Research Article

Decision-Support Framework for Selecting the Optimal Road Toll Collection System

Marina Milenković ¹, Draženko Glavić¹ and Miloš N. Mladenović ²

¹University of Belgrade, Faculty of Transport and Traffic Engineering, V. Stepe 305, 11000 Belgrade, Serbia

²Aalto University, Department of Built Environment, Otakaari 4, 02150 Espoo, Finland

Correspondence should be addressed to Marina Milenković; marina.milenkovic@sf.bg.ac.rs

Received 8 January 2018; Accepted 22 April 2018; Published 27 May 2018

Academic Editor: Jose E. Naranjo

Copyright © 2018 Marina Milenković et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

One of the central decision-making questions in planning road tolling is the selection of the optimal toll collection system (TCS). The question of TCS selection arises in the situation when the existing TCS is to be upgraded or when TCS is selected for a newly constructed road. Considering that there are multiple TCS available nowadays, with their particular advantages and disadvantages, and that there is a range of often conflicting criteria for TCS selection, this decision-making issue belongs to the group of multicriteria decision-making (MCDM) problems. The MCDM-based methodology used in this research integrates Strengths-Weakness-Opportunities-Threat (SWOT) analysis and Fuzzy Preference Ranking Organization Method for Enrichment Evaluations (F-PROMETHEE). The expert-based decision-support framework includes a procedure for defining evaluation criteria and their weights, scoring of alternatives, and sensitivity analysis. Presented decision-support framework is tested with fourteen toll systems. Results indicate that the best-ranked TCS is the dedicated short-range communication multilane free flow. Decision-support framework is developed for transferability to different contexts, where local features can be taken into account by choosing specific alternatives, criteria, and criteria values. Finally, this development opens up opportunities for further analysis of criteria values and considerations of user attitudes in road pricing scheme planning.

1. Introduction

Road pricing scheme represents the direct charges collected for the road use, such as distance or time-based fees, and urban congestion pricing [1–5]. These charges often depend on the vehicle type, number, and configuration of vehicle axles, vehicle dimensions, trailer types, and vehicle emission class. In general, road pricing has two purposes. One purpose of road pricing is demand management, while the other purpose is a mechanism for financing road infrastructure construction, operation, and maintenance. With its strong origins in the economic theory, road pricing has been advocated as an efficient policy to account for externalities and infrastructural funding. Despite its sound purposes, road pricing is a typical example of a theoretically well-developed transport policy that has been shown difficult to implement [6]. Since road pricing is a type of a policy that radically shifts distribution of costs and benefits, this

policy is often value-laden and politely charged. One of the crucial aspects in planning road pricing scheme is public acceptability of road pricing overall. A range of previous research indicates the low public acceptability of road pricing, pointing out to the infringement of freedom and fairness [7–10]. Along with the questions of public acceptability, another crucial issue with road pricing is political acceptability and support [11–13]. For example, politicians often perceive road pricing as complicated new charge for something that is free [12]. Moreover, political unacceptance of road pricing might originate from preference for policies with highly visible benefits and distributed and low-visibility costs [13, 14]. Consequently, planning road pricing scheme often requires balancing contradicting objectives that planners and infrastructure managers might have with respect to users.

An important part in the delicate process of road pricing planning is the selection of tolling system, as an important ancillary asset. Just as different optimal tool schemes relate

to different policy objectives [15], toll collection system (TCS) directly affects the user's experience and consequently acceptance of road pricing scheme. Additional challenge in the decision-making process emerges from the fact that the choice of a particular TCS assumes the operational responsibility for the next 10 to 20 years. This long-term responsibility for TCS asset is particularly important for agencies with large road pricing systems, often responsible for large-scale investment into a single TCS. In practice, the agency is facing a choice between a multitude of TCS currently in use. Nowadays, TCS used worldwide include manual and automatic coin machine (ACM), vignettes, dedicated short-range communication (DSRC) with barriers, DSRC multilane free flow (MLFF), barcode, radiofrequency identification (RFID) with barriers, RFID open road tolling (ORT), global navigation satellite system/cellular network or vehicle positioning system (GNSS/CN or VPS), automated number plate recognition system (ANPR), infrared, tachograph, smart card, and smartphones (Figure 1). These systems differ in their performance, if one considers, for example, accuracy, costs, or interoperability. Bearing in mind the many and diverse interests at stake, each TCS has a range of advantages and drawbacks from the standpoint of road manager and user. For example, different TCS respond differently to the need to maximize the toll revenue, which is often an important criterion for road managers. On the contrary, different TCS cater differently to the user needs for reducing delays and costs or improving level of service (LOS) and safety.

Taking into account the importance of TCS in the effectiveness of the road pricing scheme, as well as large-scale investment and conflicting criteria related to a multitude of alternative TCS, transport planners face a challenging question—which TCS should we select? Previously, only one study has dealt with the issue of selecting the optimal TCS [16]. This study from India considered five alternative TCS including barcode-based ETC, RFID-based ETC, ANPR ETC, VPS ETC, and active infrared system. A multicriteria decision-making method fuzzy VIKOR was used, concluding that the ETC system based on RFID technology was the best of all considered options. Thus, with this gap in the previous research, the objective of this paper is the development of a decision-support framework for selecting the optimal TCS. The next section will present an expert-based methodological framework centered on Fuzzy Preference Ranking Organization Method for Enrichment Evaluations (F-PROMETHEE) multicriteria decision analysis technique. Moreover, the methodological framework integrates Strengths-Weakness-Opportunities-Threat (SWOT) analysis. Decision-support framework is tested with fourteen toll systems, in the context of the newly constructed motorway. Following the results from the implemented decision-support framework (DSF), the discussion of implications is provided, including recommendations for future research.

2. Methodology

Considering the multitude of conflicting criteria stemming from both planners and users' perspective, as well as a

range of advantages and disadvantages that each TCS has, decision-making is not intuitive. Lack of intuitiveness originates from the fact that TCS selection problem cannot be easily organized due to large number of interdependencies and is thus not easily specified in advance. As TCS selection does not have a conventional mathematical formulation, the choice of the optimal TCS belongs to the category of semistructured decision problems [17]. The challenge of semistructured problem is contrasted with the fact that agency often has additional requirements. These agency's requirements might include the need that comparison of alternatives is analytically based and that there is cross-referencing to the relevant sources of information, transferability among locations or agencies, and communication of evaluation results in a multifaceted form [18]. On the contrary, transport planners and road managers often have extensive experience with their transport system. Consequently, this expert knowledge can be an essential resource for aiding the selection of the optimal TCS.

Considering the semistructured nature of the TCS selection problem and the extensive expert knowledge about the transport system, there is an opportunity for a DSF based on multicriteria decision-making (MCDM) methodology. MCDM refers to the process of making decisions between a number of alternatives by defining the decision criteria and their weights. The application of MCDM results in the ranking of alternatives, from the most to the least favorable, thus allowing comparison of alternatives. Some common methods for MCDA in transport applications include the technique for order of preference by similarity to ideal solutions (TOPSIS) [19, 20], analytic hierarchy process (AHP) [21–23], grey evaluation method (GE) [24, 25], simple additive weighting (SAW) [26], and elimination and choice expressing reality ELECTRA [27]. In particular, MCDM methods are often used for formulating DSFs for optimal technological system selection [28–36].

This DSF centers on Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), as the outranking method. When contrasted with other multicriteria analysis methods, PROMETHEE performs better in dealing with the problems having a large number of alternatives [37–41]. On the contrary, the capability to deal with a large number of alternatives is not the case with the AHP method [42]. In practice, PROMETHEE is a group of methods, where PROMETHEE I is used for partial ranking of alternatives and PROMETHEE II is used for complete ranking of alternatives [37]. In order to overcome the uncertainty in the process of the selecting optimal toll collection system, we utilize the extension of the PROMETHEE with fuzzy numbers (F-PROMETHEE). As a fuzzy subset of real numbers, fuzzy numbers are included to deal with subjective dilemma that comes from using linguistic variables for problem representation [43]. As a result, the use of fuzzy numbers allows consideration of vagueness inherent in this decision-making context through the user friendliness from linguistic evaluations. The integration of PROMETHEE I and II, as well as other elements into a DSF, is presented in the following section.

