A NEW PUBLIC TRANSPORTATION PRICING STRATEGY: THE EVALUATION OF THE RENT-BASED FARE

by
Ahmet Karakurt
B.S., Civil Engineering, Istanbul University, 2014
M.Sc., Civil Engineering, Boğaziçi University, 2017

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

Graduate Program in Civil Engineering
Boğaziçi University
2021

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor, Assoc. Prof. Ilgın Gökaşar for guiding and supporting me over the years. Her patience, support, and expertise in the transportation field made the completion of this study possible.

I would also like express my sincere appreciation to committee members Assoc. Prof. Muhammed Deveci, Assoc. Prof. Yusuf Kuvvetli, Assist. Prof. Dr. Mehtap Işık and Assoc. Prof. Özer Çinicioğlu for their time, constructive comments and questions.

I would also like to thank Alper Göktuğ Tamer, Buğrahan Karabulut, Ramazan Ege Uzun, İsmail Uysal and Umutcan Kılıç in the Department of Civil Engineering for their help and support.

My special thanks go to my dearest mother Güler Karakurt and my precious father Saffet Karakurt, who never left me alone and who have always been the mastermind for dealing with difficult times. I also would like to thank my sisters Rabia, Süreyya and Feyza who are supporters of me all the time. I would like to extend my deep gratitude to my friends for their unconditional support and encouragement.

To the memory of my grandmother...and to my newborn nephew Zeynep Vera...

ABSTRACT

A NEW PUBLIC TRANSPORTATION PRICING STRATEGY: THE EVALUATION OF THE RENT-BASED FARE

The growth of cities increases passengers' travel distances and it brings a variety of costs associated with this. This study aims to develop a new public transportation pricing system by encouraging people to rent houses in regions that will shorten their travel distances. The rent-based pricing system is created using the Nonlinear optimization model. İzmir Suburban System is chosen to introduce the new type of pricing system. Within the scope of the study, four alternative public transportation pricing systems, defined as flat fare, distance-based fare, zonal and rent-based fare, are evaluated by public transportation experts. To prioritize these alternatives, four aspects are determined, namely cost, transportation, social and political, and there are 13 criteria present under these aspects. Alternatives, aspects, and sub-criteria are explained through a comprehensive literature review. The priorities of criteria and aspects are evaluated with the CRiteria Importance Through Intercriteria Correlation (CRITIC) method and the Analytical Hierarchy Process (AHP). The new T2NN-based Multi-Attributive Border Approximation area Comparison (MABAC) method is introduced to provide a straightforward and flexible decision-making tool for researchers and practitioners. The results show that rent-based fare is the most advantageous alternative. The high reliability and robustness of the integrated CRITIC and MABAC based type-2 neutrosophic model are demonstrated with the comparative and sensitivity analyses.

ÖZET

YENİ BİR TOPLU ULAŞIM FİYATLANDIRMA STRATEJİSİ: KİRA BAZLI ÜCRETLENDİRMENİN DEĞERLENDİRİLMESİ

Şehirlerin büyümesi yolcuların seyahat mesafelerini artırmakta ve buna bağlı olarak çeşitli maliyetleri beraberinde getirmektedir. Bu çalışma, insanları seyahat mesafelerini kısaltacak bölgelerde ev kiralamaya teşvik ederek, yeni bir toplu ulaşım ücretlendirme sistemi geliştirmeyi amaçlamaktadır. Kiraya dayalı fiyatlandırma sistemi, Doğrusal Olmayan Optimizasyon modeli kullanılarak oluşturulmuştur. Yeni tip fiyatlandırma sistemini tanıtmak için İzmir Banliyö Sistemi seçilmiştir. Çalışma kapsamında sabit ücretlendirme, mesafe bazlı ücretlendirme, bölgesel ve kiraya dayalı ücretlendirme olarak tanımlanan dört alternatif toplu taşıma fiyatlandırma sistemi toplu taşıma uzmanları tarafından değerlendirilmektedir. Bu alternatifleri önceliklendirmek için maliyet, ulaşım, sosyal ve politik olmak üzere dört boyut belirlenmiş ve bu boyutlar altında 13 kriter yer almaktadır. Alternatifler, kriterler ve alt boyutlar kapsamlı bir literatür taraması ile tanıtılmaktadır. CRITIC (CRiteria Importance Through Intercriteria Correlation) yöntemi ve Analitik Hiyerarşi Süreci (AHP) ile kriterler ve boyutların önceliği değerlendirilmektedir. Araştırmacılar ve uygulayıcılara basit ve esnek bir karar verme aracı sağlamak için yeni T2NN (type-2 neutrosophic numbers) tabanlı MABAC (Multi-Attributive Border Approximation area Comparison) yöntemi tanıtılmaktadır. Sonuçlar, kira bazlı ücret fiyatlandırmasının en avantajlı alternatif olduğunu göstermektedir. Entegre CRITIC ve MABAC tabanlı tip-2 nötrosofik modelin yüksek güvenilirliği ve sağlamlığı karşılaştırmalı analizler ve duyarlılık analizleri ile gösterilmektedir.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS iii
ABSTRACT iv
ÖZET v
LIST OF FIGURES ix
LIST OF TABLES x
LIST OF SYMBOLS xiii
LIST OF ACRONYMS/ABBREVIATIONS xvi
1. INTRODUCTION 1
1.1. Introduction and Background 1
1.2. Problem Statements 2
1.3. Goals and Objectives 3
1.4. Outline of the Dissertation 4
2. LITERATURE REVIEW 5
2.1. Public Transportation Pricing Methods 5
2.1.1. Flat Fare 6
2.1.2. Distance-Based Fare 7
2.1.3. Zonal Pricing 8
2.2. Rent and Transportation 8
2.3. Public Transportation Pricing Evaluation Criteria 13
2.3.1. Cost Aspect 15
2.3.1.1. Operating Costs 17
2.3.1.2. User Costs 19
2.3.1.3. Expert Cost 20
2.3.2. Transportation Aspect 20
2.3.2.1. Travel Time 21
2.3.2.2. Travel Comfort 21
2.3.2.3. Switch to a Personal Vehicle 21
2.3.2.4. Personal Mobility 22
2.3.3. Social Aspect 23
2.3.3.1. Environmental Cost 23
2.3.3.2. Quality of Life 24

2.3.3.3. Decentralization of the Cities 24
2.3.4. Political Aspect 25
2.3.4.1. Public Acceptability 25
2.3.4.2. Political Success 26
2.3.4.3. Deployment of Resources 27
3. CASE STUDY 29
3.1. Introduction 29
3.2. Passenger Data 29
3.2.1. İzmir Urban Rail Mass Transit System (IZBAN) 29
3.2.2. Data Collection 31
3.2.3. Survey Design 33
3.3. Housing Data Around IZBAN Stops 35
3.4. Preliminary Analysis 37
3.4.1. Analysis of Passenger Data 37
3.4.2. Analysis of Housing Data 47
4. EVALUATION OF THE PUBLIC TRANSPORTATION PRICING CRITERIA 51
4.1. Introduction 51
4.2. Expert Data for the Evaluation of PT Pricing Methods 51
4.3. Analytic Hierarchy Process 53
4.4. Analysis and Results 57
4.5. Discussion 61
5. AN INTEGRATED CRITIC AND MABAC BASED TYPE-2 NEUTROSOPHIC MODEL FOR PUBLIC TRANSPORTATION PRICING SYSTEM SELECTION 63
5.1. Introduction 63
5.1.1. Objectives of the Study 64
5.1.2. The Motivation for Using Type-2 Neutrosophic Numbers 65
5.1.3. The Motivation for Using CRITIC and MABAC Methods 65
5.1.4. Contributions of the Study 66
5.2. Literature Review 67
5.2.1. Decision-Making Approaches for Transportation Pricing 67
5.2.2. MABAC Method 72
5.2.3. Research Gaps 74
5.3. Problem Definition 76

5.3.1. Case Scenario 76
5.3.2. Alternatives 77
5.3.3. Definition of Criteria 78
5.4. Methodology 81
5.4.1. Preliminaries 81
5.4.2. The Hybrid Type-2 Neutrosophic Model for Public Transportation Pricing. 85
5.5. Results and Discussion 95
5.5.1. Experimental Results 95
5.5.2. Ranking Discussion 102
5.5.3. Comparative Analysis 104
5.5.4. Sensitivity Analysis 106
5.5.5. Managerial Implications 108
6. A PROPOSED RAIL TRANSPORTATION PRICING: RENT-BASED PRICING .. 109
6.1. Introduction 109
6.2. Background 110
6.3. A Proposed Rail Transportation Pricing 114
6.4. Methodology 116
6.4.1. Case Study 117
6.4.2. Data 117
6.4.3. Cluster Analysis 117
6.4.4. Model Building 120
6.5. Results 124
6.6. Managerial Implications 130
6.7. Conclusion 131
7. CONCLUSION AND RECOMMENDATIONS 132
REFERENCES 138
APPENDIX A: TICKET TARIFFS AND MAXIMUM DISTANCES BASED ON STATIONS 166
APPENDIX B: DETAILED MATRICES USED IN CHAPTER 5 168

LIST OF FIGURES

Figure 3.1. IZBAN stations (Source: Google Maps). 30

Figure 3.2. The primary and secondary catchment area of Tepeköy Station. 36

Figure 3.3. Rent price changes according to stations. 49

Figure 3.4. Rent price per m^2 changes according to stations. 50

Figure 4.1. Comparison part of the survey. 53

Figure 4.2. The hierarchy between criteria. 57

Figure 5.1. The flowchart of the hybrid type-2 neutrosophic model for public transportation pricing 86

Figure 5.2. The sensitivity analysis of the integrated neutrosophic decision-making model 107

Figure 6.1. Public transportation pricing types. 116

Figure 6.2. Flowchart of the rent-based pricing process. 116

Figure 6.3. Silhouette scores by K-means and Agnes methods. 124

LIST OF TABLES

Table 2.1. The public transportation affordability index for 27 cities. 12

Table 2.2. Public transportation pricing optimization studies in the literature. 14

Table 2.2. Public transportation pricing optimization studies in the literature (Cont.) 14

Table 2.3. Operating cost studies in the literature. 18

Table 2.3. Operating cost studies in the literature (Cont.) 18

Table 2.3. Operating cost studies in the literature (Cont.) 18

Table 3.1. Card types and tariffs. 31

Table 3.2. Travel distance and ticket tariff for a journey to Alsancak, and rent prices in counties 34

Table 3.3. Travel behavior descriptive statistics. 38

Table 3.3. Travel behavior descriptive statistics (Cont.). 39

Table 3.4. Descriptive statistics for departure and arrival stations. 40

Table 3.5. Descriptive statistics of user cost components. 41

Table 3.6. Descriptive statistics of travel distance and travel price. 42

Table 3.7. Comparisons between travel time, price, comfort and waiting time. 42

Table 3.8. Travel distance and rent price selection for various scenarios. 44

Table 3.9. Demographic results of the survey. 45

Table 3.10. Descriptive statistics of age and household size. 45

Table 3.11. Distribution of income, rent price and car ownership. 46

Table 3.12. Closest IZBAN stations to participants. 47

Table 3.13. Rent price, house size, distance and rent per m^2 descriptive results. 48

Table 4.1. The first, second, and third parts of the survey are in general terms. 52

Table 4.2. Saaty's (1990) 9 point scale. 54

Table 4.3. Random Consistency Index. 56
Table 4.4. Pairwise comparison of main criteria. 58
Table 4.5. Pairwise comparison of cost criteria. 58
Table 4.6. Pairwise comparison of transportation criteria. 59
Table 4.7. Pairwise comparison of social criteria. 59
Table 4.8. Pairwise comparison of political criteria. 59
Table 4.9. Consistency results 60
Table 4.10. Local and global priorities. 61
Table 5.1. Survey of the available decision-making approaches for transportation pricing 71
Table 5.1. Survey of the available decision-making approaches for transportation pricing (Cont.) 71
Table 5.2. Survey of the MABAC method. 75
Table 5.2. Survey of the MABAC method (Cont.) 75
Table 5.2. Survey of the MABAC method (Cont.). 75
Table 5.2. Survey of the MABAC method (Cont.). 75
Table 5.3. T2NN linguistic variables to distinct experts. 88
Table 5.4. T2NN linguistic variables for evaluating alternatives. 91
Table 5.5. The information about the experts. 95
Table 5.6. The T2NN expert reputation matrix. 96
Table 5.7. The reputation of the experts. 97
Table 5.8. Experts' evaluations of the public transportation pricing systems under the criteria. 98
Table 5.9. The normalized decision matrix and average normalized evaluations. 100
Table 5.10. The correlation coefficient matrix, standard deviations, information

measures, and criteria importance. 100

Table 5.11. The weighted normalized decision matrix and the border approximation area..... 101

Table 5.12. The distance matrix, assessment scores, and ranks of the public transportation pricing systems. 102

Table 5.13. The characteristic of different type-2 neutrosophic approaches. 105

Table 5.14. The comparison of different T2NN-based approaches. 106

Table 6.1. Rent per m^2 in the districts along the IZBAN route. 115

Table 6.2. Cluster characteristics. 125

Table 6.3. Regression analysis of income and rent price. 126

Table 6.4. Non-linear optimization results. 127

Table 6.5. Rent-based fare, distance-based fare, and flat fare comparison. 128

Table 6.6. Ticket revenue comparison. 129

Table 6.7. Alternative ticket revenue comparison. 130

Table A.1. Ticket tariffs and maximum distances based on stations. 166

Table A.1. Ticket tariffs and maximum distances based on stations (cont). 167

Table B.1. The T2NN initial decision matrices. 168

Table B.2. The T2NN aggregated decision matrix. 169

Table B.3. The score decision matrix, extreme values, and criteria types. 169

LIST OF SYMBOLS

A	Set of alternatives
A_{ff}:	Affordability index
a_{ij}	The comparison of the i th criteria and the j th criteria.
B_i, $i \in$ A	Assessment score of the alternative A_i
C	Set of criteria
C^-	Set of cost criteria
C^+	Set of benefit criteria
CI	The consistency index
CR	The consistency ratio
D	Set of invited experts
e	Index of invited experts, e=1, …, k
e	The level of precision
G	Weighted normalized decision matrix
G_{ij}, $i \in$ A, $j \in$ C	Weighted normalized evaluation of the alternative A_i under the criterion C_j
i	A household member
i	Index of alternatives, i=1, …, m
j	Index of criteria, j=1, …, n
k	Number of invited experts
l	Auxiliary index
L	The number of strata
m	Number of alternatives
n	Number of criteria
N	The number of sample units in the population
n	The total number of sample units
n_i	The number of sample units to allocate to stratum i
N_i	The number of sample units within stratum i
O	Border approximation area
O^-	Lower approximation area

