	9
C11	(0.11,3.14,9)	(0.33,3.89,9)	(0.11,2.03,9)	(0.11,1.29,5)	0.111	9
C12	(0.11,1.29,7)	(0.33,3.518,9)	(0.11,2.03,7)	(0.11,3.14,9)	0.111	9
C13	(0.11,2.72,9)	(0.556,3.37,9)	(0.11,2.08,9)	(0.11,2.40,9)	0.111	9
C14	(1.67,4.92,9)	(0.33,1.64,5)	(0.33,3.98,9)	(0.33,3.51,9)	0.333	9

$\tilde{w}_j$ values from Table 6 are used to compute the fuzzy weighted decision matrix for the alternatives. For example, for alternative A1, the fuzzy weight for criteria C1 (Tangibles) is given by:

$$\tilde{v}_{ij} = (0.33, 0.704, 1)(.)(1, 5.667, 9) = (0.333, 3.988, 9)$$

Likewise, we compute the fuzzy weights of the three alternatives for the remaining criteria (Table 9). Then, the fuzzy positive ideal solution (A^*) and the fuzzy negative ideal solutions (A^-) are computed using Eqs. (10) and (11) for the three alternatives. For example, for criteria C1 (Tangibles), A^- = (0.111,0.111,0.111) and A^* = (9,9,9). Similar computations are performed for the remaining criteria. The results are presented in last two columns of Table 9.

Then, we compute the distance d_v (.) of each alternative from the fuzzy positive ideal matrix (A^*) and fuzzy negative ideal matrix (A^-) using Eqs. (12) and (13). For example, for alternative A1 and criteria C1, the distances $d_v(A_1,A^*)$ and $d_v(A_1,A^-)$ are computed as follows:

$$d_v(A_1,A^-) = \sqrt{\frac{1}{3}[(0.333-0.111)^2+(3.988-0.111)^2+(9-0.111)^2]} = 5.597$$

$$d_v(A_1,A^*) = \sqrt{\frac{1}{3}[(0.333-9)^2+(3.988-9)^2+(9-9)^2]} = 5.777$$

Likewise, we compute the distances for the remaining criteria for the four alternatives. The results are shown in Table 10.

Table 10
Distance d_v (A_i,A^*) and d_v (A_i,A^-) for alternatives

Criteria	d_v (A_i,A^-)				d_v (A_i,A^*)			
	A1	A2	A3	A4	A1	A2	A3	A4
C1	5.597	5.420	5.283	5.420	5.777	6.141	6.420	6.141
C2	5.420	5.420	2.860	5.574	6.141	6.141	7.303	5.806
C3	5.402	4.072	5.833	4.139	6.17	6.758	5.642	6.591
C4	1.725	1.703	5.855	5.148	7.761	7.820	5.508	6.946
C5	2.694	5.786	5.460	5.32	6.741	5.178	5.435	5.588
C6	5.573	5.987	5.697	5.573	5.916	5.287	5.773	5.916
C7	5.493	5.839	5.493	5.493	6.026	5.410	6.026	6.026
C8	5.711	4.139	5.323	5.323	5.646	6.591	6.327	6.327
C9	4.008	5.169	5.155	5.259	6.996	6.815	6.90	6.388
C10	5.136	5.238	5.238	5.238	5.856	5.696	5.696	5.696
C11	5.420	5.574	5.248	2.902	6.141	5.806	6.515	7.169
C12	4.033	5.494	4.127	5.420	6.885	5.917	6.617	6.141
C13	5.347	5.469	5.254	5.297	6.27	5.856	6.498	6.386
C14	5.712	2.796	5.427	5.328	4.840	6.954	5.777	5.917

Table 11
Closeness coefficient (CC_i) of the three alternatives

	Alternatives			
	A1	A2	A3	A4
A–	67.27	68.11	72.26	71.44
A+	87.18	86.37	86.44	87.04
Cci	0.435	0.4408	0.455	0.4507