FIGURE 1: Toll collection systems.

FIGURE 2: Proposed decision-support framework.

2.1. Decision-Support Framework. The DSF involves a procedure, presented in the Figure 2, to be organized as an expert-based workshop. The figure shows subprocesses as well as outputs from each subprocess. Involvement of stakeholders in the decision-making process has been especially highlighted before [44] and is thus an important aspect of the proposed DSF. As Figure 2 shows, first step includes description of the MCDM problem with a definition of the TCS goals. During workshops, the authors first defined a set of alternatives, as TCS used worldwide. Then, SWOT analysis, including a discussion about strengths, weakness, opportunities, and threats of each alternative, was conducted to help experts get better understanding of the alternative.

In general, groups of experts should be between four and six people, to allow sufficient diversity of opinions while still having possibility for simultaneous discussion. In addition, by bringing in experts with different roles and backgrounds, discussion allows for complementary knowledge exchange in a constructive setting framed by SWOT. In this particular workshop, four tolling experts from the fields of transport planning, traffic operations, transport policy, and transport economics have participated. This combination has allowed for a sufficient diversity of opinion to emerge, while still being able to have a common understanding on some of the core issues. SWOT-related processes are colored blue in Figure 2. TSC characteristics: in the workshop, the experts discussed

the MCDM task, tolling options, definition of criteria and their weights. Next, sets of the criteria were defined, as well as the criteria weights. The values of the criteria weights were determined using subjective fuzzy evaluations by experts. Then, the experts scored alternatives per each criterion using subjective fuzzy evaluations. Processes using fuzzy logic are colored green in Figure 2. The F-PROMETHEE was used for ranking the alternatives. While implementing the PROMETHEE, the preference functions were defined for each of the considered criteria, as well as the values of the parameters for the selected preference functions. This method determined the values of the positive and negative outranking flows, as well as the net outranking flow, which led to the ranking of the alternatives. Following the alternative ranking, the sensitivity analysis was conducted in order to determine the stability interval for each of the considered TCS alternatives. Processes that rely on PROMETHEE are colored red in Figure 2. The following subsections elaborate on each of the DSF subprocesses.

2.1.1. Establishing Decision Context. The first subprocess involves the definition of TCS goal and all the possible alternative TCS, as well as the criteria list for evaluating the alternatives. The definition of the criteria is preceded with a SWOT analysis of the TCS alternatives. SWOT analysis is a structured planning method that helps evaluate the strengths, weaknesses, opportunities, and threats of each TCS, as follows:

Strengths: characteristics (relative) of the toll alternative that give it an advantage over other alternatives

Weaknesses: characteristics (relative) of the toll alternative that represent disadvantage relative to other alternatives

Opportunities: characteristics (absolute) of the toll alternative that could be used for its advantage during implementation

Threats: characteristics (absolute) of the toll alternative that could be a cause of issues during implementation.

In this DSF, the objective of SWOT is to enable experts to better understand alternatives and their scores and as well define criteria. SWOT is selected as a technique that has minimum structure, thus not overburdening the discussion with its process but allows focus on substance. Having a divergent method is particularly important in this subprocess, because it allows expert knowledge acquisition from both explicit and implicit knowledge, as well as from knowledge about transport system from different aspects. Procedurally, as experts are discussing strengths, weaknesses, opportunities, and threats of different TCS alternatives, they are exchanging knowledge and identifying issues and potential criteria to be discussed, selected, and categorized. Consequently, although SWOT analysis is an output in itself, the process of getting to this output is important for knowledge development among the group of experts. As a result, this DSF subprocess results in refinement of alternatives, their scores, and criteria, as

FIGURE 3: Graphical presentation of a triangular fuzzy number.

well as the objective per criterion, i.e., minimization or maximization.

2.1.2. Determination of Criteria Weight. Determination of the weights is the second subprocess in this DSF. SWOT analysis is used to assist the process of criteria weighting by deepening knowledge of toll alternative characteristics. The relevant linguistic terms are defined in order to assess the criteria individually, instead of using pairwise comparisons. These determined linguistic terms are then expressed by triangular fuzzy numbers. Linguistic definitions for the criteria weight and their corresponding fuzzy numbers are shown in Table 1. Graphical interpretation of a triangular fuzzy number is presented in Figure 3, where a is the lower and b is the upper limit, while m is the point where membership function μ is equal to one.

Experts evaluate the criteria weights in the form of linguistic terms. In order to define the weight factor of each criterion, each expert is presented with a list of criteria defined in the previous step. Then, linguistic expert evaluations are converted into related fuzzy numbers. Next, the importance of each criterion (i), taking into account the estimates of all experts (k), is determined as follows:

$$W_i = (a_i, m_i, b_i) \rightarrow W_i = \left[\min(a_{ik}), \frac{\sum_{k=1}^k m_{ik}}{k}, \max(b_{ik}) \right] \quad (1)$$

The fuzzy numbers were defuzzified by using the distance minimization method suggested by Asady and Zendehman [58] as given below:

$$W_{\text{defuzzified}} = m + \frac{b - a}{4} \quad (2)$$

Defuzzified values are then normalized as follows:

$$W_{\text{normalized}} = \frac{w_i}{\sum_{i=1}^n w_i}, \quad (3)$$

where

TABLE 1: Linguistic terms and corresponding fuzzy numbers.

Linguistic terms		Triangular fuzzy number
For determination of criteria weight	For scoring alternative per criteria	
Very Low (VL)	Very Weak (VW)	(0.00, 0.00, 0.15)
Low (L)	Weak (W)	(0.00, 0.15, 0.30)
Medium Low (ML)	Medium Weak (MW)	(0.15, 0.30, 0.50)
Medium (M)	Medium (M)	(0.30, 0.50, 0.70)
Medium High (MH)	Medium High (MH)	(0.50, 0.70, 0.85)
High (H)	High (H)	(0.70, 0.85, 1.00)
Very high (VH)	Very high (VH)	(0.85, 1.00, 1.00)

i denotes number of criteria ($i = 1, 2, \dots, n$);

k denotes number of decision-makers ($k = 1, 2, \dots, p$);

j denotes number of alternatives ($j = 1, 2, \dots, m$);

a_{ik} denotes left threshold of fuzzy number estimated by expert k for criteria i ;

m_{ik} denotes midpoint of fuzzy number estimated by expert k for criteria i ;

b_{ik} denotes right threshold of fuzzy number estimated by expert k for criteria i ;

W_i denotes weight of criteria i .

2.1.3. Scoring of Alternatives. In addition to assessing the weight of the criteria, tolling experts are responsible for scoring alternatives, also partially relying on information provided from SWOT analysis. In order to evaluate the performance of each alternative on the basis of the defined criteria, the expert opinions are collected as linguistic terms, defined in Table 1. Due to the fact that determination of analytical scoring is not possible for such a large number of criteria and alternatives, linguistic scale is used. Linguistic expressions are then transformed into the corresponding fuzzy numbers (Table 1). The values of the fuzzy numbers boundaries are the same as those during the activity of criteria weighting. The estimates of all experts were taken into account using (1). The obtained fuzzy numbers were then defuzzified using (2) and normalized using (3).

2.1.4. Evaluation of Alternatives. The detailed procedure for evaluation of alternatives using PROMETHEE II method consists of five steps [see [38, 39]]. The subprocess starts with the determination of deviations based on pairwise comparisons. This step is then followed by applying a relevant preference function for each criterion defined in subprocess 2 above. Step three involves calculating global preference index, while step four involves calculating positive and negative outranking flows for each alternative and partial ranking. The subprocess ends in step five, with the calculation of net outranking flow for each alternative and with complete ranking [38, 39].

PROMETHEE is based on pairwise comparisons and the specificity of this method is preference function. Its rule is that difference in values for each pair of alternatives leads to the range from zero to one, per criterion. In this way,

normalization of values and obtaining information about the preferences of each alternative in relation to each, according to each of the criteria, are achieved.