O^+	Upper approximation area
$O_j, j \in \mathrm{C}$	Border approximation area under the criterion C_j given by the experts
$P_{ij}, i \in \mathrm{A}, j \in \mathrm{C}$	Distance of the alternative A_i from the border approximation area under the criterion C_j
R	Normalized decision matrix
RI	Random consistency index
$R_{ij}, i \in \mathrm{A}, j \in \mathrm{C}$	Normalized evaluation of the alternative A_i under the criterion C_j given by the experts
TD	Travel distance
TP	Travel price
$U_j, j \in \mathrm{C}$	Information measure of the criterion C_j
w_i	Importance weight
$x_i(p_i, y)$	The number of public transport journeys by a household member for a month
y	Household income or expenditure
$\tilde{F}_{\tilde{\mathrm{M}}}(y)$	Falsity membership of y in $\tilde{\mathrm{M}}$
$\tilde{I}_{\tilde{\mathrm{M}}}(y)$	Indeterminacy membership of y in $\tilde{\mathrm{M}}$
$S(\tilde{\mathrm{M}})$	Score function of $\tilde{\mathrm{M}}$
$\tilde{\mathrm{Z}}$	T2NN aggregated decision matrix
$\tilde{\mathrm{V}}$	T2NN expert reputation matrix
$\tilde{T}_{\tilde{\mathrm{M}}}(y)$	Truth membership of y in $\tilde{\mathrm{M}}$
$\tilde{Q}_e, e \in \mathrm{D}$	T2NN aggregated reputation of the invited expert D_e
$\tilde{V}_e^{(1)}, e \in \mathrm{D}$	T2NN (self-)appraisal of the experience of the invited expert D_e
$\tilde{V}_e^{(2)}, e \in \mathrm{D}$	T2NN (self-)appraisal of the expertise of the invited expert D_e
$\tilde{\mathrm{B}}^e, e \in \mathrm{D}$	T2NN initial decision matrix by the invited expert D_e
$\tilde{Z}_{ij}, i \in \mathrm{A}, j \in \mathrm{C}$	T2NN aggregated evaluation of the alternative A_i under the criterion C_j given by the experts

$\tilde{B}_{ij}^{e},\ i\in$A, $j\in$C, $e\in$D	T2NN evaluation of the alternative A_i under the criterion C_j given by the invited expert D_e
$\bar{R}_j,\ j\in$C	Average normalized evaluation of the alternatives under the criterion C_j given by the experts
$\xi_1,\ \xi_2$	Trade-off parameters of the reputation of invited experts, ξ_1, $\xi_2\in[0,1]$
$\delta_e,\ e\in$D	Reputation of the invited expert D_e, $\delta_e\in[0,\ 1]$
$\omega_j, j\in$C	Importance of the criterion C_j, $\omega_j\in[0,\ 1]$
$\sigma_j, j\in$C	Standard deviation of the criterion C_j
$\rho_{jk}, j,\ k\in$C	Correlation coefficient among the criteria C_j and C_k
λmax	The largest eigenvalue

LIST OF ACRONYMS/ABBREVIATIONS

2TLN	2-Tuple Linguistic Neutrosophic
3PL	Third-Party Logistics
ACS	The American Community Survey
AGNES	Agglomerative Nesting
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
AT	Access Time
B&H	Bosnia and Herzegovina
BF	Bipolar Fuzzy
BNN	Bipolar Neutrosophic Number
BWM	Best Worst Method
CA	Comparative Analysis
CCSD	Correlation Coefficient and Standard Deviation
CI	Consistency Index
CIP	Constraint Integer Programming
CL	Complete Linkage
CNT	Center for Neighborhood Technology
CO2	Carbon Dioxide
CR	The Consistency Ratio
CRITIC	Criteria Importance Through Intercriteria Correlation
DBF	Distance-Based Fare
DEMATEL	Decision Making Trial and Evaluation Laboratory
DID	Difference-In-Differences
ELECTRE	Elimination Et Choix Traduisant La Realite
FARE	Factor Relationship
FF	Flat Fare
FMEA	Failure Mode and Effect Analysis
FN	Fuzzy Neutrosophic
GA	Group Average

GDM	Group Decision-Making
GIS	Geographical Information System
GST	Gray System Theory
H+T	Housing and Transportation
HFLT	Hesitant Fuzzy Linguistic Term
I2TL	Interval 2-Tuple Linguistic
IE	Illustrative Example
IT	Information Technology
IVFR	Interval-Valued Fuzzy-Rough
IZBAN	İzmir Urban Rail Mass Transit System
LBWA	Level Based Weight Assessment
LDA	Linguistic Distribution Assessment
LN	Linguistic Neutrosophic
MABAC	Multi-Attributive Border Approximation Area Comparison
MAIRCA	Multi-Attributive Ideal-Real Comparative Analysis
MBTA	Massachusetts Bay Transportation Authority
MDCM	Multi-Criteria Decision-Making
MIP	Mixed-Integer Programming
MSD	Mean-Squared Deviation
NIS	Negative Ideal Solution
NWHF	Normal Wiggly Hesitant Fuzzy
NWHFLT	Normal Wiggly Hesitant Fuzzy Linguistic Term
P2TL	Picture 2-Tuple Linguistic
PIS	Positive Ideal Solution
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
PSVNHFS	Probabilistic Single-Valued Neutrosophic Hesitant Fuzzy
PT	Public Transportation
PULT	Probabilistic Uncertain Linguistic Term
RB	Rent-Based Fare
RER	Réseau Express Régional
RI	Random Consistency Index

RP	Rough Plithogenic
RVV	Relative Value Vectors
SA	Sensitivity Analysis
SAT	Satisfiability
SCIP	Solving Constraint Integer Programs
SL	Single-Linkage
SVN	Single-Valued Neutrosophic
SVNLT	Single-Valued Neutrosophic Linguistic Term
SWARA	Step-Wise Weight Assessment Ratio Analysis
SWOT	Strengths, Weaknesses, Opportunities, and Threats
T2NN	Type-2 Neutrosophic Number
T2NNWA	2 Neutrosophic Number Weighted Averaging
TOD	Transit-Oriented Development
TOPSIS	The Order Preference by Similarity to Ideal Solution
TT	In-Vehicle Travel Time
UAC	Unit Access Cost
UC	User Cost
UTC	Unit Travel Cost
UWC	Unit Waiting Time Cost
WT	Waiting Time
WTP	Willingness to Pay
ZF	Zonal Fare

1. INTRODUCTION

1.1. Introduction and Background

Countries allocate significant resources to transport infrastructures, such as bridges, roads, and public transport networks. Such investments sometimes suffer or lose their function when policymakers refuse to implement appropriate policies. Public transportation plays an important role in low-car-dependency countries (Zhao and Zhang, 2019). As a result, the success of public transport infrastructure is crucial in these countries. The sustainability of transit systems and the improvement of inadequate transit systems have been the subject of more recent studies. For this reason, the issue of pricing systems, which affect the performance of urban transportation, has gained in popularity recently.

Pricing structures are usually categorized as fixed, distance-based, and zonal (Batarce & Mulley, 2016). The flat fare is a uniform charging system independent of distance and duration. Distance-based fare is calculated on the distance traveled. In zonal pricing, the price is fixed within regions and varies from region to region. Public transport pricing systems are evaluated primarily in terms of cost, transport, social and environmental considerations (Fearnley, 2013; Nassi & da Costa, 2012). However, another assessment criterion is the political aspect, which has been ignored to date and is crucial for municipalities. So far, researchers have only evaluated public transport pricing systems for users and operators (Brown, 2018; Daskin et al., 1988; Tsai et al., 2008; Liu et al., 2017; Ma et al., 2017; Schöbel, 1995; Farber et al.,2014; Guzman et al., 2018; Zhao & Zhang, 2019; Deng et al., 2014; Huang et al., 2016; Cheng et al., 2015; Deng et al., 2014; Cervero, 1981; Yamada, 1985; Wang et al., 2018; Zhang et al., 2017). However, existing pricing policies are still insufficient to ensure sustainability and are harmful to operators and users alike.

Beyond the user and operator dimension, it is necessary to evaluate the issue from a broader perspective and in line with the fundamental principles of urban transportation to achieve an ideal pricing system. There are many benefits of encouraging short-haul travel.

In addition to low transport costs, travel over short distances to avoid traffic congestion is highly valued by some (Wardrip, 2011).

There is a significant relationship between travel distance, transportation cost, and rent price. According to economic theory, house prices should be influenced by the value of the decrease in travel time (Hess and Almeida, 2007). Consequently, a rent-based pricing system may encourage people to pay higher rent instead of higher transit costs, and travel short distances.

The study pursues three principal objectives. The first is to assess the importance of criteria by Criteria Importance Through Intercriteria Correlation (CRITIC) method and the Analytic Hierarchy Process (AHP). The second objective is to develop the new the Type-2 Neutrosophic Number (T2NN) based Multi-Attributive Border Approximation area Comparison (MABAC) method for the public transportation pricing system selection problem. The third is to create an example of a Rent-Based Fare system for IZBAN (İzmir Urban Rail Mass Transit System) using Non-linear optimization.

1.2. Problem Statements

Increasing migration from rural areas to modern cities has led to excessive growth of cities lately. However, urban expansion increases travel distances and transportation costs. Inequality and discrimination are also central issues associated with urban growth. Since the high rents in the city centers force the impoverished people to live out of the city by paying a lower rent. However, this may significantly increase transportation costs to households who avoid paying high rents.

Recently, an essential method for measuring total housing and transportation costs called Housing and Transportation (H+T) Affordability Index has been developed for various locations within cities (Isalou et al., 2014). The Housing and Transportation Affordability Index guides individuals and increases their financial resilience. The Center for Neighborhood Technology (CNT) deems a neighborhood affordable, if a household

spends 30% or less of their income on housing and adds another 15% for transportation costs (Guerra & Kirschen, 2016). Households should plan their financial costs appropriately and make affordable housing and transport choices. If not, there is a danger of being unable to meet other basic needs, which may cause financial stress to individuals.

People living far from the city center prefer using personal vehicles instead of public transportation. Switching to use personal vehicles causes traffic congestion, air pollution, environmental pollution, decrease in public transportation quality and travel comfort (because of the less investment caused by less usage of public transportation), increase in travel times, and decrease in quality of life. However, centralized and compact cities increase financial efficiency and eliminate these negative effects in the transportation system. In addition, operators can manage their budgets more efficiently by providing more efficient and less expensive transportation services in centralized cities. Thus, political success may also be guaranteed.

This thesis proposes a new rent-based transportation pricing policy that overcomes all these problems and encourages people to live close to their working and social environment. In addition, the study includes a comparison of current transport pricing methodologies with the rent-based pricing system by public transport experts.

1.3. Goals and Objectives

This dissertation aims to introduce a new public transportation fare system based on rent prices. This goal is accomplished through the following sub-objectives:

- Determining the public transportation pricing types and the relationship between rent and public transportation by performing a comprehensive literature review,
- Defining the evaluation criteria of public transportation pricing,
- Introducing the public transportation model studied, namely IZBAN,
- Collection and preliminary analysis of travel behavior and rental price data on either side of the IZBAN line,

- Evaluating public transportation criteria importance with Analytic Hierarchy Process and the novel T2NN-based CRiteria Importance Through Intercriteria Correlation (CRITIC) method,
- Ranking the public transportation pricing systems with the new T2NN-based Multi-Attributive Border Approximation area Comparison (MABAC) method,
- Applying Cluster Analysis based to stations,
- Proposing a Nonlinear Optimization approach to a new fare planning that is based on rent price, income, and ridership.

1.4. Outline of the Dissertation

This thesis consists of seven chapters. The first chapter is the introduction of the thesis and summarizes the definition of the problems, the background of the study, and the aims of the study. The second part covers a literature review on public transportation pricing types, rental and public transportation relationships, and public transportation pricing criteria. The third chapter explains the case study and preliminary analyses relating to the IZBAN data and rent data mentioned in the thesis. The fourth chapter contains an analysis of the criteria that influence the choice of public transportation pricing schemes, and their relative importance. The order of priority for the criteria is developed using a different method in the fifth chapter, and the best public transportation price model is selected. In the sixth section, an example of the proposed model was developed, and the findings are presented. The final chapter includes conclusions, contributions, limitations, and future recommendations.

2. LITERATURE REVIEW

2.1. Public Transportation Pricing Methods

Pricing systems are crucial agents for operating the transportation system. Fare structures are broadly categorized as flat fares, distance-based fares, and zonal fares (Batarce & Mulley, 2016). These systems have many potential outcomes, such as collecting and controlling fares, chancing travel behavior, and economic sustainability. However, it should be noted that public transportation pricing systems have different advantages and disadvantages under various scenarios.

Public transportation pricing studies are mostly related to the comparison of fare systems or optimizing the existing fare system (See Table 2.2.). A study using detailed travel log data from California investigate the equity outputs of low and high-income passengers under different fare structures (Brown, 2018). It is observed that using a distance-based pricing system instead of a fixed fare has greatly increased the equity and ridership (Daskin et al., 1988; Tsai et al., 2008). Similarly, some studies prioritize social benefits and fairness. In addition, distance-based pricing is recommended instead of flat fare (Liu et al., 2017; Ma et al., 2017). However, Schöbel (1995) argues that if the difference between the zonal pricing and the distance-based fare is low, the zonal pricing is fairer. Survey methods with a before and after approach are helpful for the comparison in such studies dealing with fare system change.

Some studies focus on maximizing social benefit in urban transportation pricing (Guzman et al., 2018; Zhao & Zhang, 2016; Deng et al., 2014). A study investigates the effects of distance-based pricing on different demographic features (Farber et al., 2014). Results reveal that distance-based fare benefits low-income, elderly, and non-white populations. However, some researchers claim that distance-based tariff significantly increases the transportation cost for low-income groups (Zhao & Zhang, 2019). Deng et al. (2014) create an operator benefit optimization model by considering flat fare and distance-

based fare. In the study, it is stated that flat fare is applicable only when the government provides sufficient financial subsidies or economic support for a low-price policy. A distance-based fare structure is better to attract more short-haul passengers.

Understanding the impacts of transportation pricing requires an understanding of possible demand responses (Transportation Research Board, 1994). Changes in fare policies are often designed to improve the service quality and accessibility of public transport networks. Litman (2004) argues that reducing urban transportation costs and improving service levels are necessary steps to reduce problems such as traffic congestion and environmental pollution. In addition, the long-term negative effects of increasing ticket tariffs on ridership are highlighted with the example of a burden on income, traffic congestion, and environmental pollution. Similarly, Sharaby & Shiftan (2012) argue that the fare reduction increases demand for public transportation and people tend to public transportation instead of personal vehicles and taxi. However, high ridership rates may increase in-vehicle crowdedness and decrease service quality. Goodwin (1992) points out that pricing has a robust cumulative effect on travel demand and the behavioral response due to cost changes occurs over time.