Table 12
Experiments for sensitivity analysis

Expt no.	Definition	Alternatives				Ranking
		A1	A2	A3	A4	
1	$W_{C1-C14} = (1,1,3)$	0.404	0.410	0.422	0.421	A3 > A4 > A2 > A1
2	$W_{C1-C14} = (1,3,5)$	0.430	0.437	0.449	0.448	A3 > A4 > A2 > A1
3	$W_{C1-C14} = (3,5,7)$	0.441	0.453	0.458	0.457	A3 > A4 > A2 > A1
4	$W_{C1-C14} = (5,7,9)$	0.447	0.463	0.464	0.463	A3 > A4 > A2 > A1
5	$W_{C1-C14} = (7,9,9)$	0.473	0.496	0.486	0.486	A2 > A3 > A4 > A1
6	$W_{C1} = (7,9,9)$, $W_{C2-C14} = (1,1,3)$	0.431	0.425	0.430	0.435	A4 > A1 > A3 > A2
7	$W_{C2} = (7,9,9)$, $W_{C1,C3-C14} = (1,1,3)$	0.422	0.428	0.406	0.449	A4 > A2 > A1 > A3
8	$W_{C3} = (7,9,9)$, $W_{C1-C2,C4-C14} = (1,1,3)$	0.417	0.407	0.443	0.420	A3 > A4 > A1 > A2
9	$W_{C4} = (7,9,9)$, $W_{C1-C3,C5-C14} = (1,1,3)$	0.380	0.384	0.456	0.423	A3 > A4 > A2 > A1
10	$W_{C5} = (7,9,9)$, $W_{C1-C4,C6-C14} = (1,1,3)$	0.392	0.433	0.438	0.435	A3 > A4 > A2 > A1
11	$W_{C6} = (7,9,9)$, $W_{C1-C5,C7-C14} = (1,1,3)$	0.419	0.447	0.438	0.435	A2 > A3 > A4 > A1
12	$W_{C7} = (7,9,9)$, $W_{C1-C6,C8-C14} = (1,1,3)$	0.419	0.447	0.435	0.435	A2 > A3 > A4 > A1
13	$W_{C8} = (7,9,9)$, $W_{C1-C7,C9-C14} = (1,1,3)$	0.431	0.409	0.430	0.430	A1 > A3 > A4 > A2
14	$W_{C9} = (7,9,9)$, $W_{C1-C8,C10-14} = (1,1,3)$	0.404	0.420	0.427	0.446	A4 > A3 > A2 > A1
15	$W_{C10} = (7,9,9)$, $W_{C1-C9,C11-14} = (1,1,3)$	0.417	0.425	0.435	0.435	A3 > A4 > A2 > A1
16	$W_{C11} = (7,9,9)$, $W_{C1-C10,C12-14} = (1,1,3)$	0.422	0.439	0.430	0.409	A2 > A3 > A1 > A4
17	$W_{C12} = (7,9,9)$, $W_{C1-C11,C13-14} = (1,1,3)$	0.401	0.436	0.423	0.437	A4 > A2 > A3 > A1
18	$W_{C13} = (7,9,9)$, $W_{C1-C12,C14} = (1,1,3)$	0.422	0.447	0.432	0.435	A2 > A4 > A3 > A1
19	$W_{C14} = (7,9,9)$, $W_{C1-C13} = (1,1,3)$	0.441	0.398	0.438	0.435	A1 > A3 > A4 > A2
20	$W_{C4} = (7,9,9)$, $W_{C1-C3,C5-C14} = (1,1,3)$	0.380	0.384	0.456	0.423	A3 > A4 > A2 > A1
21	$W_{C4} = (1,1,3)$, $W_{C1-C3,C5-C14} = (7,9,9)$	0.486	0.511	0.475	0.489	A2 > A4 > A1 > A3