The PROMETHEE I partial ranking is based on the computation of two preference flows. Φ^+ (positive flow) is a measure of the strength of the alternative, while Φ^- (negative flow) is a measure of the weakness of the alternative. PROMETHEE I partial ranking allows incomparability, which usually happens when one alternative is good in a subset of criteria in which another one is weak and vice versa [59]. The possibility of incompatibility is excluded by introducing the characteristic of net outranking flow which denotes the difference between the positive and negative outranking flows. Thus, alternative a is preferred to alternative b in the PROMETHEE II ranking only if it is preferred to b according to the net preference flow. In this particular case, aP^IIb only if $\Phi(a) > \Phi(b)$ [60]. Thus, PROMETHEE II provides a complete ranking of the alternatives from the best to the worst ones [59].

2.1.5. Sensitivity Analysis. As the last subprocess, sensitivity analysis is essential for determining the changes of alternative ranking due to changes in the value of particular criteria weight. As part of PROMETHEE, weight sensitivity analysis can be done using Walking Weights or Stability Intervals analysis [60]. For this DSF, we have implemented Stability Intervals, which shows how the Φ score and the PROMETHEE II ranking vary as a function of the weight of a criterion and identifies the interval of stability of the first place and complete ranking.

3. Application of the Decision-Support Framework

Decision-support framework is tested with fourteen toll systems, in the context of the newly constructed motorway. DSF has been implemented in a workshop setting, with participation by four tolling experts from the fields of transport planning, traffic operations, transport policy, and transport economics. Experts' number has been decided based on the general recommendations that group activity is usually most effective in groups of four to six people.

3.1. Description of the Alternative TCS. Toll collection has changed historically from manual toll collection to various forms of electronic toll collection. The development of digital

TABLE 2: Description of the alternative TCS.

TCS	Description of the alternative TCS
Manual	This system relies on cash payment for motorway usage which is conducted manually by tolling staff. Driver has to stop her vehicle at the toll station and pay to officer who is responsible for it. Officer determines the amount to be paid on the basis of the characteristics and classification of vehicles, and the distance traveled by the vehicle. Since paying takes some amount of time, queuing is usual for this tolling type [45].
ACM	It is a machine with a slot for inserting coins or paper money. Driver has to stop her vehicle and pay a certain amount of money on the basis of the classification of vehicles, and the distance traveled by the vehicle. This technology has better service time when compared to the manual TCS, consequently resulting in lower delays.
Vignette	It is a sticker which, once bought, pays the toll for a specific time period. There are vignettes which pay the toll in the duration of several days, week, month or a year. The vignette must be applied to the car windshield. The so-called electronic vignettes are not in the form of stickers, but the number of the car's registration plate is inserted into the system for the days the vignette is paid for. The control of the participants is performed with the help of the database, traditional stopping on the roadside and penalizing the violators.
DSRC with barriers	It is a type of non-contact TCS where the users do not have contact with toll booths or cashiers. Users can choose bills to be sent once a month or choose a prepaid model. A vehicle does not have to stop at the toll plaza; it only needs to reduce its speed in order to establish the contact and recognition through the on-board unit (OBU) to pass. In the meantime, all data are recorded in the central toll system of the operator.
DSRC MLFF	In this system, antennas are set on gantries, on particular locations (e.g., between two interchanges) along the highway with road pricing. Antennas detect traffic flow and record the use on the OBU, as well as in the central toll collection system of the operator for further processing and payment. The technology used in MLFF system is designed so that the vehicles can maintain their speed and change lanes (including emergency stop lanes) while passing below the collection portal.
Barcode-based	This system is a subcategory of ETC. Within this system, the barcode is a sticker applied to the windshield of the vehicle which is read by a laser scanner while the vehicle passes through the toll gate [46].
RFID with barriers	This system contains the OBU or sticker installed on the front windshield of the vehicle. At toll gate, either prepaid or postpaid system is read by a RFID frequency reader, [16]. RFID reader is a device used to communicate with an RFID tag, via radio waves [47]. A vehicle does not have to stop at the toll gate; it only needs to reduce its speed in order to establish the contact and recognition so that system can let the vehicle pass.
RFID ORT	This system contains the OBU installed on the front of the vehicle. At the toll gate, this system is read by a RFID frequency reader [16]. The technology used in RFID ORT system is designed so that the vehicles can maintain their speed and change lanes (including emergency stop lanes) while passing below the collection portal.
GNSS/CN	It includes a global navigation satellite system incorporated with the cellular networks. This TCS functions using a global positioning system unit (GPS/Galileo/Glonass) installed on the OBU which stores the route coordinates of the vehicle and sends the transaction information to toll collection central system through global mobile communication system (GSM/3G/4G) [48–50].
ANPR	It uses a stationary camera for recording and identifying the registration plate numbers of vehicles passing through the toll gates. The detected registration plates are paired in the database and the toll is deducted (a particular amount of money is taken). If the recorded plate number is not read accurately or not found in the database, an enforcement violation alarm is generated to alert the authorities. In this manner, two issues are simultaneously solved – identifying the vehicles for toll collection and issuing/recording the violation enforcement alert [51, 52].
Infrared	This system is similar to DSRC with barriers TCS; the only difference is that it has an active infrared unit installed in the vehicle which contains all the information [53–55].
Tachograph-based	It records the mileage driven by the user through an OBU connected electronically to the vehicle's odometer, measuring the vehicle's mileage. A tachograph system which is in place in New Zealand requires manual, rather than electronic, data collection [56].
Smart card	It represents a memory card in which the details of a particular person and certain amount of money are stored. Smart cards must be recharged with some amount of money and whenever a person wants to pay the toll, she needs to insert her smart card and deduct an amount of money. The smart card based toll collection system functions on the basis of contact communication between the smart card and the reader [57].
Smartphones	It is not matured TCS and it is in stages of constant development. An example of mobile and Smartphone ETC integration is the m-Toll, Ptooll, GeoToll, and PayTollo projects. This TCS relies on the use of smartphone capabilities, such as WiFi, 4G, GSN, and NFC connection to authenticate, validate and charge road users without the need for any additional hardware for the end user.

TABLE 3: SWOT matrix for alternative TCS.

TCS	Strengths	Weaknesses	Opportunities	Threats
Manual	Backup tolling option for OBU non-equipped motorway users; No user investment	Low LOS, Long queues, High Opex; Increased emissions; Health and safety risks for toll operators	-	Thefts
ACM	Additional tolling option on toll plazas	Stopping, small coin values	-	No exact amount of coins
Vignette	Stimulating the everyday users to use motorways; Decrease of noise; Decrease of air pollution; Savings in infrastructure costs	Applicability; Not fair pricing for foreigners and occasional users; Many stickers on the windshield visually degraded vehicles; High enforcement costs; The difficulties of controlling all vehicles	Temporary tolls; Additional toll system for certain vehicle categories	Acceptance of a wider driving population; Frequent control of the driver; Being considerably more expensive for occasional users; No interoperability
DSRC				
DSRC with barriers	Payment without stopping; No queuing; Decrease of VOC; Decrease of TTC; Reduced environmental degradation; Pay in accordance with travelled kilometres; Large number of DSRC OBUs currently in operation	Inefficiency for occasional users without OBU; High capital expenditure and maintenance cost of tolling infrastructure; Difficulty in modifying the tolled network once implemented	Easy transition from existing manual system to ETC; Ability to provide/support other value added services through the OBU; Interoperability	Low % of users with OBUs
DSRC MLFF	Payment without decreasing the speed; No delays; Without increase of VOC and TTC; Increase of traffic safety; Minimum of environmental degradation; Pay in accordance with travelled kilometres; High reliability & performance, low signal interference; Large number of DSRC OBUs currently in operation; User friendly	Inefficiency for occasional users without OBU; High enforcement costs; The difficulties of controlling vehicles without OBU. Necessity to install road-side infrastructure (gantries) along the road; High capital expenditure and maintenance cost of tolling infrastructure; Difficulty to modify the tolled network once implemented	Increasingly common technology; Efficiency for drivers and toll operators; Ability to provide/support other value added services through the OBU; Interoperability	Avoiding payment of tolls; Being less profitable in low traffic volume roads
Barcode-based	Technology which does not require complex system; Pay in accordance with travelled kilometres	Unreliability; Lower accuracy during bad weather; Lack of flexibility; Low rate of reading data; Low passenger comfort	-	Theft of barcode label
Infrared	Payment without stopping; No queuing; Decrease of VOC; Decrease of TTC; Less environmental degradation; Pay in accordance with travelled kilometres; High rate of reading data; High reliability; Accurate in all-weather condition	The problem of interference with other signals; High Opex and Capex	Easy transition from existing manual to calm active infrared system	The problem of interference with the frequencies of other devices; The lack of interoperability
RFID				
RFID with barriers	Payment without stopping; No queuing; Decrease of VOC; Decrease of TTC; Less environmental degradation; Pay in accordance with travelled kilometres; High rate of reading data	High Opex and Capex; The problem of interference with the frequencies of other devices; Inefficiency for occasional users without OBU	Increasingly common technology; Efficiency for drivers and toll operators; Low RFID sticker/OBU price	The angle of object installation and compatibility having an important role in the reliability and punctuality of these systems
RFID ORT	Payment without stopping; No queuing; Decrease of VOC; Decrease of TTC; Less environmental degradation; Pay in accordance with travelled kilometres; High rate of reading data	The problem of interference with the frequencies of other devices; Inefficiency for occasional users without OBU	Increasingly common technology; Efficiency for drivers and toll operators; Low RFID sticker/OBU price	The angle of object installation and compatibility having an important role in the reliability and of punctuality these systems