2.1.1. Flat Fare

The flat fare is a pricing system widely used in public transportation. It is the application of a fixed price regardless of the distance and time traveled. However, many have criticized that flat fare is unfair (Liu et al., 2017; Cheng et al., 2015). Because short-haul customers heavily subsidize long-haul passengers (Cervero, 1981). Therefore, a flat fare system is suitable for compact cities and short travel distances. The flat fare usually cannot meet the long-haul operating costs (Yamada, 1985). Yet, the transportation systems should be sustainable. The ticket tariff should cover the operating costs and be affordable for the users. The implementation of higher fares to cover operating costs creates inequities for short-haul travelers. After all, the system is easy to implement and control. There is no need for return machines, extra equipment, or extra labor.

Flat fare studies focus on optimizing existing prices or comparison with distance-based pricing systems in terms of social equity. Wang et al. (2018) examine the effect of switching from flat fare to distance-based fare on demand. The study reveals that ridership decreases 23% for the total and 9% for the morning peak hours. It is also noted that passengers, who travel long distances during peak hours and therefore pay a high price, are more sensitive to changes in the charging system. Zhang et al. (2017) investigate the effects of switching from a flat fare to a logging ticket on travel behavior and demand. Hierarchical Tree-Based Regression models are used in the study. The results show that the new policy reduces ridership considerably in the first month but gradually returns to the previous level after four months.

2.1.2. Distance-Based Fare

In a distance-based fare system, ticket prices vary according to the number of kilometers traveled (Borndörfer et al., 2012). Prices are fixed up to a certain distance. After a certain distance, the fare is calculated per km. The system is preferred in terms of operational cost coverage (Wang et al., 2020). However, the collection of distance-based fare is complicated (Yang et al., 2012). To get a refund, the transport card must be scanned again at the destination stop. Fixed operating cost increases because of the need for return machines. In addition, passenger queues may occur at reimbursement points or passengers may forget to collect reimbursement fees. Long-haul passengers pay more, while short-haul passengers pay less (Maadi & Schmöcker, 2018). Even if it seems fair, ticket prices may be hard to afford for low incomes and living in rural areas far from the city center. However, if the fare is affordable and most passengers travel short distances, it may be difficult to cover operating costs. Besides, not knowing the cost of the trip before arrival can confuse passengers (Borndörfer et al., 2012; Batarce & Mulley, 2016).

Previous studies have investigated the effects of the distance-based pricing system on social equality. Many researchers argue that flat fare is unfair for short-haul and off-peak users (Cervero, 1981). Zhao & Zhang (2019) claim that the system may reduce the mobility of some groups and feel excluded as passengers living far from the city center pay more fees. Farber et al. (2014) create an ordinal/continuous model of trip generation and traveled

distance into a Geographical Information System (GIS) Decision Support System to assess the social equity impacts of distance-based fare. The results indicate that switching to a distance-based tariff is unfair to different subgroups. Another study states that low-income passengers travel shorter distances (Brown, 2018). Outcomes cannot be generalized since demographic structures are changeable.

2.1.3. Zonal Pricing

In zonal pricing, different pricing methods are applied within and between each zone by making regional distinctions (Otto & Boysen, 2017). A fixed price is applied within the zones and there is a fare change between the zones. The ticket price depends on the beginning and ending zone of the journey. Zones can be predefined or dynamically created depending on network conditions and allow a reasonable trade-off between pricing complexity and the coordinating ability of the pricing plan (Flath et al., 2014).

Zonal pricing is easier to implement compared to distance-based pricing. Passengers are less confused because of the limited variety of fare combinations between zones. However, it may appear unfair to pay less for a long distance in a zone instead of traveling short-distance between two zones. Another problem with this system is the difficulty in determining the zone boundaries. Extensive research is required to establish the boundaries fairly. According to the U.S. Urban Transit Administration (1976) report, seven cities switched from zonal pricing to either flat fares or far less graduated fare structures in the early seventies (Wachs, 1981). In a study, the multinomial logit mode choice model is developed to measure the monetary value of travel time (Ma et al., 2017). Researchers use a cumulative opportunity measure to examine the effect of price increases on job accessibility. Zonal pricing is proposed instead of a flat fare structure to achieve better equity.

2.2. Rent and Transportation

Households with easy access to public transport may spend less on transportation and therefore more on housing (Kilpatrick et al., 2007). In addition, economic theory says that

house prices should be influenced by the value of travel time savings (Hess and Almeida 2007). In addition to low transportation costs, short-distance travel to avoid traffic congestion and reduce the carbon footprint is highly valued by some (Wardrip, 2011). Haig (1927) claims that rents and distance from the city center are inversely correlated. In the model, it is assumed that the total rent expenses and transportation costs are constant in the city center and equal the annual maximum transportation expenditure of those living outside the city center. A study applies an empirical method using rent data in Tokyo- Japan, to examine how the clustering of train and subway stations affects rental prices in their surroundings (Sadayuki, 2018). The results reveal a reducing effect of the proximity order of each station, even after consideration of the distance effect.

The review study prepared by Wardrip (2011) contains the determinations of different researchers on the change in premium provided by transportation on house prices. In a study, it is mentioned that the transportation premium for house prices varies between 6 percent and 45 percent (Cervero, 2004). Another study dealing only with heavy and light rail systems reveals a maximum premium of 32% (Hess & Almeida, 2007). Duncan (2008) summarizes the available research and assigns a value of 0-10%. Another indicates a range of 3-40% (Diaz & McLean, 1999).

In early studies of the relationship between transport improvement and the price component, these items are collectively defined as friction costs (Haig, 1927). Transportation improvement results in reduced friction if other factors are constant. Another study examines the effects of transportation system improvements on rental prices between two rail-connected regions (Chau and Ng, 1998). The results show that by increasing the speed and frequency of trains, the commuting time is shortened. As a result, people tend outside the city, and the difference in rents between downtown and isolated areas decreases.

Researchers tend to investigate transit-oriented development (TOD) which aims to maximize access to public transport (Holmes & van Hemert, 2008). The purpose of a transit-oriented development zone is to raise the use of public transport. This requires a strong integration of infrastructure and land use (Curtis et al., 2016). In the TOD zone, the public transport station is located in the center of the region. The center is surrounded by high-

density development to low-density development. One study demonstrates that a balance model is established to design the rail transit corridor, considering the house rent, travel cost, and capacity constraints of the TOD's housing supply (Zhang et al., 2021). The optimization model aims to maximize profit and social welfare. It is concluded that TOD can significantly increase the revenue of the operation public transportation system. Another topic includes overall TOD rankings and individual walkability measurements (Schlossberg & Brown, 2004). According to the study, the location of pedestrian-hostile streets has a dramatically negative effect on the pedestrian environment surrounding public transport stops.

The property value is related to the geographical relations between public transportation stops and the surrounding residential area (Sadayuki, 2018). In a study, the direct marginal price impact of a new commuter train service following changes in access to stations is estimated by a difference-in-differences (DID) estimator in the hedonic price model for single-family house sales (Dubé et al., 2013). Results indicate that property tax income for involved municipalities raises since the opening of a new commuter train service generates a premium for houses around the stations. In another study, a DID model is used to analyze the difference in property value changes between the near and far houses (Evans, 2016). The results demonstrate that there is not a significant difference between changes in property values of near and far houses.

Transport and housing costs are bonded, and theories and models of urban form, suburbanization, and housing markets are built on this bond (Alonso 1960, 1964, Muth 1969, Mills 1972, Brueckner 1987). Households should plan their financial costs properly and make affordable choices in their housing and transportation choices. Otherwise, there is a danger of not being able to meet other essential needs, which can cause financial stress on individuals. Recently, an essential method for measuring total housing and transportation costs called Housing and Transportation (H+T) affordability index for various locations within cities has been developed by summing housing costs and transportation costs and dividing them into income (Isalou et al., 2014).

The housing and transportation affordability index can guide people and enhance their financial resistance. The transportation expenditure should not exceed more than 20% of the

total income and the combination with a housing expenditure should be less than 45% of the total income for affordable life (Litman, 2013). According to the Center of Neighborhood Technology (CNT), a neighborhood is ideal if a household spends 30% or less of its income on housing and 15% on transportation costs (Guerra & Kirschen, 2016). According to current information, which is provided, by The American Community Survey (ACS), detailed information on household size and composition is required for the 30% standard approach to affordability and the residual-income approach (Herbert et al., 2018). The national consumer expenditure survey notes that American households spend an average of 18% of their income on transportation (Guerra & Kirschen, 2016). However, America's Rental Housing data in 2016 reveal that 21 million tenant households fail to meet the 30% standard and are housing cost-burdened (Herbert et al., 2018). While the travel price is an important issue for all demographic groups, the issue is of greater importance for rural, younger, and lower-income individuals (Mattson, 2012). Unlike developed countries, the share of transportation expenditure in household income in developing countries can be much higher. In a Housing and Transportation (H+T) Affordability Index study applies in Qom City-Iran, the findings indicate that suburban households spend over 57% of their monthly income on housing and transportation, well above the 45% spent by households in the central district (Isalou et al., 2014). Another study's result shows that transportation costs exceed 20% of spending costs where the minimum is 22.9% to the maximum of 38.3% in four low-cost housing areas in Kuala Lumpur City, Malaysia (Yusoff et al., 2014). As it is demonstrated, the ratios of transportation cost per income in different geographies are different. Public transportation is widely used instead of personal vehicles in undeveloped and developing countries. Therefore, researchers do not ignore public transportation affordability. Transportation affordability is also explored, particularly in the context of public transportation. The affordability of public transportation is defined by Gomez-Lobo (2011) as

$$\mathrm{Aff}_l = \frac{\sum_{i=1}^{N} x_i(p_i, y).p}{y} \tag{2.1}$$

where $x_i(p_i,y)$, the number of public transport journeys by a household member i for a month, and y, household income or expenditure.

Carruthers et al. (2005) replace the number of trips *i*, 60 trips per month for each person. In a study, it is seen that public transportation cost per income rate stands at 18.6 percent of poor households and 10.2 percent for non-poor households (Region, 2004). It means that low-income passengers and residents in the suburbs have longer travel distances than non-poor, and which causes their reduced welfare under the current tariff regime. Table 2.1. by Carruthers et al. (2005) shows the public transport affordability index of 27 cities.

Table 2.1. The public transportation affordability index for 27 cities.

	City	Affordability Index	
		Average	Bottom Quintile
1	Sao Paulo	11%	107%
2	Rio de Janeiro	6%	63%
3	Brasilia	6%	59%
4	Cape Town	4%	38%
5	Buenos Aires	4%	26%
6	Mumbai	9%	23%
7	Kuala Lumpur	5%	22%
8	Mexico City	3%	19%
9	Chennai	8%	19%
10	Manila	5%	17%
11	Krakow	6%	17%
12	Amsterdam	6%	16%
13	Moscow	4%	15%
14	Guangzhou	4%	14%
15	Warsaw	4%	11%
16	New York	3%	10%
17	Los Angeles	3%	10%
18	Chicago	3%	10%
19	Singapore	2%	10%
20	Beijing	3%	9%
21	Seoul	4%	9%
22	Shanghai	2%	6%
23	Cairo	3%	6%
24	Budapest	3%	6%
25	London	2%	5%
26	Prague	2%	4%
27	Bangkok	1%	4%

2.3. Public Transportation Pricing Evaluation Criteria

Unsustainable investments in public transportation are one of the most critical issues affecting the economy, the environment and political reputation. It results in a reduction in financial resources, dissatisfaction within society and an increase in traffic density. Providing alternative modes of public transport that are accessible to all, and at an ideal price are basic solutions to this problem. Safe, efficient, and sustainable mobility for all passengers can be achieved through an efficient fare system. Service providers apply different pricing systems to manage their operating expenditures on the transportation system. They monitor operating costs and passenger satisfaction levels, make decisions accordingly and set the price or change in the system. Public transportation fare type is particularly important for the proper functioning of the system.

Public transport pricing systems are evaluated mainly in terms of cost, transportation, social and environmental aspects (Fearnley, 2013; Nassi & da Costa,2012). However, the system should also be evaluated from a political perspective because the pricing system affects the budget and the success of local governments.

Operating and user expenses are the cost components and are always in conflict (Martinez, 2009). Operators require the pricing scheme to cover operational costs. On the other hand, passengers demand shorter and cheaper trips (Otto & Boysen, 2017). However, reduced public transportation ticket prices may increase ridership and reduce the quality of service. Conversely, fare increases due to public transportation maintenance costs may reduce ridership and improve service quality. The balance between public transportation price and demand has a positive effect on the operator and the user. Expert cost also makes a difference in the systems. This stems from the complexity of the fare system. However, public transit pricing studies usually consider operating and user costs, as shown in Table 2.2.

Table 2.2. Public transportation pricing optimization studies in the literature.

Author	Year	Mode	Area	Model	Criteria
Xueyu & Jiaqi	2013	Railway	China	Bi-level Programming Model, Particle Swarm Optimization Algorithm	Operating Cost
Deng et al.	2014	Railway (Metro line)	China	Nonlinear Optimization Model, Simulated Annealing	Operating Cost
Borndörfer et al.	2012	Bus, Tram, Railway, Ferry	Germany	Nonlinear Optimization Model	Operating Cost
Huang et al.	2016	Bus	China	Bi-level Programming Model, Genetic Algorithm	Operating Cost
Parry & Small	2009	Bus, Railway	USA & UK	Analytical Model	User Cost, Operating Cost, Capital Cost
Liu et al.	2017	Railway (Metro Line), Bus	China	Bi-level Programming Model, Genetic Algorithm	Operating Cost, User Cost
Tang et al.	2017	Bus	China	Mixed-Integer Nonlinear Programming Model, Penalty Algorithm	Operating Cost, User Cost
Jansson et al.	2015	Bus	Sweden	Algebraic Model	Operating Cost, User Cost
Kaddoura et al.	2015	Bus	Germany	Agent-Based Modelling	User Cost, Operating Cost, Capital Cost
Wang & Deng	2019	Railway (Metro line)	China	Nonlinear Optimization Model, Simulated Annealing	Operating Cost, User Cost
Yook & Heaslip	2014	Bus, Railway	USA	Bi-level Programming Model, Genetic Algorithm	Operating Cost, User Cost

Table 2.2. Public transportation pricing optimization studies in the literature (Cont.).