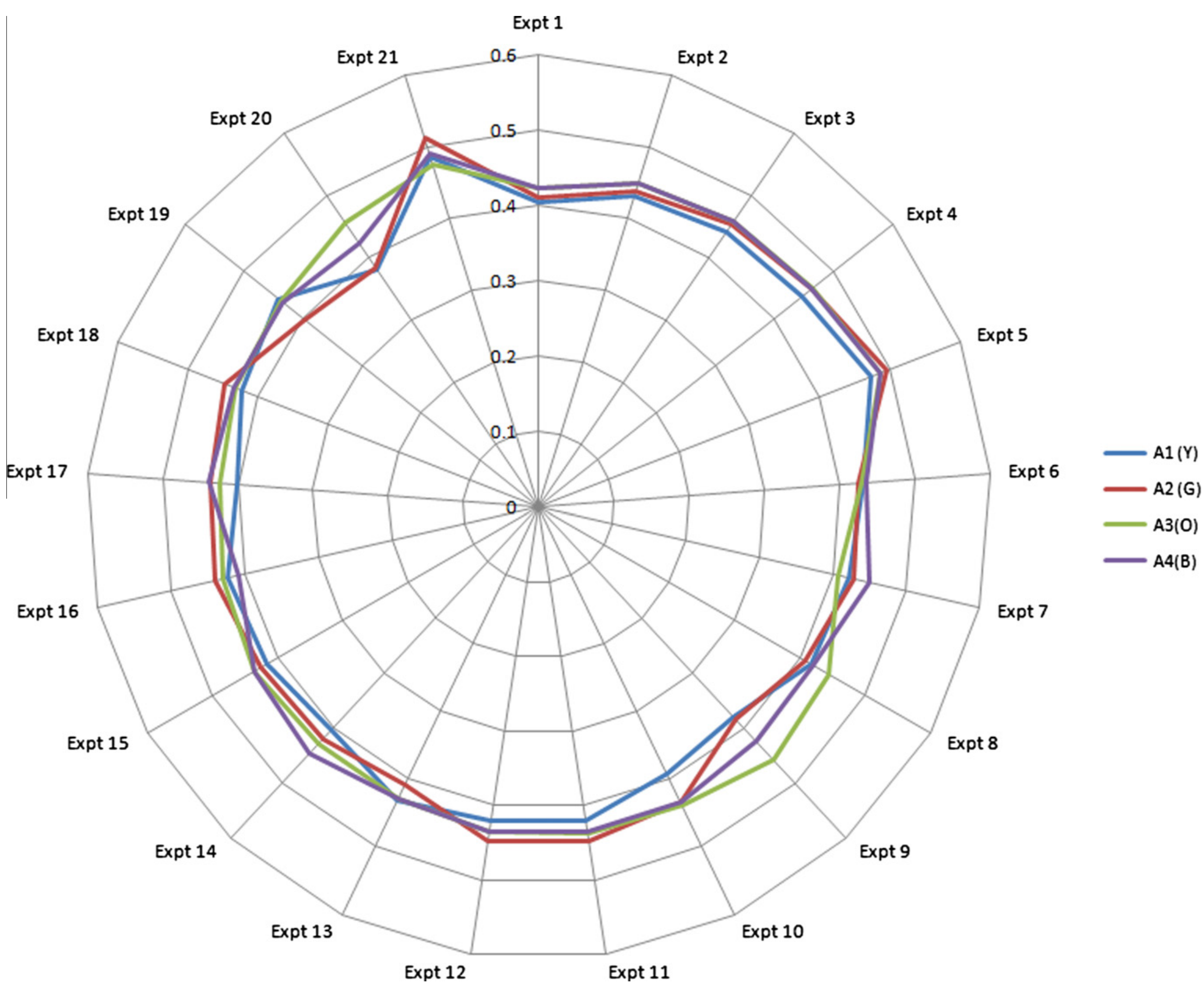

Fig. 3. Results of sensitivity analysis.