TABLE 3: Continued.

TCS	Strengths	Weaknesses	Opportunities	Threats
Smart card	Reduced queuing time; Small decrease of VOC; and TTC; Environmental degradation	Payment with stopping; Reliability	Reduced number of toll employees	An insufficient number of Smart card users;
ANPR	Payment without stopping; No queuing; Decrease of VOC; Decrease of TTC; Less environmental degradation; No OBU; Ability to deliver cost savings for automatic handling processing, subject to fine tuning and secondary processing methods used; Most successful when combined with other technologies; No performance restrictions regarding vehicle speeds	Requires good quality license plates; Susceptibility to poor lighting and weather conditions; Access to needed vehicle data of foreigners vehicle database; Cost of manual checking that can increase operational costs; Suitability for supporting relatively simple charging policies	Continuous improvements in video camera quality; Always being required for enforcement; Increased overall safety	Thefts and toll avoiding; Lack of standardisation of license plates; Manual verification needed for full effectiveness subject to level of “tuning”
GNSS/CN	Payment without stopping; Payment without decreasing the speed; No delays and queuing; Without increase of VOC and TTC; Minimum of environmental degradation; Pay in accordance with travelled kilometres; Increase of traffic safety; Flexibility to define and modify what is to be charged and how it is to be charged; Once installed, less costly to maintain; Easily expandable to other roads and regions	Privacy of the user's movement; High Opex and Capex; Inefficiency for occasional users without OBU; High enforcement costs; Less used and mature technology than other technologies; Accuracy errors in certain sections of the tolled network, such as parallel free roads and intersections; Additional roadside devices that need to be installed	Route guidance; Increased overall and traffic safety; Ability to provide/support other necessary to be pursued value-added services through the OBU; traffic information, speed control	Interoperability; Gaining the public support regarding the mobility privacy policy
Tachograph-based	Absence of privacy and data protection issues; Investment in tolling infrastructure relatively independent of the tolled network within the area; Low toll collection costs; Maintenance of tolling infrastructure is limited to cross-border control stations	Rigidity in defining and modifying what is to be charged and how it is to be charged within the tolled area; Low accuracy of the tolling technology ($\pm 4\%$); Complex and costly on-board unit; No interoperability; High start-up costs of cross-border control stations; Not commonly used technology	-	Additional position services which cannot be provided through the OBU; No interoperability
Smartphones	Flexibility to define and modify what is to be charged and how it is to be charged; Little physical tolling roadside infrastructure investment; No need for in-vehicle device or costly enforcement infrastructure; User-friendly interface; Interoperability with other tolling technologies; Low maintenance costs	Device battery duration; Less used and mature technology than other options; Ability to become obsolete quickly, given technological developments in the sector; Variable proliferation of mobile and smart phones in different areas; Some areas not having appropriate GSM coverage; No proven data about accuracy on certain sections of the tolled network, such as parallel free roads and intersections; Not being able to classify vehicles; No standards currently available	Continuous technological improvements in position mobile phone and smartphone industry; Possibility of integrating toll payment with other user services; interoperability	Data protection issue in relation to the cellular network used to track user position

TABLE 4: Groups of criteria and description of criteria.

Criteria group (group of criteria)	Criteria	Description
(1) Technical operation	Interoperability	Interoperability with other toll collection systems inside a country or in other countries.
	Flexibility	Ability of a technology to be used for other purposes (paying for parking, gas, or congestion charge, as well as for navigation, traffic control, vehicle theft prevention etc.).
	Efficiency	The capacity per lane as capability of a system to register and identify the number of vehicles at the same time, based on data rate and system complexity.
	Reliability/accuracy	The ability of a system to correctly identify vehicle's identity and payment options, especially in poor weather conditions.
	Enforcement	The amount of resources engaged for enforcement. Share (percentage) of those who avoid payment.
(2) Traffic operations	Level of service	The impact of the system on the level of service of traffic flow (speed, volume/capacity ratio).
	Traffic safety	The impact of the system on the traffic safety.
	Number of stops	The number of stops during the tolling.
	Delays	The increase in travel time that each of the systems causes.
(3) Financial	Average cost for user	Value that the user has to pay for using the system.
	Ratio of revenues/costs	The value of the ratio of revenues/costs for each system.
	Capex	Value of capital costs, as the size of the capital expenditures of each system.
	Opex	Value of operational costs, as the size of operation expenditures of each system.
(4) Environmental	Visual impact of defacing ambient environment	How each system visually defaces the ambient environment.
	Air pollution	To what extent the system contributes to air pollution.
	Noise	To what extent the system contributes to noise pollution.
(5) Socio-economic	Fair pricing	Whether the system is fair to all users. Payment for what is used.
	User friendliness	Easiness of using the system.
	Aesthetic effect on the vehicle	How the equipment that each system requires affects the aesthetic effect of the vehicle.
	Possibility of theft and fraud	Possibility of system's theft and fraud in general.

technology has been extremely dynamic in recent years and has led to the rapid application of numerous technologies in toll collection. Short description of alternative TCS is given in Table 2.

3.2. SWOT Analysis of Toll Alternatives. Results of SWOT analysis conducted during the workshop are represented in Table 3. Resulting SWOT matrix has assisted experts in further DSF steps, when defining the criteria and scoring the alternative per criterion.

3.3. Criteria List and Groups. During the workshop, experts have decided on the list of criteria which were then grouped. As Table 4 shows, the groups of criteria have been divided into technical operation, traffic operation, financial, environmental, and socioeconomic criteria. Each group contains three to five criteria that cover all characteristics of TCS alternatives, while total number of criteria is twenty. Table 4 also provides a brief description of each criterion.

3.4. Criteria Weights. During the workshop, experts have also assigned criteria weights using the fuzzy-based process described in Section 2. Table 5 provides the evaluations of four experts participating in the study expressed by linguistic terms. The final defuzzified and normalized values of criteria weight are shown in Table 6.

3.5. Scoring of Alternatives and Base Matrix of Input Data. Experts were scoring alternatives per criterion, but due to large number of criteria and alternatives, Table 7 shows an example of scoring for one criterion, namely "interoperability". Defuzzified values of alternatives' scores per criterion estimated by experts are shown in Table 8.

Table 9 shows the type of particular criteria, which preference function was selected for each criterion, and what the values of each parameter for each preference function are.

3.6. PROMETHEE I and II Alternative Ranking. The PROMETHEE Table (Table 10) displays the Φ , Φ^+ , and

TABLE 5: The importance of criteria according to experts expressed by linguistic terms.