Author	**Year**	**Mode**	**Area**	**Model**	**Criteria**
Tirachini et al.	2014	Bus	Australia	Multimodal Social Welfare Maximization Model	Operating Cost, Capital Cost
Chin et al.	2016	Railway (Metro line)	Canada	Stochastic User Equilibrium Model	Unspecified
Lam & Zhou	2000	Bus, Railway	China	Bi-level Programming Model, Heuristic Solution Algorithm based on a Sensitivity Analysis	Unspecified
Chien & Tsai	2007	Railway (Metro line)	USA	Sensitivity Analysis	Operating Cost, User Cost (but not specified)
Tsai et al.	2008	Railway	Taiwan	Nonlinear Optimization Model	Operating Cost
Li et al.	2009	Bus, Railway (Metro line)	China	Network Equilibrium Model	Operating Cost, User Cost (but not specified)
Li et al.	2012	Railway	China	Analytical Model, Heuristic Solution Algorithm	Operating Cost, Capital Cost, User Cost (but not specified)
Zhou et al.	2005	Bus, Railway	China	Bi-level Programming Model, Heuristic Solution Algorithm	Operating Cost
Neumann	2007	Bus, Railway	Germany	Discrete Choice Model	Operating Cost (but not specified)
Borndörfer et al.	2006	Bus, Railway	Netherlands	Nonlinear Optimization Model	Operating Cost (but not specified)
De Borger et al.	1996	All	Belgium	A Static Partial Equilibrium Model	Social Cost

Travel time, travel comfort, switching to a personal vehicle and personal mobility are evaluated within the scope of transportation criteria. In a system where operational costs are covered, the frequency of service increases (Tirachini & Antoniou, 2020). This shortens waiting time and travel time (Wang et al., 2020). Short journeys result in comfortable journeys while high demand decreases comfort (Chowdhury et al., 2015). Reasonable prices, reliable service, security, and high-frequency increase the attraction of public transport, and personal mobility (Giuliano, 2005). If there is no clear plan for local employment or alternative modes of transport, increased personal mobility often fuels the trend toward decentralized housing development (Leao & Elkadi, 2012). When people are not satisfied with the transportation system and ticket tariff, they tend to personal vehicles if they have one.

Other factors affecting public transport pricing are environmental and social factors including environmental pollution, quality of life, and decentralization of cities. Environmental pollution increases in response to high demand and travel frequency. Short and comfortable journeys have a positive effect on the quality of life. The transportation pricing system also affects urbanization. Public transport systems are not designed to serve low-density and dispersed urban areas. The more decentralized is, the more difficult and expensive it becomes to serve urban areas by public transport (Neto et al., 2008).

Pricing policies are directly relevant to the public. Many citizens can accept an established pricing system where transportation problems are perceived as serious (Schade & Schlag, 2003). A comfortable, rapid, inexpensive, and fair transport system is more acceptable to society. This, in turn, benefits political success (Gärling & Schuitema, 2007). On the other hand, an unsustainable public transport system results in ineffective use of resources. This frequently leads to political failure.

2.3.1. Cost Aspect

Previous studies show that there are various interpretations in the classification of transit costs. Xueyu and Jiaqi (2013) assume that operating cost, travel demand, willingness to pay, competition between transportation modes, financial targets, and government

regulations are the factors affecting public transit fares. Pozdena and Merewitz (1978) examine rail costs by dividing them into fixed and variable costs and fixed costs into operating and investment costs. Wirasinghe & Seneviratne (1986) examine urban transportation costs under four headings: user cost, operating cost, rail cost (resulting from land acquisition, construction, station, and maintenance costs), fleet cost depending on ridership. Stone et al. (1992) consider costs only as operating and investment costs. Liu et al. (1996) establish the objective function, which includes driving costs, rail operating costs, rail fleet costs, and rail line costs. Savage (1997) assumes only operating and investment costs. Parajuli and Wirasinghe (2001) categorize rail system costs as user costs, operating costs, and environmental costs as noise and pollution. Jha & Oluokun (2004) divide costs into three categories; investment cost (land acquisition and construction of facilities such as stations and parking), train operating cost, travel frequency-dependent operating cost, and user cost (access to the station, travel time). Similarly, O'sullivan (2007) indicates the rail cost under capital costs but does not consider the fleet cost as the main parameter. The capital costs cover the purchase of vehicles and the laying of railroads. Operating costs depend on labor, fuel, and maintenance costs of vehicles and rails. The cost of time is a function of travel time. Jha et al. (2007) evaluate rail and station construction costs, expropriation costs, and excavation costs as part of operating costs. In addition, access to the station, travel time and waiting time are defined as user costs. Martinez (2009) examines the user time cost, user money cost, and system operating cost under public transit costs. The cost of running the system is linked to fuel and energy costs. Unlike other studies, external costs are also described as major costs. Health, accident, social costs, and carbon emissions are assessed under external costs. Similarly, Verma et al. (2011) include the user cost with capital and operating costs for their model and present an objective function. Wenxing and Shuai (2012) examine costs on internal and external costs. Planning and design costs, construction costs, and operating costs are categorized as internal. Congestion, noise, air pollution, and other environmental factors are considered external. Li et al. (2012) divide rail transit costs into train operating cost, rail line cost, and station cost. Unlike others, Tsai (2012) claims that only operational costs have an impact on public transportation prices.

2.3.1.1. Operating Costs

Ticket price is a crucial tool in terms of operating costs since it is a major source of income (Paulley et al., 2006). Reducing operating costs appears to be a solution to maintain the financial situation and maximize profit, but it is difficult to implement. Operating costs include a wide range of components such as the energy cost of the trains, the personnel cost, and the cost of the running station. However, many studies do not differentiate operating costs. Table 2.3. shows the components used in different studies related to the problem.

Parry and Small (2009), Li et al. (2018), Feifei & Haicheng (2013), Ma et al. (2017) systematically examine operating costs under fixed and variable costs. Wirasinghe & Seneviratne (1986), Jha & Oluokun (2004), Jha et al. (2007), Martinez (2009), Li et al. (2012), Ma et al. (2017) select the components of operating costs depending on the objective of their studies. In the model of Chien & Tsai (2007), an average value is determined for hourly operating costs by using maintenance, insurance, labor, energy consumption, and management expenses. Another model is created by adding travel times at the peak and off-peak hours, headway between vehicles, and operating periods. Similarly, Tsai et al. (2008), Li et al. (2018), and Deng et al. (2014) use the same operating cost parameters and create new models by adding railway and station costs. Railway maintenance, signaling and management costs are accepted as railway costs. The cost of the station includes the costs of maintaining and operating the station and depends on the number of stops.

Table 2.3. Operating cost studies in the literature.

Author	**Purpose**	**Component of operating cost**	**Year**
Wirasinghe & Seneviratne	Optimizing line length	The length of the rail line The total corridor demand for travel during the commute period The operating cost of a train per passenger per unit distance	1986
Jha & Oluokun	Optimizing station locations	Number of stops	2004
Chien & Tsai	Maximizing profit for a transit route by jointly optimized temporal headways and differential fares	Maintenance cost Insurance cost Labor cost Energy consumption cost Administrative cost	2007
Jha et al.	Optimizing rail transit route	Track-related construction cost Station construction cost Right-of-way cost Earthwork cost Rail operating cost	2007
Tsai et al.	Distance-based fares and headway optimization of an intercity transportation system	Vehicle operating cost Route cost Station cost	2008
Martinez	Calculating the benefits of the advanced integrated rail service	Vehicle operating cost System operating cost (fuel subsidies)	2009

Table 2.3. Operating cost studies in the literature (Cont.).

Author	Purpose	Component of operating cost	Year
Parry and Small	Optimal pricing of rail and bus transit systems.	Fixed operating cost Variable operating cost • In-vehicle travel time divided by passengers-miles per person (annual) • Vehicle-miles per person • Variable cost per vehicle hour	2009
Tsai et al.	Optimizing temporal service headway and differential fare	Daily operating cost Line's cost Station cost	2012
Kim et al.	Minimize the cost of rail transit operation	Station spacing Maximum gradients Maximum acceleration (deceleration) rate Power Passengers/Car Time value Tractive, braking energy costs	2012
Li et al.	Optimizing the design variation of a rail transit line	The fixed component of train operating cost Variable operating cost • The fleet size of the rail line • The variable component of train operating cost	2012

Table 2.3. Operating cost studies in the literature (Cont.).

Author	Purpose	Component of operating cost	Year
Wenxing & Shay	Formulation of the fare by accurate calculation of the total cost of urban rail transit.	Management cost Financial cost Operating expenses	2012
Feifei & Haicheng	Optimizing fares, frequency, and the number of carriages	Fixed cost Variable cost • The cost is proportionate to ridership • The incremental cost per departure	2013
Deng et al.	Establishing an optimization model with the system efficiency, operators' interests, system regulation goals, and system costs.	Train operating cost Rail line cost Rail station cost	2014
Ma et al.	Optimizing service frequency	Fixed costs • Construction cost • Labor cost Variable costs • Energy is consumed • Maintenance cost • Depreciation cost	2017

2.3.1.2. User Costs

User costs are defined as the expenses to which passengers are exposed. Waiting time, comfort, and travel time are essential parameters for the passengers. These characteristics are also considered in the selection of public transportation modes. User costs have been the subject of various studies on urban transport.

Deng et al. (2014) benefit from the simulated annealing algorithm. The study contains the optimization of public transit fares under an elastic demand. User costs are detailed as waiting time, in-vehicle time, congestion cost, and ticket price in the study. Parry & Small (2009) ignore congestion cost for the rail system and consider access time, in-vehicle time, and waiting time. Verma et al. (2011) aim to identify an optimal rail corridor in terms of users and operators. A Geographical Information System based approach has been used for optimization since the complexity of the model. Waiting time, in-vehicle travel time, and access-egress time are considered user costs. Zhu et al. (2017) tackle the timeline design problem for the urban rail line. In the study, a bi-level optimization model is solved by using a two-stage genetic algorithm. The value of time, penalty costs, waiting time, and in-vehicle time are considered user costs. However, Chen & Nie (2017) distinguish the penalty cost and other parameters. Tirachini et al. (2010) develop a model to minimize the user and operating costs. A crowd-related penalty factor for the in-vehicle time is added to the model. Many researchers have evaluated user costs based on access and egress time, waiting time, in-vehicle travel time, and the value of time (Chien & Schonfeld, 1998; Almujibah & Preston, 2019; Zhao et al., 2018; Li et al., 2018). Samanta & Jha (2011) develop a problem of combinatorial optimization on the layout of a rail line. The problem is resolved by using a genetic algorithm based on a GIS database. User cost is expressed as multiplying demand with the sum of all user cost components (ATxUAC, UTCxTT, UWCxWT).

Parajuli & Wirasinghe (2001) offer an analytical decision model for the selection of public transport systems. In the study, user costs are presented as waiting costs, access and egress costs, and rising costs.

Operating and user costs interact inversely. Reducing the waiting time, cost requires increasing the frequency of headways but increases operating costs. Verma & Dhingra (2006) minimize both operating costs and waiting time. Waiting time is the only parameter considered as user costs in the study. Lai & Schonfeld (2012) associate unit user cost with daily demand and travel time. Chowdhury & I-Jy Chien (2002) create a model for optimizing the coordination of the intermodal transit network and refer to user costs as total waiting cost, in-vehicle time cost, and transfer cost.

2.3.1.3. Expert Cost

Some public transport pricing systems may require special research. In this sense, it is necessary to get support from experts. Especially complex fare systems are in this scope. Decision-makers can observe which pricing system brings additional costs. The expert cost is considered as a sub-criterion under the cost aspect for a fair comparison with existing fare systems since rent-based pricing requires expert support. Rent-based pricing needs passengers' rent and transportation cost data for each station. Analysis and determining ticket tariff requires serious expert support. Also, in a zonal pricing system, determining the zone boundaries fairly needs extra expert labor.

2.3.2. Transportation Aspect

Passengers' choice of transportation modes depends on several factors such as travel times, total cost, comfort, reliability. However, the operating principles of the transportation system depend on the ability to meet the operating costs. If operating costs are not met, the service frequency may be reduced. This may increase user costs by increasing waiting time and travel time. If ticket prices are low, ridership is generally high. High ridership decreases travel comfort depending on the in-vehicle crowd and delays are incurred when the passenger unloads (Hendrickson, 1981). Ridership and operating costs, which are strongly related to the public transportation pricing system can result in switching to the use of personal vehicles or a decrease in personal mobility. This criterion is evaluated with the sub-criteria such as travel time, travel comfort, switch to a personal vehicle, and personal mobility.

2.3.2.1. Travel Time

Travel time is a component of the performance function for transit service (Hendrickson, 1981). Reducing travel time is recognized as a vital factor in satisfying the needs of public transport users (Stradling, 2002). One study sought to answer the question of how many more travelers are willing to pay more for public transport to reduce travel time by 50% by using the Fuzzy analytical hierarchy process in five satisfaction factors (Salarzadeh Jenatabadi et al., 2016). The results show that short travel time is the most important factor for the users' WTP (willingness to pay). High-ticket tariffs can reduce the demand for public transportation. In this case, public transportation frequency is reduced to meet the operational costs. Thus, as the waiting time increases, leading the travel time and the user cost increase. Travel time is an important factor in the selection of the transportation fare system, as it also affects public acceptability. Less travel time is more attractive for users.

2.3.2.2. Travel Comfort

Many studies consider that in-vehicle comfort is a key to service quality. Eboli & Mazzula (2009) use comfort level for measuring service quality. Vehicle overcrowding and the serviceability of the heating system are considered to be the widespread reasons for dissatisfaction in the public transportation system (Edvardson, 1998). Qin (2014) and Palma et al. (2013) measure the overcrowding rate by a load factor and the number of people standing per square meter. Low-ticket tariffs increase the crowdedness of vehicles. On the contrary, in higher-fare systems, it is easy to establish a comfortable setting with a decrease in demand. Therefore, the ridership sourced by the transportation pricing system is crucial for the evaluation of travel comfort.

2.3.2.3. Switch to a Personal Vehicle

Communities are suffering from the growing use of personal vehicles and related impacts such as increased traffic congestion, parking problems and air pollution (Zhou et al., 2020). The challenges are of significant interest to transport planners, policymakers and

researchers. If public transportation is not accessible and ticket prices are high, people tend to personal vehicles. Unlike their high-population counterparts, people in low-population areas switch to personal vehicles if ticket prices increase (Paulley et al, 2006). Similarly, some researchers claim that the rise in public transport fares is associated with passenger loss due to commuters' behavioral responses such as switching to car travel (Wang et al., 2015; Zhang et al., 2017).