Then, we compute the distances d_i^* and d_i^- using Eqs. (12) and (13). For example, for alternative A1 and criteria C1, the distances d_i^* and d_i^- are given by:

$$d_i^- = \sqrt{\tfrac{1}{3}[(0.333-0.111)^2+(3.988-0.111)^2+(9-0.111)^2]}+\sqrt{\tfrac{1}{3}[(0.111-0.111)^2+(3.148-0.111)^2+(9-0.111)^2]}+\ldots+\sqrt{\tfrac{1}{3}[(1.667-0.111)^2+(4.926-0.111)^2+(9-0.111)^2]}=67.28$$

$$d_i^* = \sqrt{\tfrac{1}{3}[(0.333-9)^2+(3.988-9)^2+(9-9)^2]}+\sqrt{\tfrac{1}{3}[(0.111-9)^2+(3.148-9)^2+(9-9)^2]}+\ldots+\sqrt{\tfrac{1}{3}[(1.667-9)^2+(4.926-9)^2+(9-9)^2]}=87.18$$

Likewise, using distances d_i^* and d_i^- (Eq. (14)), we compute the closeness coefficient (CC_i) of the four alternatives. For example, for alternative A1, the closeness coefficient is given by:

$$CC_i = d_i^-/(d_i^- + d_i^+) = 67.28/(67.28+87.18) = 0.435$$

Likewise, CC_i for the other three alternatives are computed. The final results are shown in Table 11.

By comparing the CC_i values of the four alternatives (Table 11), we find that A3(Orange Line) > A4(Blue Line) > A2(Green Line) > A1(Yellow Line). Therefore, alternative A3(Orange Line) is chosen as the metro line with best service of quality by the 60 users of metro services in Montreal.

4.1. Sensitivity analysis

To investigate the impact of criteria weights (denoted by W_{Ci} for criteria Ci where $i = 1,2,\ldots,n$) on the selection of alternative with best service quality, we conducted the sensitivity analysis. 21 experiments were conducted. The details of the 21 experiments are presented in Table 12 below.

It can be seen in Table 12, that in the first five experiments, weights of all criteria are set equal to (1,1,3), (1,3,5), (3,5,7), (5,7,9) and (7,9,9) respectively. In experiments 6–19, the weight of each criteria is set as highest (7,9,9) one by one and the remaining criteria are set to the lowest value (1,1,3). The goal is to see which criteria is most important in influencing the decision making process. For example, in experiment 6, the criteria C1 has the highest weight = (7,9,9) whereas the remaining criteria have weight = (1,1,3). In experiment 20, the weight of the cost criteria (C4) is set as highest and the others are set at lowest whereas in the 21st and the last experiment, the weight of the cost criteria (C4) is set as lowest and the others are set as highest. The results of the sensitivity analysis are presented in Fig. 3.

It can be seen from Table 12 and Fig. 3 that out of 21 experiments, alternative A3 has the highest score in nine experiments (Experiment number 1–4, 8–10, 15, 20). In six experiments (Experiment number 5, 11, 12, 16, 18, 21), the alternative A2 has emerged as the winner. In four experiments (Experiment number 6, 7, 14, 17), A2 is the winner and in the remaining two experiments (Experiment number 13, 19), A1 is the winner. Therefore, we can say that the decision making process is relatively sensitive to the criteria weight with alternative A3 (Orange Line) emerging as the winner (42.8% votes).

5. Conclusion

In this paper, we present a hybrid approach based on SERVQUAL and fuzzy TOPSIS for evaluating service quality of urban transportation systems. The proposed approach comprises of three steps. In step 1, we develop a SERVQUAL based questionnaire for collecting data for evaluating the quality of metro transportation services. The questionnaire is distributed to metro transit users in Montreal. In step 2, the questionnaire responses are aggregated to generate an overall performance score for measuring service quality using Fuzzy TOPSIS. The alternative with the highest score is finally chosen. In the third and the last step, we perform sensitivity analysis to determine the influence of criteria weights on the decision making process.

The strength of our approach is the ability to perform assessment of quality of service of transportation systems under partial or lack of quantitative information. An application of the proposed approach is demonstrated on metro transportation service of Montreal.

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