Group of criteria	Criteria	DM1	DM2	DM3	DM4
(1) Technical operation	Interoperability	MH	H	H	MH
	Flexibility	M	ML	H	H
	Efficiency	VH	H	VH	VH
	Reliability	VH	VH	VH	VH
	Enforcement	MH	ML	H	M
(2) Traffic operations	Level of service	VH	MH	H	H
	Traffic safety	H	M	H	H
	Number of stops	H	M	H	H
	Delays	H	H	H	H
(3) Financial	Average cost for user	H	MH	MH	MH
	Revenue/cost ratio for road agency	ML	M	VH	VH
	Capex	M	MH	H	VH
	Opex	ML	ML	H	VH
(4) Environmental	Visual degradation of road environ.	L	ML	ML	M
	Air pollution	M	ML	MH	MH
	Noise	L	L	MH	MH
(5) Socio-economic	Fair pricing	MH	M	H	H
	User friendliness	MH	MH	MH	MH
	Aesthetic effect on the vehicle	ML	M	M	ML
	Possibility of theft and fraud	H	H	H	H

TABLE 6: The values of criteria weights.

	Fuzzy Weight (W_i)	$W_{\text{defuzzified}}$	$W_{\text{normalized}}$
Interoperability	(0.50, 0.73, 1.00)	0.85	0.05
Flexibility	(0.15, 0.60, 1.00)	0.81	0.05
Efficiency	(0.65, 0.95, 1.00)	1.04	0.06
Reliability	(0.80, 1.00, 1.00)	1.05	0.06
Enforcement	(0.15, 0.56, 1.00)	0.78	0.05
Level of service	(0.50, 0.81, 1.00)	0.94	0.06
Traffic safety	(0.30, 0.73, 1.00)	0.90	0.06
Number of stops	(0.30, 0.73, 1.00)	0.90	0.06
Delays	(0.65, 0.80, 1.00)	0.89	0.05
Average cost for user	(0.50, 0.69, 1.00)	0.81	0.05
Revenue/cost ratio for road agency	(0.15, 0.70, 1.00)	0.91	0.06
Capex	(0.30, 0.74, 1.00)	0.91	0.06
Opex	(0.15, 0.60, 1.00)	0.81	0.05
Visual degradation of road environment	(0.00, 0.31, 0.65)	0.48	0.03
Air pollution	(0.15, 0.53, 0.80)	0.69	0.04
Noise	(0.00, 0.40, 0.80)	0.60	0.04
Fair pricing	(0.30, 0.69, 1.00)	0.86	0.05
User friendliness	(0.50, 0.65, 0.80)	0.73	0.04
Aesthetic effect on the vehicle	(0.15, 0.40, 0.65)	0.53	0.03
Possibility of theft and fraud	(0.65, 0.80, 1.00)	0.89	0.05

Phi- scores. The alternatives are ranked according to the PROMETHEE II complete ranking.

Analyzing the flows given in Table 10 it can be concluded that two best-ranked tolling options according to PROMETHEE I partial ranking and according to PROMETHEE II complete ranking are DSRC MLFF (Phi

= 0.0425) and RFID ORT (Phi = 0.0454). They are followed by the alternatives with slightly lower values of net flow (GNSS/CN and Smartphone), while the other alternatives have significantly poorer values of positive, negative, and net flow. The lowest ranked alternative is the Manual TCS.

TABLE 7: The opinion of decision makers for each alternative on the basis of criterion “Interoperability”.

Criteria	Alternatives (TCS)	DM1	DM2	DM3	DM4
Interoperability (C1)	Manual	W	M	MW	W
	ACM	W	W	MW	W
	Vignette	W	VW	MW	W
	DSRC with barriers	H	MH	M	MW
	DSRC MLFF	H	MH	MH	M
	RFID with barriers	W	MW	M	MW
	RFID ORT	W	MW	MH	M
	Barcode	VW	W	W	W
	GNSS/CN	VH	VH	VH	H
	ANPR	H	M	MH	M
	Infrared	W	MW	MW	W
	Tachograph	VW	W	W	W
	Smart card	VW	W	M	M
	Smartphone	H	MH	H	VH

3.7. Sensitivity Analysis. Table 11 shows the sensitivity analysis results, as the possible range of criteria weights values needed to keep the complete ranking unchanged or for the first place to remain unchanged.

4. Discussion and Conclusion

Planning road pricing scheme is a delicate and often politically charged process, highly dependent upon user and political acceptability for a successful implementation. In this context, toll collection system is crucial for effectiveness of road pricing scheme, both from the standpoint of road managers and from the standpoint of road users. Moreover, toll collection system installation is usually a large-scale investment. Thus, the selection of the optimal toll collection system is a very important decision in the process of planning a road pricing scheme. However, decision-makers are often faced with a choice between a range of alternatives, which often have conflicting advantages and disadvantages. Considering the significance of the toll collection system selection, this research provides a decision-support framework. The discussion here will focus on elaborating the application of this decision-support framework under the assumption of inter- and intraorganizational learning.

In addition to the described framework, results include a systematized analysis of fourteen toll collection systems using SWOT analysis, including their technical and operation characteristics. From the SWOT matrix, one can observe that this analysis itself provides decision-makers with a deeper understanding of advantages and limitations of toll collection systems. Here, it is important to highlight those features that are common to many of toll collection systems. One could then easily identify groups of technologies based on their effect on the traffic flow. For example, manual tolling certainly belongs to the group of technologies that require full stopping for the road pricing transaction to occur. On the other hand, technology such as ANPR with barriers might require deceleration (approximately 30–50 km/h), while GNSS-CN does not require any reduction in vehicle's

velocity. Nonetheless, despite its usefulness to organizational learning, SWOT analysis itself is insufficient to help decision-makers select the optimal toll collection system.

Results indicate that the DSRC MLFF, GSNN-CN, and RFID ORT are grouped in the top of ranking. In particular, DSRC MLFF toll system has a narrow advantage over RFID ORT toll technology, while the GSNN-CN technology achieved somewhat worse value for financial criteria (Capex and Opex). Furthermore, smartphone technology got something worse score for traffic criteria (traffic safety). However, when the final ranking is compared to the ranking obtained in the study of Vats et al. (2014), some differences can be noticed. Vats et al. (2014) determined that the optimal alternative for India was the ETC system based on RFID technology, while ANPR and VPS occupied the second and third place, respectively. It should be noted that the research presented here includes additional technologies which were not included in the study by Vats et al. (2014). Moreover, the study presented here contains a larger number of criteria, as well as a greater number of experts from various fields that participated in the evaluation.

In addition to the ranking results, sensitivity analysis provides several other conclusions. First, regarding sensitivity to changes in the technical criteria, one can conclude that the first place is stable in a range from 0%–8.84% up to 0%–100% depending on the criterion. Second, regarding sensitivity to changes in the traffic operations criteria, one can conclude that the first place is stable in a range from 2.89%–15.25% up to 0%–100% depending on the particular criterion. Third, regarding sensitivity to changes in the financial criteria, one can conclude that the ranking of the first place remains stable with increase within 0.00%–8.02% for criterion “average cost for user”, within 1.39%–100% for criterion “revenue/cost ratio”, and within 7.73%–27.62% for criterion “Capex and Opex”, respectively. Fourth, with respect to changes in the environmental criteria, the ranking of the first place is stable in the range up to 100%, depending on the criterion. Lastly, regarding sensitivity to changes in the socioeconomic group of criteria, the ranking of the first place is stable in range

TABLE 8: Defuzzified alternatives' scores matrix.