There are also studies claiming the opposite. Woo et al. (2020) study the use of own- and cross-price elasticity estimates in managing the demand for public transport in Hong Kong. The findings show that lower public transport fares had minimal impact on ridership. It is emphasized that approaches such as accessibility and improving travel time performance would be beneficial to reduce traffic congestion, vehicle emissions, and to hinder switching to a personal vehicle. Similarly, a multivariate regression model is established to understand the effect of public transport fare policies on public transport usage in Beijing (Zhang et al., 2018). The reduction in public transport fares mostly increases the preference rate in a short time, but this effect gradually decreases over time. The results show that in the long run, lower public transport fares do not increase preferability.

2.3.2.4. Personal Mobility

Mobility could be defined as the ability of people to move from one place to another easily and freely. Economic pressure, accessibility, the complexity of the transfer corridors, and fare systems can adversely affect urban mobility. Besides, an increase in waiting and travel time caused by low service frequency negatively affects mobility.

Galindez and Mireles-Cordov (2001) define a mobility index by using travel speed and average vehicle occupancy as performance factors. In another study, the absence of tariff subsidies and their effects on access to work are identified based on an analysis of threats to urban mobility (Santos et al., 2020). The findings show that mass transit systems without tariff integration with other transportation modes cannot meet the mobility conditions of vulnerable socio-economic groups affected by transportation costs. Free-fare transit policies

are accepted as an appropriate tool to improve citizen mobility and increase transit ridership (Štraub, 2020). However, it may be risky to meet the operating cost.

2.3.3. Social Aspect

Social aspects include environmental costs, quality of life, and decentralization of cities. Evaluating transportation from a social aspect requires a multidisciplinary perspective. Pricing systems are generally evaluated by the monetary value of costs and transportation parameters. However, there is a limited study that evaluates the social aspects of transportation pricing.

2.3.3.1. Environmental Cost

Many parts of the world are increasingly experiencing the effects of climate change. Transportation is one of the reasons for greenhouse gas emissions (Dirgahayani, 2013). Switching to public transportation and reducing personal vehicle usage provide significant benefits to the environment since motor vehicles, especially cars, are an important source of air pollution in big cities. Also, long journey time and high ridership play a role in increasing environmental pollution. Many cities develop innovative policies to create sustainable urban mobility and increase the efficiency of public transport systems.

Few empirical studies examine the environmental effects of changes in public transport fares. In Beijing, public transport fares are decreased in 2006 to improve air quality, and then public transport fares increase and distance-based pricing is introduced in 2014. A study investigates the impact of the increase in public transport fares on air quality (Yang & Tang, 2018). The results show that air pollution increased by 16.28% in the short term, but did not affect the air quality in the long term. Another study is estimated the environmental co-benefit potentials of both improving air quality and reducing CO_2 emissions by an urban transit improvement project introduced in the Indonesian Special Region Province of Yogyakarta (Dirgahayani, 2013). The results show that it potentially contributes to the

reduction of global and local environmental pollution, especially by switching from motorcycles, cars, and conventional buses to the Trans-Jogja public transport system.

2.3.3.2. Quality of Life

Empirical studies indicate that uncertainties in travel times and traffic congestion significantly increase passengers' stress levels, so that, travel time affects passengers' quality of life (İmre & Çelebi, 2017). Reducing travel time allows people to use their time more efficiently. So, people can devote more time to themselves and their social environment. This situation positively affects the quality of life. A pricing system that will even indirectly affect life quality is more attractive.

In a study, a strategic land use transportation model is applied to evaluate the impact of the congestion pricing scheme and of increasing public transport frequencies (Guzman et al, 2015). It is found that improving public transport frequency achieves greater social welfare levels than congestion pricing, but may require greater subsidies to public transport and have a negative financial impact on operators. Verbich & El-Geneidy (2017) analyze different transit fare purchases in Montreal, Canada. It is stated that low-income individuals, single-parent, immigrants, and individuals with low education levels are transit-dependent and the findings show that especially low-income individuals spent more money on public transportation fare for a month (Manaugh and El-Geneidy, 2012; Foth et al., 2013).

2.3.3.3. Decentralization of the Cities

Developed countries aim to build an integrated and multimodal transport system that takes advantage of the full potential of public transport. The "compact city", "multimodality", "intensification" and "mixing" are new buzzwords for urban and regional planning (Stojanovski, 2013). The compact city is a sustainable urban form and its benefits are the efficient use of lands, protects agriculture, sustainable forms of transportation, less dependency on cars, a reduction in greenhouse gas emissions, social and cultural facilities within easy access of everybody, and viable local businesses (Jenks, 2019). However, compact city is a challenge for the designed cities for individual vehicles in the past century.

In research using quantitative statistical methods to determine the effect of transportation on the urban compactness index, the results show that the length ratio of public transportation routes negatively affects the urban compactness index and travel distances tend to be shorter in a compact city (Aulia et al., 2021). A qualitative study, in which data is collected through in-depth interviews with housing market experts, aims to identify elements considered important for improving compact city liveability for various groups (Kotulla et al., 2019). Panel experts highlight public transport is one of the key elements of the built environment to enhance compact city livability.

As seen from the literature, public transportation systems play an important role in the change of urbanization. The population shift from urban to suburban areas is a result of improved public transport links between urban and suburban areas (Chau and Ng, 1998). It may cause decentralization of the city, and the financial burden of improvements along a commuter line may be enormous for operators (Aggarwala, 2012). A centralized city in a single point is easy to manage public transportation. This also prevents cities from regional differences in service accessibility.

2.3.4. Political Aspect

There is a huge gap in the literature on the political assessment of transportation pricing. The examined topics of this section are public acceptability, political success, and deployment of resources. All topics interact with each other. Political success may be seen as a result of public acceptability and deployment of resources.

2.3.4.1. Public Acceptability

Public acceptance is defined as to which the public perceives a change in any field to be positive or negative. Public acceptability is an important prerequisite for the successful implementation of pricing strategies. However, empirical findings have shown that the public acceptance of such strategies is low.

Public acceptability leads to changes in travel behavior. Low fares are often thought to increase ridership, so high fares are often viewed negatively for public acceptability. However, there are also studies claiming that the reduction in ticket tariff changes travel behavior limitedly (Woo et al., 2020; Zhang et al., 2018). In those studies, it is mentioned that although the low fare increases the preferability of public transportation in a short time, this effect disappears over time. The reason can be considered as the decrease in travel comfort and service quality with the increase in ridership. Also, demographic factors such as age, gender, and income may affect public acceptability.

In a study, different determinants of public acceptability are identified and analyzed based on the heuristic acceptability model in the survey conducted in four European cities (Schade & Schlag, 2003). The analyses show that the acceptability of the pricing strategies is usually quite low, and the degree of public acceptance is positively associated with the social norm, personal outcome expectation, and perceived effectiveness. Previous studies also evaluate the issue determining public acceptance of urban transport pricing options (MIRO, 1995; Bartley, 1995; Jones, 1995; Schlag & Schade, 2000);

- Policies should be well explained to the society with their background, objectives, and implementation method.
- The usage of financial gains should be demonstrated.
- Fairness issues should be explained to society correctly, and the perception of inequality and injustice should be prevented.

2.3.4.2. Political Success

Political feasibility is a major constraint in implementing public transport policies. Public acceptance is a key determinant of political feasibility and is essential for policy success. Therefore, it is important to understand the factors that influence public acceptance for the implementation of effective policy mechanisms (Kallbekken, 2013).

Studies on the impact of transportation policies on political achievements are limited. One study argues that the revenue from congestion pricing on highways will have a great

chance of political success, especially if it is distributed to the cities where highways pass (King et al., 2007). An article deals with the decision-making process in public transport system applications with the factors such as travel demand, urban development, and the environment (Mackett & Edwards, 1998). In the study, it is claimed that building a rail-based system, especially in terms of political factors, is seen as a positive attempt to provide an alternative to the car, and those who do this have achieved significant success. In a study, the transport policy priority of politicians and citizens regarding restrictive instruments and public transport instruments is demonstrated (Christiansen, 2020). The findings show that politicians tend to prioritize restrictive instruments, while citizens tend to prioritize reducing public transport fares.

2.3.4.3. Deployment of Resources

The operator may require a mechanism developed to finance the deficit since the government provides transport services at rates below the relevant marginal cost. Public transport can contribute to the efficiency of the city and the needs of the poor in big cities, but it can impose a heavy financial burden. In German public transport, most cost reduction measures involve reducing workers' revenues (Buehler & Pucher, 2011).

One of the most important factors in ensuring financial sustainability is fare systems. Data from Pioneer Institute shows that most Massachusetts Bay Transportation Authority (MBTA) services operate at a loss regarding fees collected, and this is also common in many other U.S. public transit systems. For example, the commuter train generates $238.6 million income from passengers but costs $384.4 million to operate each year (Pioneer Institute, 2019). Rail systems operate inefficiently in many cities of Turkey, as travel behavior is not analyzed realistically or arrangements are not developed to increase ridership (CIRIT, 2016). In addition, the financial sustainability of the projects cannot be ensured and municipalities are under financial burden since the capital cost of rail systems is higher than other public transportation systems.

A system whose operating costs are covered by the pricing system may no longer be a burden to the municipality. It may even pave the way for other investments by reducing the

financial burden. A system where resources are used properly and that makes a profit is more attractive to both the operators and the public.

3. CASE STUDY

3.1. Introduction

Four different data are used in the study. The passenger data is obtained through face-to-face questionnaires with 606 people. Travel behavior is examined with travel frequency, journey days, travel time, travel distance, PT mode, access type to IZBAN, travel price, outward and arrival journey times. The user cost part consists of the access time, in-vehicle time, the waiting time questions. Demographic characteristics of the passengers include age, gender, education, occupation, household income, and household size. The second data set is related to the rent prices around IZBAN stops. The data consists of the rent price, house size, distance between the house and IZBAN stops (by feet and aerial viewpoint). The third and fourth data sets are obtained for the evaluation of public transportation pricing systems. 5 public transportation experts are selected from the industry for this survey. Due to the Covid-19 pandemic, these surveys are collected via Google forms. These last two data sets are explained in chapter 4. In this chapter, only the passenger data set and rent data set will be introduced.

3.2. Passenger Data

3.2.1. İzmir Urban Rail Mass Transit System (IZBAN)

The public transportation pricing system in İzmir is quite changeable. While the flat fare is used in bus, metro, and tram; the distance-based fare is applied in some bus lines operating at long distances and in the suburban trains. IZBAN has served since 2010 and provides the connection between Aliağa and Selçuk. It is one of the largest urban rail mass transit systems connected to the airport in Turkey (İzmir Banliyö Sistemi, 2019). First, IZBAN was operated with 31 stations. Next, this increased to 32 with the opening of the Hilal station and then to 38 with the opening of the Torbalı line. Stations increased to 40

with the opening of Sağlık and Selçuk in 2019. Hilal and Halkapınar stations are the intersection points of İzmir Metro and IZBAN.

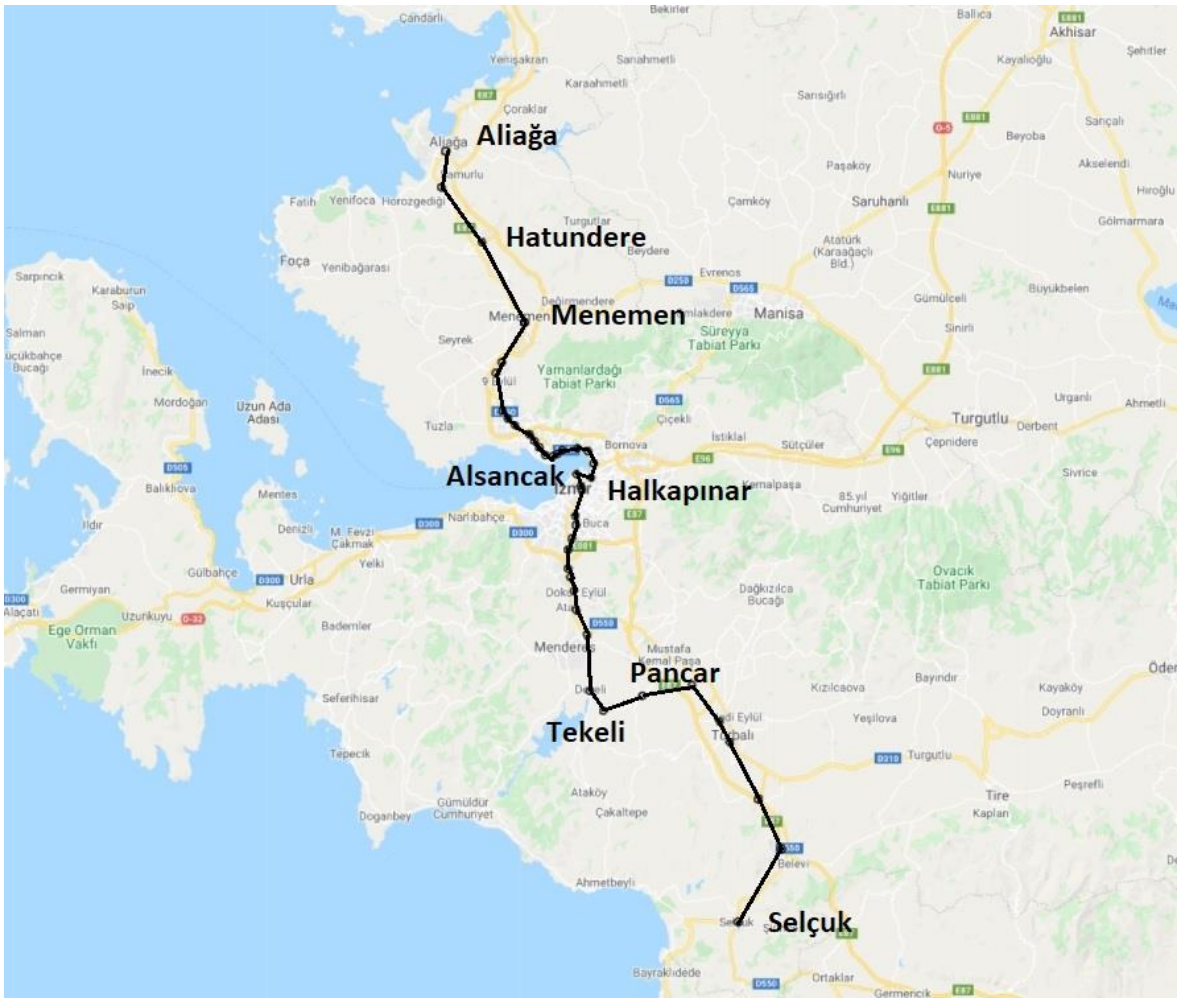

Figure 3.1. IZBAN stations (Source: Google Maps).

IZBAN carries 650 thousand passengers per day and the length of the line is 136 km. The line will extend to Bergama and reach 185 kilometers after the project is completed (İzmir Banliyö Sistemi, 2019). IZBAN has started to serve with flat fare and it switched to the distance-based pricing system in 2018. First, the ticket price for the maximum distance from the departure station is collected. Then, the distance not traveled is refunded at the arrival station.

The ticket tariff in IZBAN is 2.86 TL for the full fare, 1.65 TL for the student, 2.20 TL for the teacher, and 1 credit for the staff if you travel below the flat fare distance limit which is 25 km. However, the pricing system implies some problems for passengers. Before the journey, passengers must have a different amount of money depending on the departure station (See Table A.1 and Table A.2). For example, a passenger whose departure stop is Aliağa must always have 10.60 TL on the transportation card. This calculation is made according to the farthest stop (for this example, Selçuk). This is often evaluated as costly by passengers. Another issue is that passengers may forget to take refunds from machines at arrival stations. These reasons may encourage passengers to use other public transportation modes instead of IZBAN.

Transportation card types are diverse in İzmir. Table 3.1. shows card types and tariffs in IZBAN. The flat fare is charged up to 25 km and the distance-based fare is charged after 25 km.

Table 3.1. Card types and tariffs.

Card type	Full fare	Student	Teacher	Between the ages of 60-65	Over 65	Staff
Flat fare (TL)	2.86	1.65	2.20		0	1 credit
Distance-based fare (TL)	TP=2.86+0.07 x(TD-25)	TP=1,65+0.04x (TD-25)	TP=2.20+0.05x(TD-25)		0	2 or 3 credit

Year 2018, 1 $ = 3.75 TL

3.2.2. Data Collection

Within the scope of the data collection part;

- IZBAN's station information and line length,
- distance between stations,
- travel time between stations,

- number of annual passengers for each stop,
- ticket tariffs in flat rate system (from the opening of IZBAN till the system change),
- travel price between each stop in distance-based pricing system,

are obtained from İzmir Metropolitan Municipality Suburban and Rail System Investments Department.

According to the data, a small preliminary survey is conducted and the suitability of the questions is evaluated for a more comprehensive questionnaire. Subsequently, the passengers using IZBAN are surveyed. The questionnaire is designed to understand the travel behavior of passengers and establish a new pricing system based on rent prices.

The interviewer-assisted method is commonly used by researchers for data collection. This method is divided into two categories; personal interviews and telephone interviews. Telephone interviews have some disadvantages such as the possibility of participants not being able to clearly understand the questions, the risk of not completing the questionnaire, and time limitation. Moreover, the target group for the thesis is IZBAN passengers. So, it is difficult to reach IZBAN passengers with telephone interviewing. All these reasons have shown that personal interviewing is the best choice for this study.

The number of surveys for each train station based on the ridership is calculated to improve the statistical efficiency of the survey. De Vries, 1986's formulation is given as

$$n_i = n\left(\frac{N_i}{\sum_{i=1}^{L} N_i}\right) = n\left(\frac{N_i}{N}\right) \tag{3.1}$$

where n is the total number of sample units, n_i is the number of sample units to allocate to stratum *i*, L is the number of strata, N_i is the number of sample units within stratum *i*, N is the number of sample units in the population.

3.2.3. Survey Design

The questionnaire consists of two different parts. The first part is aimed to determine the travel behavior, user costs, and demography of participants. The second part is aimed to determine passenger's priorities about public transportation, and importance level related to renting price and travel distance. Revealed preference and stated preference methods are applied to the questionnaire.

The revealed preference part consists of the demographic information, travel behavior features; and the user costs obtained as the numeric results. In the pre-questionnaire, the rent-distance relationship is not affected by the instant situations of travel behaviors. Hence, questions are designed to determine the card type, travel frequency, mean travel time, travel days, outward and return journey hours, access type to IZBAN, departure and arrival stations, travel purpose and most preferred public transportation mode. In the demographic part, questions are related to gender, age, education, occupation, monthly household income, the closest IZBAN stop, car ownership, rent status, and rent price. The third part questions aim to learn in-vehicle travel time, waiting time, and access time (from home to IZBAN and from turnstile to platform).

To determine willingness to pay for rent depending on the travel distance, a stated preference questionnaire is used. Real estate index reports of the most popular websites in Turkey are searched. The mean rent price in the counties is obtained. Only the Alsancak neighborhood is evaluated separately from the other neighborhoods in the Konak county since it is a well-known attraction center in İzmir, located in the center of the city, and the rent prices are much higher than other parts of the county. In this regard, Table 3.2. is created. According to Table 3.2., the highest rent price corresponds to the Alsancak neighborhood with 2200 TL and the lowest rent price corresponds to Torbalı county with 700 TL. Stated preference questions consist of two variables. These are rent prices and the daily mean travel distance for a round trip. Therefore, a minimum of 700 TL and a maximum of 2200 TL are selected as a border for rent price. The maximum rent price and the minimum travel distance are kept constant in the first option. The minimum rent price is kept constant and the travel

distance is changed in the other option. The distance change is chosen based on the Alsancak and Selçuk stops between 0 km and 76.99 km.

Table 3.2. Travel distance and ticket tariff for a journey to Alsancak, and rent prices in counties.

Stations	**Distance (Km)**	**Rent price (TL)**	**Ticket tariff (TL)**
Selçuk	76.99	1000	7.16
Torbalı	48.69	700	4.90
Cumaovası	21.23	990	3
Gaziemir	13.11	1390	3
Şirinyer	6.00	1380	3
Alsancak	0.00	2200	0
Bayraklı	7.06	1310	3
Karşıyaka	11.77	1580	3
Çiğli	18.85	1250	3
Menemen	32.97	995	3.64
Aliağa	58.55	1070	5.68

The stated preference method is also used in the other part concerning the expectations of the passengers from public transportation. Ticket price, travel time, waiting time, and comfort are chosen as factors. Each factor is compared with other factors. This section aims to understand the importance of transportation factors for users.

The number of IZBAN passengers is 84,450,567 according to 2018 IZBAN data. This number is 231,371 for a day. The sample size is calculated as 400 with the formula (3.2) of Yamane (1967) by taking population size as 231,371 and assuming a 95% confidence level and P = 0.5

$$n = \frac{N}{1 + N(e^2)} \tag{3.2}$$

where *n* is the sample size, *N* is the population size, *e* is the level of precision.

606 questionnaires are administered in total. Annual ridership in the stations is considered to determine the count of participants for each station. This calculation is performed by multiplying the percentage distribution of the stations with the total number of surveys. For example; the annual ridership at the Şirinyer station is 7,848,161 and participants are 72; the annual ridership at the Ciğli station is 3,478,991 and participants are 32. The survey has some limitations. Some groups are excluded from the survey. Passengers under the age of 18 are not sufficient to answer financial questions since many of them live with family and are dependent financially. Also, university students staying in dormitories are excluded from the study since rent price is crucial for the study.

3.3. Housing Data Around IZBAN Stops

Studies have shown that transportation facilities significantly affect property prices (Sadayuki, 2018). However, this effect fades as the distance increase from the transport system. Hence, researchers define a zone namely a "catchment area" and have calculated its borders (Chiarazzo et al., 2014; Pilgram et al., 2018). Based on the study of Şahin & Gokaşar (2020), primary and secondary catchment areas are accepted respectively between 0-850 meters and 850-1900 meters (See Figure 3.2.). For the rent data set, catchment areas are located around IZBAN stops. In Turkey, there are several websites for renting or selling houses, land, and shop. Sahibinden.com and Hürriyet Emlak are the most popular ones. Also, they enable customers to search on the map and around IZBAN stations. So, these are selected for data collection. The housing data consists of rent, size (m^2), distance to the IZBAN station by feet, and aerial viewpoint. While calculating the distance to stops, a google map is used.

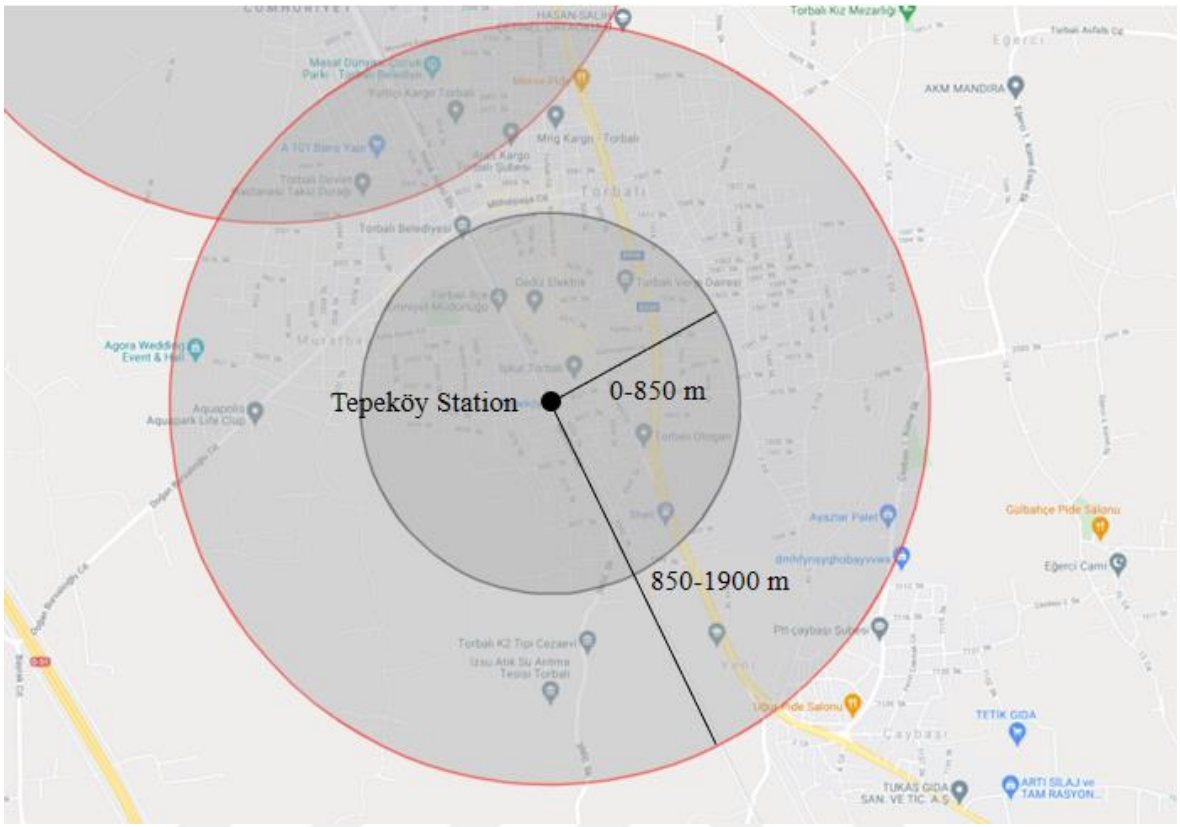

Figure 3.2. The primary and secondary catchment area of Tepeköy Station.

A total of 1693 data are collected from each stop, with 30 for the primary catchment area and 30 for the secondary catchment area. Some IZBAN stops are located in rural areas (Biçerova, Hatundere, Develi, Tekeli, Pancar) or in the airport area (Havaalanı). Some stops (Cumaovası, Halkapınar, Turan) are built only for transfer with other PT modes. Rent data can not be obtained at a sufficient level, since there is no residential area around such stops. Distance between two stops is quite changeable on the IZBAN line. Some houses are located in two or even three catchment areas. In this case, the distance to both stops is taken into account.

3.4. Preliminary Analysis

3.4.1. Analysis of Passenger Data

The core results of the passenger survey are given in this section. Public transportation cards are full fare, student, teacher, 60-65 ages, over 65, and staff. Ticket tariffs by card type are shown in Table 3.3. The results have shown that 67% of the respondents pay the full fare; this is followed by the student card with 24.8%. In terms of journey frequency, 27.90% of passengers use IZBAN 5 days a week or more. However, 10.20% of the passengers use IZBAN less than once a month. Average journey time rest on passengers' estimation. It is seen that the average journey time is short for 34.70% of passengers and very long for 0.70%. Outward journeys have the highest rate between the hours 06:00-10:00 with 39.90%. These hours are also the peak hours and the in-vehicle crowd is high. Unsurprisingly, the least usage of IZBAN for the outward journey is between 20:00-24:00 with a %1.80 rate. Considering the return trips, a more heterogeneous distribution can be seen. Return journeys between 16:00-20:00 and 20:00-24:00, constitute 89.6% of all returns. The highest rate is between 16:00-20:00 with a 47.40% rate, the lowest rate is between 06:00-10:00 with a 0.70% rate. Employees are the reason for these results. It is seen that in-week travel has the highest share with 43.10% rate, weekend and both weekend and in-week travels have almost the same rate with 28.70% and 28.20%. 41.30% of the passengers make their trips for visiting. On the other hand, school and work trips cover almost half of the transportation purposes with a 48.10% rate. Only 1.20% of passengers use IZBAN for an emergency such as a hospital. This rate may be the result of using the taxi or personal vehicle in emergency conditions. 49.80% of users reach IZBAN by foot, 45.20% of them use other public transportation modes. Furthermore, 3.60% of passengers prefer to use their cars. The highest use rate in public transportation modes belongs to IZBAN with 44.20%. The least belongs to ferry with 1.80% since many IZBAN stops are far from the coast.

Table 3.3. Travel behavior descriptive statistics.

Questions		Frequency	Percent (%)
Rental Status	*Yes*	237	39.1
	No	369	60.9
Card Type	*full fare*	406	67.0
	student	150	24.8
	teacher	8	1.3
	60 years	19	3.1
	staff card	14	2.3
	Over 65 free card	9	1.5
Journey Frequency	*5 or more times a week*	169	27.9
	3-4 times in a week	103	17.0
	1-2 times in a week	154	25.4
	1-3 times in a month	118	19.5
	Less than once a month	62	10.2
Mean Travel Time	*very short*	79	13.0
	short	210	34.7
	short middle	132	21.8
	middle	94	15.5
	long middle	68	11.2
	long	19	3.1
	very long	4	0.7
Journey Days	*In-week*	261	43.1
	Weekend	174	28.7
	Both	171	28.2
Outward Journey Time	*06:00-10:00*	236	38.9
	10:00-13:00	134	22.1
	13:00-16:00	142	23.4
	16:00-20:00	83	13.7
	20:00-24:00	11	1.8
Return Journey Time	*06:00-10:00*	4	0.7
	10:00-13:00	8	1.3
	13:00-16:00	51	8.4
	16:00-20:00	287	47.4
	20:00-24:00	256	42.2

Table 3.3. Travel behavior descriptive statistics (cont.).