Criteria	Manual	ACM	Vignette	DSRC with barriers	DSRC MLFF	RFID with barriers	RFID ORT	Barcode	GNSS/CN	ANPR	Infrared	Tacho- graph	Smart card	Smart- phone
Interoperability	0.06	0.04	0.04	0.10	0.11	0.06	0.08	0.02	0.14	0.10	0.05	0.02	0.06	0.12
Flexibility	0.01	0.03	0.00	0.11	0.11	0.09	0.09	0.02	0.11	0.10	0.08	0.05	0.08	0.12
Efficiency	0.03	0.04	0.04	0.09	0.11	0.08	0.11	0.05	0.11	0.05	0.09	0.06	0.04	0.10
Reliability	0.09	0.06	0.07	0.08	0.07	0.07	0.07	0.05	0.09	0.05	0.07	0.06	0.08	0.08
Enforcement	0.02	0.03	0.13	0.01	0.10	0.01	0.10	0.07	0.10	0.08	0.09	0.10	0.05	0.09
Level of service	0.01	0.03	0.04	0.08	0.10	0.08	0.10	0.06	0.10	0.10	0.08	0.08	0.04	0.09
Traffic safety	0.03	0.03	0.07	0.07	0.09	0.07	0.09	0.08	0.10	0.10	0.08	0.09	0.03	0.06
Number of stops	0.12	0.12	0.11	0.06	0.04	0.06	0.04	0.08	0.04	0.06	0.07	0.06	0.11	0.05
Delays	0.15	0.13	0.13	0.06	0.03	0.06	0.03	0.08	0.03	0.04	0.07	0.04	0.10	0.03
Average cost for user	0.08	0.09	0.12	0.06	0.06	0.06	0.05	0.07	0.07	0.05	0.07	0.08	0.09	0.05
Revenue/cost ratio	0.03	0.06	0.07	0.08	0.09	0.08	0.09	0.07	0.07	0.08	0.07	0.07	0.06	0.09
Capex	0.07	0.06	0.05	0.08	0.07	0.08	0.06	0.08	0.09	0.07	0.08	0.07	0.06	0.07
Opex	0.10	0.07	0.09	0.06	0.07	0.06	0.07	0.06	0.08	0.07	0.06	0.07	0.06	0.07
Visual degrad. of road environ.	0.10	0.09	0.05	0.09	0.05	0.09	0.05	0.09	0.05	0.05	0.09	0.05	0.08	0.05
Air pollution	0.12	0.10	0.08	0.07	0.04	0.07	0.04	0.09	0.04	0.06	0.07	0.06	0.10	0.05
Noise	0.10	0.08	0.07	0.07	0.07	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.08	0.07
Fair pricing	0.08	0.06	0.01	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
User friendliness	0.01	0.03	0.02	0.08	0.11	0.08	0.10	0.06	0.11	0.09	0.08	0.07	0.05	0.11
Aesthetic effect on the vehicle	0.02	0.02	0.17	0.07	0.07	0.07	0.08	0.13	0.08	0.02	0.08	0.09	0.05	0.05
Possibility of theft and fraud	0.13	0.11	0.12	0.03	0.05	0.03	0.05	0.11	0.04	0.08	0.07	0.09	0.07	0.05

TABLE 9: Preference parameters for alternative ranking.

Criteria	The nature of criteria (Min/Max)	Weight	Preference function	Values of parameter p
Interoperability	max	0.05	V-shape	0.12
Flexibility	max	0.05	V-shape	0.12
Efficiency	max	0.06	V-shape	0.08
Reliability	max	0.06	V-shape	0.04
Enforcement	min	0.05	V-shape	0.12
Level of service	max	0.06	V-shape	0.09
Traffic safety	max	0.06	V-shape	0.07
Number of stops	min	0.06	V-shape	0.08
Delays	min	0.05	V-shape	0.12
Average cost for user	min	0.05	V-shape	0.07
Revenue/cost ratio	max	0.06	V-shape	0.06
Capex	min	0.06	V-shape	0.04
Opex	min	0.05	V-shape	0.04
Visual degradation of road environ	min	0.03	V-shape	0.05
Air pollution	min	0.04	V-shape	0.08
Noise	min	0.04	V-shape	0.03
Fair pricing	max	0.05	V-shape	0.07
User friendliness	max	0.04	V-shape	0.10
Aesthetic effect on the vehicle	min	0.03	V-shape	0.15
Possibility of theft and fraud	min	0.05	V-shape	0.10

TABLE 10: Ranking of the toll alternatives using PROMETHEE method.

Rank	Multicriteria flows	Phi	Phi+	Phi−
1	DSRC MLFF	0.2348	0.2773	0.0425
2	RFID ORT	0.2297	0.2752	0.0454
3	Smartphone	0.2200	0.2708	0.0509
4	GNSS/CN	0.2180	0.2961	0.0781
5	DSRC with barriers	0.1506	0.2277	0.0770
6	ANPR	0.1148	0.2142	0.0995
7	RFID with barriers	0.0995	0.1957	0.0962
8	Infrared	0.0172	0.1448	0.1277
9	Tachograph	−0.0148	0.1384	0.1532
10	Smart card	−0.1296	0.1163	0.2459
11	Barcode	−0.1718	0.0861	0.2579
12	ACM	−0.2721	0.0747	0.3467
13	Vignette	−0.3146	0.0835	0.3981
14	Manual	−0.3816	0.0850	0.4666

from 0.00%–12.06% up to 0%–100%, depending on the criterion.

Here, it is important to highlight the importance of defining and weighting criteria for evaluation of alternative TCS. The suggested decision-making process presented in this study indicates that agency's staff should incorporate their knowledge of specific expert areas along with the agency's objectives. One way this knowledge is incorporated is by defining criteria as well as by grouping them. With this in mind, the presented decision-support framework provides an extensive list of possible criteria for evaluation. These criteria and their group have to be based on the long-term goals that specific transport agency has for its overall system.

For example, an agency that is responsible for dominantly regional and intercity motorway network might have different objectives from an agency that is dominantly responsible for suburban or urban motorway tolling. In addition, expert knowledge is particularly important in determining criteria weights. Special attention should be paid to determining criteria weight since they have a crucial role in the analytical procedure for determining the final ranking of alternatives.

In addition to the elements of the proposed decision-support framework above, it is important to highlight also the aspects of the process itself, in the context of organizational learning. In particular, special attention should be paid to the expert knowledge acquisition. The decision-support process

TABLE II: Stability intervals matrix for criteria weight regarding the complete ranking and the first place.

Criteria	Complete ranking remains unchanged (%)	First place remains unchanged (%)
Interoperability	3.18–6.03	3.18–10.57
Efficiency	0.00–7.36	0.00–100.00
Flexibility	2.86–8.32	2.25–18.44
Reliability/accuracy	1.63–6.68	0.00–8.84
Enforcement	2.86–7.26	0.00–13.96
Level of service	0.00–7.53	0.00–100.00
Traffic safety	3.97–6.30	2.89–15.24
Number of stops	0.00–7.36	0.00–100.00
An increase in travel time	0.00–15.10	0.00–100.00
Average cost for user	4.39–8.02	0.00–8.02
Ratio of revenues/costs	5.48–23.90	1.39–100.00
Capex	5.65–7.73	2.98–7.73
Opex	4.30–10.10	0.00–27.62
Visual impact of defacing ambient environment	1.25–6.48	0.00–100.00
Air pollution	0.00–5.39	0.00–100.00
Noise	0.00–14.18	0.00–100.00
Fair payment	0.00–10.56	0.00–100.00
Easy to use	0.00–11.97	0.00–100.00
Aesthetic effect on the vehicle	2.10–7.20	0.00–12.06
Possibility of theft and fraud	0.00–6.71	0.00–17.80

itself should aim at maximizing the performance of experts' decisions by minimizing human cognitive errors. In addition, the process should be able to generate several alternative plans by making changes in the decision criteria weights, which would allow experts to evaluate impacts of those changes in a matter of exploratory what-if analysis. One example of such exploratory analysis would be completely excluding a group of criteria. Such exploratory analysis has particular potential in the case of the existence of TCS in the particular area, where some aspects, such as interoperability, might be worthy of a more focused investigation.