Questions		Frequency	Percent (%)
Access to IZBAN	*foot*	302	49.8
	other pt modes	274	45.2
	taxi	6	1.0
	own car	22	3.6
	bicycle	2	0.3
Journey Purpose	*work*	201	33.2
	school	90	14.9
	visiting	250	41.3
	shopping,bank and other	58	9.6
	hospital	7	1.2
Public Transportation Type	*bus*	212	35.0
	railway	268	44.2
	ferry	11	1.8
	tramway	37	6.1
	metro	14	2.3
	dolmuş	64	10.6

Ridership is the highest in Şirinyer stop for departure. This station is located in Buca and is close to attractive avenues. The county has the highest population with 507.773 people in İzmir (TUIK, 2020). Halkapınar is an essential transfer station connected with the metro, bus, and tramway. This stop is also located close to crowded counties such as Bornova and Konak. Many of the metro passengers come from Bornova, Konak, and Balçova transfer from this stop. Hence, the ridership is substantially high here. A similar situation is seen in Hilal station. However, the only metro interacts with this stop. As expected, Kuşçuburun, Hatundere, and Biçerova stops are low-preferred stations, since they are located far from the city center and inside the rural areas. Because of the same reason, none of the participants Develi, Tekeli, Sağlık, and Belevi stations are chosen as departure. Besides, Havalanı station is built just for the airport and Selçuk is a newly built stop with Sağlık and Belevi in 2019. So, there are no users as departure stations.

Table 3.4. Descriptive statistics for departure and arrival stations.

	Station	Departure		Arrival	
		Frequency	Percent (%)	Frequency	Percent (%)
North Axix	Aliağa	16	2.6	25	4.1
	Biçerova	3	0.5	1	0.2
	Hatundere	5	0.8	1	0.2
	Menemen	27	4.5	26	4.3
	Egekent 2	17	2.8	12	2.0
	Ulukent	8	1.3	3	0.5
	Egekent	21	3.5	15	2.5
	Ata Sanayi	17	2.8	3	0.5
	Çiğli	39	6.4	26	4.3
	Mavişehir	18	3.0	14	2.3
	Şemikler	18	3.0	8	1.3
	Demirköprü	9	1.5	8	1.3
	Nergiz	13	2.1	14	2.3
	Karşıyaka	23	3.8	61	10.1
	Alaybey	8	1.3	3	0.5
	Naldöken	4	0.7		
	Turan	2	0.3	9	1.5
Central Axis	Bayraklı	19	3.1	14	2.3
	Salhane	3	0.5	11	1.8
	Halkapınar	62	10.2	55	9.1
	Alsancak	20	3.3	103	17.0
	Hilal	34	5.6	39	6.4
	Kemer	9	1.5	7	1.2
	Şirinyer	97	16.0	30	5.0
	Koşu	33	5.4	2	0.3
	Inkılap	15	2.5	2	0.3
	Semt Garajı	17	2.8	14	2.3
	Esbaş	9	1.5	45	7.4
	Gaziemir	10	1.7	19	3.1
	Sarnıç	9	1.5	9	1.5
	Havalimanı			15	2.5
	Cumaovası	5	0.8	2	0.3
	Develi				
	Tekeli			2	0.3
	Pancar	1	0.2		
	Kuşçuburun	1	0.2		
South Axis	Torbalı	9	1.5	5	0.8
	Tepeköy	5	0.8	1	0.2
	Sağlık				
	Belevi				
	Selçuk			2	0.3

The distribution of the arrival station is slightly different. Mobility is very high in Alsancak. It is the most attractive area in İzmir for companies, students, and tourists. Therefore, ridership is very high in Alsancak station. Likewise, Karşıyaka is the most attractive area in the northern part of the city. This station is located close to bazaars, avenues, and the coastal side. So many passengers select it as an arrival stop. Besides the geography, investments also affect the ridership in the stations. Esbaş station is located near a huge industrial free zone and the biggest shopping mall in İzmir. The stop is used mostly by employees and shoppers. Hence, there is a huge difference between the arrival and departure ridership of this stop. Hatundere and Biçerova are the least preferred stations for arrival too. Also, no one specified Naldöken, Develi, Pancar, Kuşçuburun, Sağlık and Belevi as arrival stations. Beyond its being new, Selçuk is a tourist destination and people rarely prefer to go.

In the second part of the survey, user cost components such as waiting time, in-vehicle time, and access time are estimated. 48.34% of the passengers stated that the access time to IZBAN is 10 minutes or less, 3.30% say more than 30 minutes. The mean access time from home to IZBAN is 14.1980 minutes. 49.83% of the passengers stated that accessing to platform from the turnstile is 1 minute or less. 0.82% stated more than 5 minutes. The mean access time to the platform is 1.7163 minutes. 63.86% of the passengers stated that they wait at stations between 5 and 10 minutes. 4.29% stated that waiting time is more than 15 minutes. The mean waiting time value is 9.2855 minutes. In-vehicle time is related to the time between entering and leaving the train gate. It is seen that in-vehicle time of 36.96% is between 10 and 20 minutes. For 1.98% of them, it is more than 60 minutes. The average in-vehicle time is 25.9620 minutes.

Table 3.5. Descriptive statistics of user cost components.

Variable	Minimum	Maximum	Mean	Std. Deviation	Variance
Access time (home to IZBAN)	2.00	100.00	14.1980	10.61523	112.683
Access (to platform)	0.16	12.50	1.7163	1.25045	1.564
Waiting time	1.00	30.00	9.2855	3.80683	14.492
In-vehicle time	3.00	105.00	25.9620	16.65601	277.423

82.84% of participants travel 26 km and below. Those are not exposed to distance-based pricing. Only 0.17% travel more than 75 km. Travel price is dependent on travel distance if over 26 km. 55.94% of the participants pay 2.86 TL. 20.13% pay discounted student tariff, 1,65 TL. 16.34% are exposed to distance-based pricing rules. The mean travel distance is 15,8231 km and the mean travel price is 2.5852 TL. The results are affected by the free or discounted ticket tariffs such as 65+ cards, teacher cards, and staff cards.

Table 3.6. Descriptive statistics of travel distance and travel price.

Variable	Minimum	Maximum	Mean	Std. Deviation	Variance
Travel distance	1.00	75.47	15.8231	13.65743	186.525
Travel price	0.00	6.39	2.5852	0.92979	0.865

In the stated preference section, the expectations for IZBAN are investigated. According to the results, participants care respectively travel time, travel price, waiting time, and travel comfort. Passengers may ignore comfort for short trips, but not for longer ones. Caring for most of the travel time is an understandable reason for the travel distance results.

Table 3.7. Comparisons between travel time, price, comfort and waiting time.

Criteria	Frequency	Percent (%)		Frequency	Criteria
Travel time	410	67.7	32.3	196	Price
Comfort	223	36.8	63.2	383	Price
Comfort	148	24.4	75.6	458	Travel time
Waiting time	47	7.8	92.2	559	Travel time
Waiting time	412	68.0	32.0	194	Comfort

Another stated preference part concerns willingness to pay the rental based on travel distances. It is observed that 45.38% of the passengers are willing to pay the least rent price (700 TL) by living furthest (80 km). The least preferred option is 700 TL rent price and 70 Km travel distance with a 0.83% rate since the change in travel distance observation from the previous choice is so small. If the highest choice is ignored, the breaking point is 30 km

travel distance. Preference rate increases till here, but then a decreasing starts. This information may provide travel distance flexibility for the passengers. It can be said that the travel distance limit is 30 km for renting a house.

The last part of the survey consists of demographic information. 62.9% of the participants are male, and 37.1% are female. 39.1% of participants pay for rent, and 60.9% live in their own homes. 48.3% of the participants have high school graduation, and the least one is doctoral graduation with a 0.8% rate. Employees are dominant among the IZBAN users. Private sector employees take the lead with a rate of 54.8%. This is followed by students with 22.1%, and public sector employees with 9.7%. The results also include housewives, retirees, and non-workers. 1.7% of the participants do not work.

Passengers under the age of 18 are not included in the study due to the dependency of living with families. The majority of the participants are in the employee group between the age of 27-59 with a 49.83% rate, and over the age of 65 is 1.49% of all passengers. The mean age of the participants is 32. Household size changes between 1 to 12 people. 31.7% of the participants' family consists of 4 people. The mean value is between 3 and 4 people.

Table 3.8. Travel distance and rent price selection for various scenarios.

Rent Price (TL)	Travel Distance (km)	Frequency	Percentage (%)		Frequency	Travel Distance (km)	Rent Price (TL)
700	80	275	45.4	54.6	331	0	2200
700	70	280	46.2	53.8	326	0	2200
700	60	292	48.2	51.8	314	0	2200
700	50	330	54.5	45.5	276	0	2200
700	40	384	63.4	36.6	222	0	2200
700	30	455	75.1	24.9	151	0	2200
700	20	521	86.0	14.0	85	0	2200
700	10	558	92.1	7.9	48	0	2200

Table 3.9. Demographic results of the survey.

Questions		Frequency	Percent (%)
Gender	*female*	225	37.1
	male	381	62.9
Education	*primary school*	71	11.7
	high school	293	48.3
	vocational school	64	10.6
	bachelor	154	25.4
	master	19	3.1
	Ph.D.	5	0.8
Occupation	*public sector*	59	9.7
	private sector	332	54.8
	student	134	22.1
	housewife	33	5.4
	retired	38	6.3
	non-worker	10	1.7

Table 3.10. Descriptive statistics of age and household size.

Variable	Minimum	Maximum	Mean	Std. Deviation	Variance
Age	18.00	76.00	31.9455	12.18109	148.379
Household size	1.00	12.00	3.4752	1.39606	1.949

Many people living with families take into account household income while purchasing something. Many researchers use household income data for the evaluation of housing and transportation affordability (Guerra & Kirschen, 2016; CNT, 2012; Isalou et al., 2014). Therefore, household income information is collected for the study. 16.8% of the passengers' household income is between 4000-5000 TL. This is the highest rate in all income groups. The average monthly household income of the participants is between 5000-6000 TL. Rent price is asked to all participants; however, some of them are living in their own house. So, we asked them “if you didn’t have a house, which price would you pay for rent?”. The highest rent choice is between 750-1000 TL with a 26.7% rate and the lowest choice is between 2750-3000 TL with a 0.5% rate. The mean rent cost is between 1000-1250

TL. Car ownership is important data for travel behavior research. 42.2% of the participants have their car, 57.8% do not have one. That is, 42.2% of them prefer IZBAN rather than a personal vehicle.

Table 3.11. Distribution of income, rent price and car ownership.

Variable		Frequency	Percent (%)
Household income	*below 2000 TL*	25	4.1
	2000-2999 TL	79	13.0
	3000-3999 TL	100	16.5
	4000-4999 TL	102	16.8
	5000-5999 TL	82	13.5
	6000-6999 TL	69	11.4
	7000-7999 TL	37	6.1
	8000-8999 TL	26	4.3
	9000-9999 TL	36	5.9
	10.000-10.999 TL	16	2.6
	11.000-11.999 TL	6	1.0
	12.000 TL and Over	28	4.6
Rent cost	*Below 500 TL*	22	3.6
	500-744 TL	66	10.9
	750-999 TL	162	26.7
	1000-1249 TL	125	20.6
	1250-1499 TL	83	13.7
	1500-1749 TL	54	8.9
	1750-1999 TL	33	5.4
	2000-2249 TL	28	4.6
	2250-2499 TL	11	1.8
	2500-2749 TL	14	2.3
	2750-2999 TL	3	0.5
	3000 TL and over	5	0.8
Car ownership	*yes*	256	42.2
	no	350	57.8

The closest IZBAN stop results are similar to the departure station. Şirinyer stop has the highest share of participants with a 16.2% rate since the population of the county is high. The result is respectively followed by Halkapınar and Çiğli stops. Kuşçuburun, Pancar, and

Tekeli are the lowest ones with a 0.2% rate. Unfortunately, some stops (Havalimanı, Develi, Sağlık, Belevi, and Selçuk) weren't selected by anybody.

Table 3.12. Closest IZBAN stations to participants.

Station	Frequency	Percent (%)	Station	Frequency	Percent (%)
Aliağa	16	2.6	Salhane	4	0.7
Biçerova	3	0.5	Halkapınar	57	9.4
Hatundere	5	0.8	Alsancak	15	2.5
Menemen	30	5.0	Hilal	30	5.0
Egekent 2	18	3.0	Kemer	10	1.7
Ulukent	8	1.3	Şirinyer	98	16.2
Egekent	20	3.3	Koşu	34	5.6
Ata Sanayi	16	2.6	Inkılap	18	3.0
Çiğli	36	5.9	Semt Garajı	16	2.6
Mavişehir	20	3.3	Esbaş	9	1.5
Şemikler	18	3.0	Gaziemir	9	1.5
Demirköprü	9	1.5	Sarnıç	7	1.2
Nergiz	16	2.6	Cumaovası	6	1.0
Karşıyaka	27	4.5	Tekeli	1	0.2
Alaybey	9	1.5	Pancar	1	0.2
Naldöken	4	0.7	Kuşçuburun	1	0.2
Turan	2	0.3	Torbalı	7	1.2
Bayraklı	19	3.1	Tepeköy	7	1.2

3.4.2. Analysis of Housing Data

The data collected from Sahibinden.com and Hürriyet Emlak include rent price, house size (m^2), distance to IZBAN stop (by feet and aerial viewpoint). Houses located in primary (0-850 m) and secondary (850-1900 m) catchment areas of IZBAN stops are selected. However, some stops are excluded from the results, since there is no rental house around them. The maximum, minimum values, means, and standard deviations of rent price, house size, distance to IZBAN by feet, and aerial in the primary and secondary catchment areas are in Table 3.13.

Table 3.13. Rent price, house size, distance and rent per m^2 descriptive results.

Location	Features	Minimum	Maximum	Mean	Std. Deviation
Primary catchment area (0-850 m)	Rent price	600.00	11000.00	1993.3962	1245.53833
	House size	40.00	395.00	113.7866	40.17698
	Distance by feet	7.00	3500.00	897.8078	588.03691
	Distance (aerial viewpoint)	10.00	850.00	511.1675	220.57626
	Rent per m^2	2.86	109.09	18.3518	10.09808
Secondary catchment area (850-1900 m)	Rent price	600.00	12500.00	2000.3195	1321.35603
	House size	22.00	410.00	116.8533	35.85760
	Distance by feet	900.00	4800.00	1718.3432	468.47372
	Distance (aerial viewpoint)	850.00	1700.00	1246.1219	253.57044
	Rent price per m^2	4.29	70.83	17.7079	10.63324

The mean rent prices in the primary catchment area are 1993,3962 TL. However, rent prices in the secondary catchment area are slightly higher since house sizes differ. Mean rent price per m^2 is higher in closer streets to IZBAN. While the mean value is 18.3518 TL/m^2 in the primary catchment area, it is 17.7079 TL/m^2 in the secondary catchment area.