It is important to highlight here that this is ultimately a decision-support and not a decision-making framework. Thus, joint discussion between experts during the workshop is an important aspect of supporting the decision-making process. Such a discussion is ultimately necessary for transparent and uniform presentation of alternative decisions. Moreover, experts should be encouraged from the start to understand the decision-making process as an iterative learning experience, where mutually agreed alternative is sought as the ultimate goal. Thus, approaching decision-making process as an iterative one allows for a range of perspectives and agency's objectives to be taken into account. Here, the process can benefit from experts with various backgrounds, such as planning, economics, operations, or maintenance. However, as the proposed decision-support framework uses fuzzy logic, subjective uncertainty can be filtered out for increasing coherence in decision-making.

The methodological framework presented here is transferable, as it can be applied to different case studies, while adopting to local specifics. As objective implementation of MCDM procedure is of the utmost importance, special

attention should be paid to identifying relevant experts to join the workshop. However, bearing in mind the need to select one alternative, there is a range of requirements that an agency needs to take into account in its decision-making procedures. The framework presented here can help in organizing road toll planning workshops by providing analysis based and transparent comparison of alternatives. Moreover, approaching these workshops as an opportunity to enhance inter- and intraorganizational learning, the framework presented here can be used as a communication medium.

On the contrary, one has to recognize that a large number of alternatives and criteria are also a disadvantage from the perspective of workload scope. In addition, for many of the alternatives, it is difficult to determine their scores per criterion in an analytical manner. Thus, the lack of analytically determined data in the scoring procedure for each of the alternatives per criterion is a limitation of this effort. Including as wide as possible range of experts can help in overcoming the challenge of missing alternative data. However, since group dynamics in workshops cannot be properly maintained with a significant number of participants, decision-makers will have to seek other solutions. Thus, one potential direction for future research is investigating the potential of using microsimulation techniques for evaluating some toll collection system effects, such as environmental pollution. In addition, when selecting the optimal toll collection system, it is also extremely significant to consider the attitudes of the highway users. In order to achieve this, agency can conduct a survey to determine the users' attitudes towards particular toll collection systems. Surveying users would provide information about their expectations, which

would contribute to the TCS ranking methodology from the users' point of view. Finally, exploration of implications for the development of emerging self-driving vehicle technology in relation to different existing toll collection technologies is an important future effort.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

All the authors declare that there are no conflicts of interest regarding the publication of this paper.

References

- [1] E. Deakin, "Toll roads: a new direction for US highways?" *Built Environment*, vol. 15, no. 3-4, pp. 185-194, 1989.
- [2] S. Ison, "Pricing road space: Back to the future? the cambridge experience," *Transport Reviews*, vol. 16, no. 2, pp. 109-126, 1996.
- [3] R. Arnold, V. C. Smith, J. Q. Doan et al., "Reducing congestion and funding transportation using road pricing in Europe and Singapore," Report No. FHWA-PL-10-030, Federal Highway Administration, Washington, D.C., USA, 2010.
- [4] D. Glavić, M. Milenković, A. Trpković, M. Vidas, and M. N. Mladenović, "Assessing sustainability of road tolling technologies," in *Proceedings of the international Congress on Transport Infrastructure AND Systems – TIS Roma, 803-810*, Roma, Italy, 2017.
- [5] D. Glavic, M. Mladenovic, T. Luttinen, S. Cicevic, and A. Trifunovic, "Road to price: User perspectives on road pricing in transition country," *Transportation Research Part A: Policy and Practice*, vol. 105, pp. 79-94, 2017.
- [6] C. H. Sørensen, K. Isaksson, J. Macmillen, J. Åkerman, and F. Kressler, "Strategies to manage barriers in policy formation and implementation of road pricing packages," *Transportation Research Part A: Policy and Practice*, vol. 60, pp. 40-52, 2014.
- [7] C. Jakobsson, S. Fujii, and T. Gärling, "Determinants of private car users' acceptance of road pricing," *Transport Policy*, vol. 7, no. 2, pp. 153-158, 2000.
- [8] S. Jaensirisak, M. Wardman, and A. D. May, "Explaining variations in public acceptability of road pricing schemes," *Journal of Transport Economics and Policy*, vol. 39, no. 2, pp. 127-153, 2005.
- [9] J. Schade and M. Baum, "Reactance or acceptance? Reactions towards the introduction of road pricing," *Transportation Research Part A: Policy and Practice*, vol. 41, no. 1, pp. 41-48, 2007.
- [10] L. Eriksson, J. Garvill, and A. M. Nordlund, "Acceptability of single and combined transport policy measures: the importance of environmental and policy specific beliefs," *Transportation Research Part A: Policy and Practice*, vol. 42, no. 8, pp. 1117-1128, 2008.
- [11] S. Pahaut and C. Sikow, "History of thought and prospects for road pricing," *Transport Policy*, vol. 13, no. 2, pp. 173-176, 2006.
- [12] D. King, M. Manville, and D. Shoup, "The political calculus of congestion pricing," *Transport Policy*, vol. 14, no. 2, pp. 111-123, 2007.
- [13] C. G. Chorus, J. A. Annema, N. Mouter, and B. van Wee, "Modeling politicians' preferences for road pricing policies: A regret-based and utilitarian perspective," *Transport Policy*, vol. 18, no. 6, pp. 856-861, 2011.
- [14] F. Oberholzer-Gee and H. Weck-Hannemann, "Pricing road use: Politico-economic and fairness considerations," *Transportation Research Part D: Transport and Environment*, vol. 7, no. 5, pp. 357-371, 2002.
- [15] H. Li, M. C. J. Bliemer, and P. H. L. Bovy, "Network reliability-based optimal toll design," *Journal of Advanced Transportation*, vol. 42, no. 3, pp. 311-332, 2008.
- [16] S. Vats, G. Vats, R. Vaish, and V. Kumar, "Selection of optimal electronic toll collection system for India: A subjective-fuzzy decision making approach," *Applied Soft Computing*, vol. 21, pp. 444-452, 2014.
- [17] C. Ragsdale, *Spreadsheet Modeling and Decision Analysis: A Practical Introduction to Business Analytics*, Nelson Education, 2014.
- [18] M. M. Abbas, M. N. Mladenovic, S. Ganta, Y. Kasaraneni, and C. C. McGhee, "Development and use of critical functional requirements for controller upgrade decisions," *Transportation Research Record*, no. 2355, pp. 83-92, 2013.
- [19] D. Teodorović, "Multicriteria ranking of air shuttle alternatives," *Transportation Research Part B: Methodological*, vol. 19, no. 1, pp. 63-72, 1985.
- [20] S. Chen, Y. Leng, B. Mao, and S. Liu, "Integrated weight-based multi-criteria evaluation on transfer in large transport terminals: A case study of the Beijing South Railway Station," *Transportation Research Part A: Policy and Practice*, vol. 66, no. 1, pp. 13-26, 2014.
- [21] S. Yedla and R. M. Shrestha, "Multi-criteria approach for the selection of alternative options for environmentally sustainable transport system in Delhi," *Transportation Research Part A: Policy and Practice*, vol. 37, no. 8, pp. 717-729, 2003.
- [22] A. Zubaryeva, C. Thiel, N. Zaccarelli, E. Barbone, and A. Mercier, "Spatial multi-criteria assessment of potential lead markets for electrified vehicles in Europe," *Transportation Research Part A: Policy and Practice*, vol. 46, no. 9, pp. 1477-1489, 2012.
- [23] M. Kumru and P. Y. Kumru, "Analytic hierarchy process application in selecting the mode of transport for a logistics company," *Journal of Advanced Transportation*, vol. 48, no. 8, pp. 974-999, 2014.
- [24] J. Li, Z. Q. Yue, and S. C. Wong, "Performance evaluation of signalized urban intersections under mixed traffic conditions by gray system theory," *Journal of Transportation Engineering*, vol. 130, no. 1, pp. 113-121, 2004.
- [25] T.-Y. Pai, K. Hanaki, H.-H. Ho, and C.-M. Hsieh, "Using grey system theory to evaluate transportation effects on air quality trends in Japan," *Transportation Research Part D: Transport and Environment*, vol. 12, no. 3, pp. 158-166, 2007.
- [26] M. Jakimavičius and M. Burinskiene, "A GIS and multi-criteria-based analysis and ranking of transportation zones of Vilnius city," *Technological and Economic Development of Economy*, vol. 15, no. 1, pp. 39-48, 2009.
- [27] M. Rogers and M. P. Bruen, "Using ELECTRE to rank options within a highway environmental appraisal-two case studies," *Civil Engineering Systems*, vol. 13, no. 3, pp. 203-221, 1996.
- [28] L. F. A. M. Gomes, "Multicriteria ranking of urban transportation system alternatives," *Journal of Advanced Transportation*, vol. 23, no. 1, pp. 43-52, 1989.

- [29] H. Oeltjenbruns, W. J. Kolarik, and R. Schnadt-Kirschner, "Strategic planning in manufacturing systems - AHP application to an equipment replacement decision," *International Journal of Production Economics*, vol. 38, no. 2-3, pp. 189-197, 1995.
- [30] O. Kulak, "A decision support system for fuzzy multi-attribute selection of material handling equipments," *Expert Systems with Applications*, vol. 29, no. 2, pp. 310-319, 2005.
- [31] M. Dağdeviren, "Decision making in equipment selection: an integrated approach with AHP and PROMETHEE," *Journal of Intelligent Manufacturing*, vol. 19, no. 4, pp. 397-406, 2008.
- [32] M. Mladenovic and M. Abbas, "A guide to effective Adaptive Traffic Control Systems," *Traffic, Engineering and Control*, vol. 53, no. 2, pp. 52-54, 2012.
- [33] M. N. Mladenovic and M. M. Abbas, "Improved decision-support making for selecting future traffic signal controllers using expert-knowledge acquisition," in *Proceedings of the 2013 16th International IEEE Conference on Intelligent Transportation Systems - (ITSC 2013)*, pp. 732-735, The Hague, Netherlands, October 2013.
- [34] M. N. Mladenovic, M. M. Abbas, S. Gopinath, and G. Faddoul, "Decision-Support System for Assessment of Alternative Signal Controllers using Expert Knowledge Acquisition," in *Proceedings of the 92nd Annual Meeting of Transportation Research Board*, Washington, D.C., USA, 2013.
- [35] M. N. Mladenovic, A. Stevanović, I. Kosonen, and D. Glavić, "Adaptive Traffic Control Systems: Guidelines for Development of Functional Requirements," in *Proceedings of the Mobil. TUM 2015-International Scientific Conference on Mobility and Transport*, Munich, Germany, 2015.
- [36] M. N. Mladenovic, K. Mangaroska, and M. M. Abbas, "Decision support system for planning traffic operations assets," *Journal of Infrastructure Systems*, vol. 23, no. 3, Article ID 05017001, 2017.
- [37] J. P. Brans, "L'ingenierie de la decision. Elaboration dinstrumentsdaide a la decision. Methode PROMETHEE," in *Laide a la Decision: Nature*, R. Nadeau and M. Landry, Eds., pp. 183-214, Instruments et Perspectives Davenir, de Universite Laval, Quebec, Canada, 1982.
- [38] J.-P. Brans, P. Vincke, and B. Mareschal, "How to select and how to rank projects: the PROMETHEE method," *European Journal of Operational Research*, vol. 24, no. 2, pp. 228-238, 1986.
- [39] M. Behzadian, R. B. Kazemzadeh, A. Albadvi, and M. Aghdasi, "PROMETHEE: a comprehensive literature review on methodologies and applications," *European Journal of Operational Research*, vol. 200, no. 1, pp. 198-215, 2010.
- [40] J. D. McMillan, W. S. Adney, J. R. Mielenz, and K. T. Klasson, "Development of a multicriteria assessment model for ranking biomass feedstock collection and transportation systems," in *Proceedings of the 27th Symposium on Biotechnology for Fuels and Chemicals*, pp. 71-87, Humana Press, 2006.
- [41] H. Safaei Mohamadabadi, G. Tichowsky, and A. Kumar, "Development of a multi-criteria assessment model for ranking of renewable and non-renewable transportation fuel vehicles," *Energy*, vol. 34, no. 1, pp. 112-125, 2009.
- [42] A. Jahan and K. Edwards, "Multi-criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design," *Butterworth-Heinemann*, 2013.
- [43] H. Zimmermann, *Fuzzy Set Theory—and Its Applications*, Kluwer Academic, Dordrecht, The Netherlands, 2nd edition, 1992.
- [44] C. Macharis, A. De Witte, and J. Ampe, "The multi-actor, multi-criteria analysis methodology (MAMCA) for the evaluation of transport projects: Theory and practice," *Journal of Advanced Transportation*, vol. 43, no. 2, pp. 183-202, 2009.
- [45] D. A. Hensher, "Electronic toll collection," *Transportation Research Part A: General*, vol. 25, no. 1, pp. 9-16, 1991.
- [46] P. Sharma and V. Sharma, "Electronic toll collection technologies: A state of art review," *International Journal of Advanced Research in Computer Science and Software Engineering*, vol. 4, no. 7, pp. 621-625, 2014.
- [47] V. Surendran, K. S. Vignesh, S. Baburaj, V. S. Vishnu, S. R. Krishnaveni, and K. S. Sowmya, "RFID Based Automated Toll Collection System," *International Journal of Computer Science and Information Technology & Security (IJCSITS)*, vol. 6, no. 1, pp. 582-585, 2016.
- [48] P. Blythe, "RFID for road tolling, road-use pricing and vehicle access control," *IEE Colloquium (Digest)*, no. 123, pp. 67-82, 1999.
- [49] I. Catling, "Road user charging using vehicle positioning systems," in *Proceedings of the Tenth International Conference on Road Transport Information and Control*, pp. 126-130, London, UK.
- [50] G. Charpentier and G. Fremont, "The ETC system for HGV on motorways in Germany: first lessons after system opening," in *Proceedings of the European Transport Conference (ETC)*, Association for European Transport, Strasbourg, France, 2003.
- [51] P. A. Sorensen and B. D. Taylor, *Review and Synthesis of Road-Use Metering and Charging Systems*, Transportation Research Board, Washington, D.C., 2005.
- [52] M. Bibaritsch and C. Egeler, "GO Maut-Enforcement: The enforcement system of the Austrian heavy goods vehicle toll," in *Proceedings of the 13th World Congress on Intelligent Transport Systems and Services, ITS 2006*, gbr, October 2006.
- [53] W.-Y. Shieh, W.-H. Lee, S.-L. Tung, and C.-D. Ho, "A novel architecture for multilane-free-flow electronic-toll-collection systems in the millimeter-wave range," *IEEE Transactions on Intelligent Transportation Systems*, vol. 6, no. 3, pp. 294-301, 2005.
- [54] M. Staudinger and E. A. Mulka, "Electronic vehicle identification using active infrared light transmission," in *ITS America 14th Annual Meeting and Exposition*, the Crossroads: Integrating Mobility Safety and Security, ITS America 14th Annual Meeting and Exposition, 2004.
- [55] S. Tropartz, E. Hoerber, and K. Gruener, "Experiences and results from vehicle classification using infrared overhead laser sensors at toll plazas in New York City," in *Proceedings of the 1999 IEEE/IEE/JSAI International Conference on Intelligent Transportation Systems*, pp. 686-691, October 1999.
- [56] European Parliament's Committee on Transport and Tourism, *Technology options for the European Electronic Toll Service*, European Union, 2014.
- [57] V. Sridhar and M. Nagendra, "Smart Card Based Toll Gate Automated System," *International Journal of Advanced Research in Computer Engineering & Technology (IJARCET)*, vol. 1, no. 5, pp. 203-212, 2012.
- [58] B. Asady and A. Zendehnam, "Ranking fuzzy numbers by distance minimization," *Applied Mathematical Modelling*, vol. 31, no. 11, pp. 2589-2598, 2007.
- [59] C. Macharis, J. P. Brans, and B. Mareschal, "The GDSS promethee procedure," *Journal of Decision Systems*, vol. 7, no. 4, pp. 283-307, 1998.
- [60] *Visual PROMETHEE 1.4 Manual*, <http://www.promethee-gaia.net/assets/vpmanual.pdf>.