Figure 3.3. shows average rent prices around the stops, Figure 3.4. shows rent prices per m^2 in primary and secondary catchment areas. From the graphs, peak levels are smoothly determined. Rent price peaks in primary catchment areas occur at Mavişehir, Salhane, and Esbaş stop. Mavişehir has recently become a popular district in İzmir. It is located in Karşıyaka and nearby Çiğli county. Luxury residences were first seen in Mavişehir. By that time, the demand for rent has increased in the region, since luxury shopping malls and private schools were opened. Transportation is provided by bus, tram, minibus, taxi, and ferry, apart from IZBAN. Salhane station is located in Bayraklı county and is very close to counties such as Bornova and Konak. The largest courthouse in İzmir is around Salhane stop. Salhane was an industrial area in the past and it has recently been home to skyscrapers, universal companies, and luxury residences. Transportation is provided by bus, minibus, taxi, tram, and metro together with IZBAN. Esbaş station is located in Gaziemir county and is close to the biggest shopping mall in İzmir and the Aegean Free Zone. Aegean Free Zone hosts many

domestic and foreign companies. So, the county is a popular choice for white collars. Torbalı county has also many factories. Employees who do not want to move away from the city center generally prefer Gaziemir instead of Torbalı. Hence, rent prices are higher than in other counties.

Hilal stop has the highest value in the secondary catchment area since the neighborhoods with high rent prices are located between the primary catchment area and the secondary catchment area around the Hilal stop. Similarly, the Nergiz stop has high rental areas between primary and secondary catchment areas. The results are parallel for rent per m^2. While Mavişehir, Salhane, and Esbaş stations have the highest rent price per m^2 in the primary catchment area, Hilal and Mavişehir stations have the highest rent prices in the secondary catchment area.

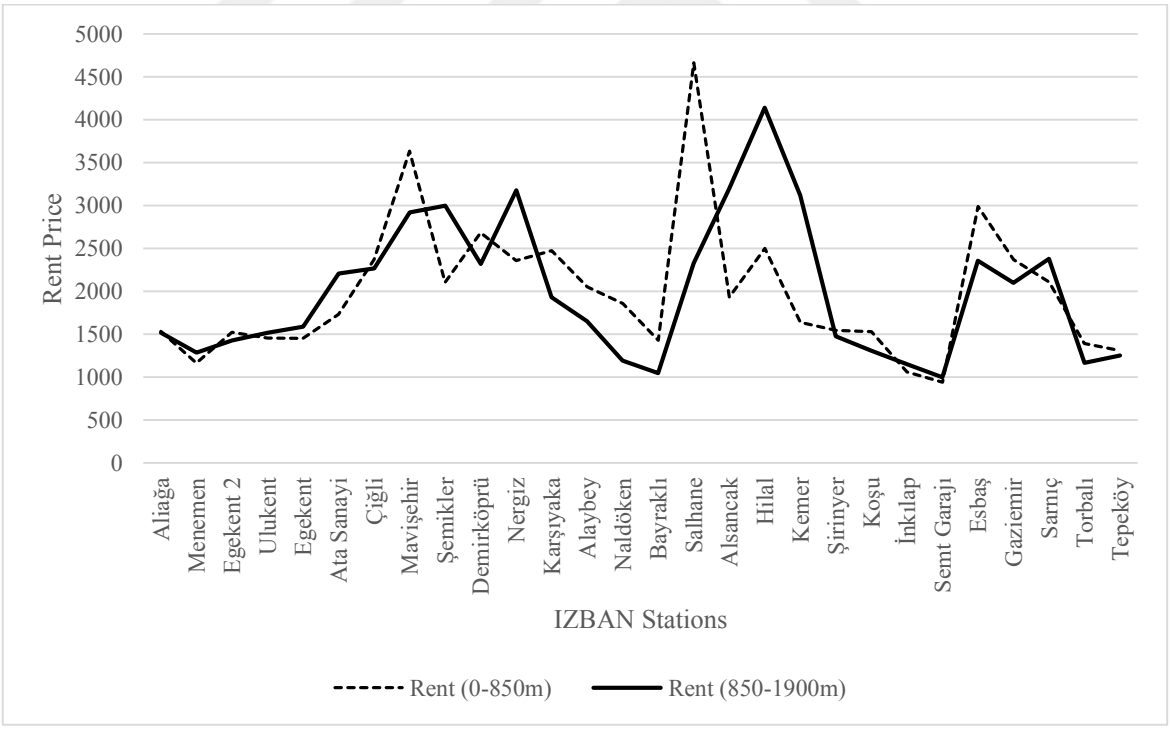

Figure 3.3. Rent price changes according to stations.

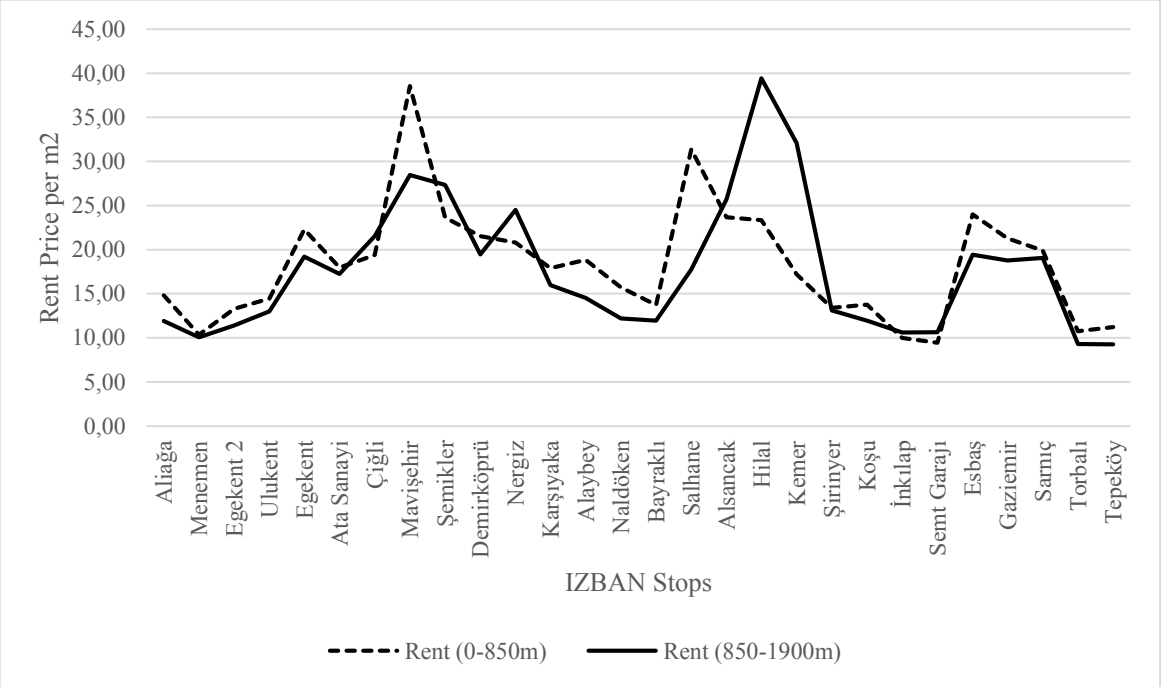

Figure 3.4. Rent price per m^2 changes according to stations.

4. EVALUATION OF THE PUBLIC TRANSPORTATION PRICING CRITERIA

4.1. Introduction

The Analytical Hierarchy Process (AHP), introduced by Saaty (1987), is a decision-making tool used by decision-makers and researchers to rationally evaluate alternatives to a goal and is based on calculating the importance of criteria. This chapter aims to describe the data collection process for both AHP and the CRITIC method described in chapter 4 and evaluates the importance weights of the criteria defined in chapter 2 through AHP. For this purpose, large-scale surveys were conducted with 5 public transportation experts.

The analysis steps consist of problem and criteria definition, the hierarchical structure establishment, pairwise comparison matrices establishment, the matrices normalization, the eigenvectors calculation, consistency ratio calculation, and global weights calculation. Excel software is used for calculating the weights in the AHP model from pairwise comparison matrices and entire analysis.

4.2. Expert Data for the Evaluation of PT Pricing Methods

A survey was prepared to evaluate four different public transportation pricing types with main and sub-criteria. Due to the Covid-19 restrictions, surveys were conducted with google forms. Questionnaires were created to understand the importance level of the main and sub-criteria of each other, and effect of alternatives on all criteria and select the best public transit pricing system.

The survey consists of four parts. The first part includes general information such as occupation, gender, experience, and expertise of the expert. The second part is oriented to measure the effect of alternatives on 4 main criteria. In the third part, questions are intended

to understand the effect of alternatives on 13 sub-criteria. The second and third parts were constituted to apply the CRITIC and MABAC based type-2 neutrosophic model. Hence, Likert type (7-point) scale was preferred for the first, second, and third parts. 5 experts are consulted to gather the scorings of each alternative under each criterion. The last part aims to establish the importance level of main and sub-criteria by the Analytic Hierarchy Process method. This part of the questionnaires is prepared according to the pairwise comparison matrices in an Excel file (See Figure 4.1.), and Saaty's (1990)'s 9-point scale is used. 5 experts are consulted to evaluate how much a criterion is more important than the others respectively. Public transportation experts are selected from the Rail System Department and Transportation Department of İzmir Metropolitan Municipality. All the experts are male and from the industry. Expert D1 expertises himself as a medium with 6 years of experience in the public transportation field. The other experts (D2, D3, D4, D5) define themselves respectively as good, medium, very good, and medium good with respectively 13,9,14,10 years experience. Details about surveys are given in Table 4.1. and Figure 4.1.

Table 4.1. The first, second, and third parts of the survey are in general terms.

Expert's	Occupation	Gender	Experience	Expertise
Evaluation part	**Alternatives:** Flat Fare (A1), Distance-based Fare (A2), Zonal Pricing (A3), Rent-based Fare (A4)		**Main Criteria**	
			Cost Aspect	
			Transportation Aspect	
			Social Aspect	
			Political Aspect	
			Sub-Criteria	
			Operating Cost (C1)	
			User Cost (C2)	
			Expert Cost (C3)	
			Travel Time (C4)	
			Travel Comfort (C5)	
			Switch to a Personal Vehicle (C6)	
			Personal Mobility (C7)	
			Environmental Cost (C8)	
			Life quality (C9)	
			Decentralization of cities (C10)	
			Public acceptability (C11)	
			Political success (C12)	
			Deployment of resources (C13)	

Factor	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Factor
Cost Aspect																		Transportation Aspect
Cost Aspect																		Social Aspect
Cost Aspect																		Political Aspect
Transportation Aspect																		Social Aspect
Transportation Aspect																		Political Aspect
Social Aspect																		Political Aspect
Operating cost																		User cost
Operating cost																		Expert cost
User cost																		Expert cost
Travel time																		Travel comfort
Travel time																		Swith to a personal vehicle
Travel time																		Personal mobility
Travel comfort																		Swith to a personal vehicle
Travel comfort																		Personal mobility
Swith to a personal vehicle																		Personal mobility
Environmental cost																		Life quality
Environmental cost																		Decentralization of cities
Life quality																		Decentralization of cities
Public acceptability																		Political success
Public acceptability																		Deployment of resources
Political success																		Deployment of resources

Figure 4.1. Comparison part of the survey.

4.3. Analytic Hierarchy Process

Decomposition, comparative judgments, and hierarchical synthesis of priorities are the three fundamental principles of AHP (Saaty, 1980). Analytical hierarchy process steps are as follows, respectively.

(i) The problem and criteria definition.

Goal and criteria used in decision-making are defined.

(ii) A hierarchical structure creation.

The principle of decomposition divides a complex problem into a hierarchy of criteria, main criteria, sub-criteria, and so on. It allows them to be configured in a hierarchy.

(iii) Pairwise comparison matrices creation.

Comparative judgments are created through pairwise comparison matrix tables between the main criteria and between the sub-criteria of each main criteria set, using Saaty's (1990) 9 point scale. These pairwise comparisons give the priority weights of the factors. In other words, they represent the importance of the factors.

Table 4.2. Saaty's (1990) 9 point scale.

Importance scale	**Definition of importance scale**
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2,4,6,8	Intermediate values between the two adjacent judgments

The principal diagonal contains entries of 1, as each factor is as important as itself. a_{ij} is the comparison of the i th criteria and the j th criteria. The a_{ji} value is the equivalent of $1/a_{ij}$

$$M = \begin{bmatrix} 1 & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} = 1/a_{1n} & \dots & 1 \end{bmatrix}.$$

(iv) Matrix normalization.

Each element is divided by its column sum and normalized by a given as

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \qquad i, j = 1,2,\ldots,n. \tag{4.1}$$

(v) Relative Value Vectors (RVV) calculation.

The sum of the normalized matrix rows is divided by the size of the matrix and averaged. Thus, importance weights are calculated for each criterion. These weights form the relative value vector. The Equation (4.2) is given below

$$w_i = \frac{1}{n} \sum_{i=1}^{n} a'_{ij} \qquad i, j = 1,2,\ldots,n. \tag{4.2}$$

(vi) Consistency rate calculation.

The Consistency Ratio (CR) value is used to determine the consistency of comparisons. If the CR value is less than 0.1, the comparison matrix is consistent. CR value is calculated as

$$CR = \frac{CI}{RI}. \tag{4.3}$$

The Consistency Index (CI) is calculated as

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4.4}$$

where λmax is the largest eigenvalue.

λmax is calculated as

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{\sum_{j=1}^{n} a_{ij} w_j}{w_i}. \quad (4.5)$$

Saaty's (1980) Random Consistency Index values are given in Table 4.3.

Table 4.3. Random Consistency Index.

Size of Matrix	RI
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.53
13	1.56
14	1.57
15	1.59

(vii) Global weights calculation.

Priority weights are divided into local priority weights and global priority weights. Local priorities represent the priority weights inside the sets. Global priority weights are calculated by multiplying the local priorities of sub-criteria by importance levels of belonged main criteria.

4.4. Analysis and Results

The 4 main criteria and 13 sub-criteria used are determined according to literature and the opinions of public transportation experts. The main criteria are Cost Aspect, Transportation Aspect, Social Aspect, and Political Aspects. The cost aspect is divided into 3 sub-criteria, Transportation aspect 4, Social aspect 3, and Political aspect 3 in itself. The hierarchical structure for the public transportation pricing system selection is given in Figure 4.2.

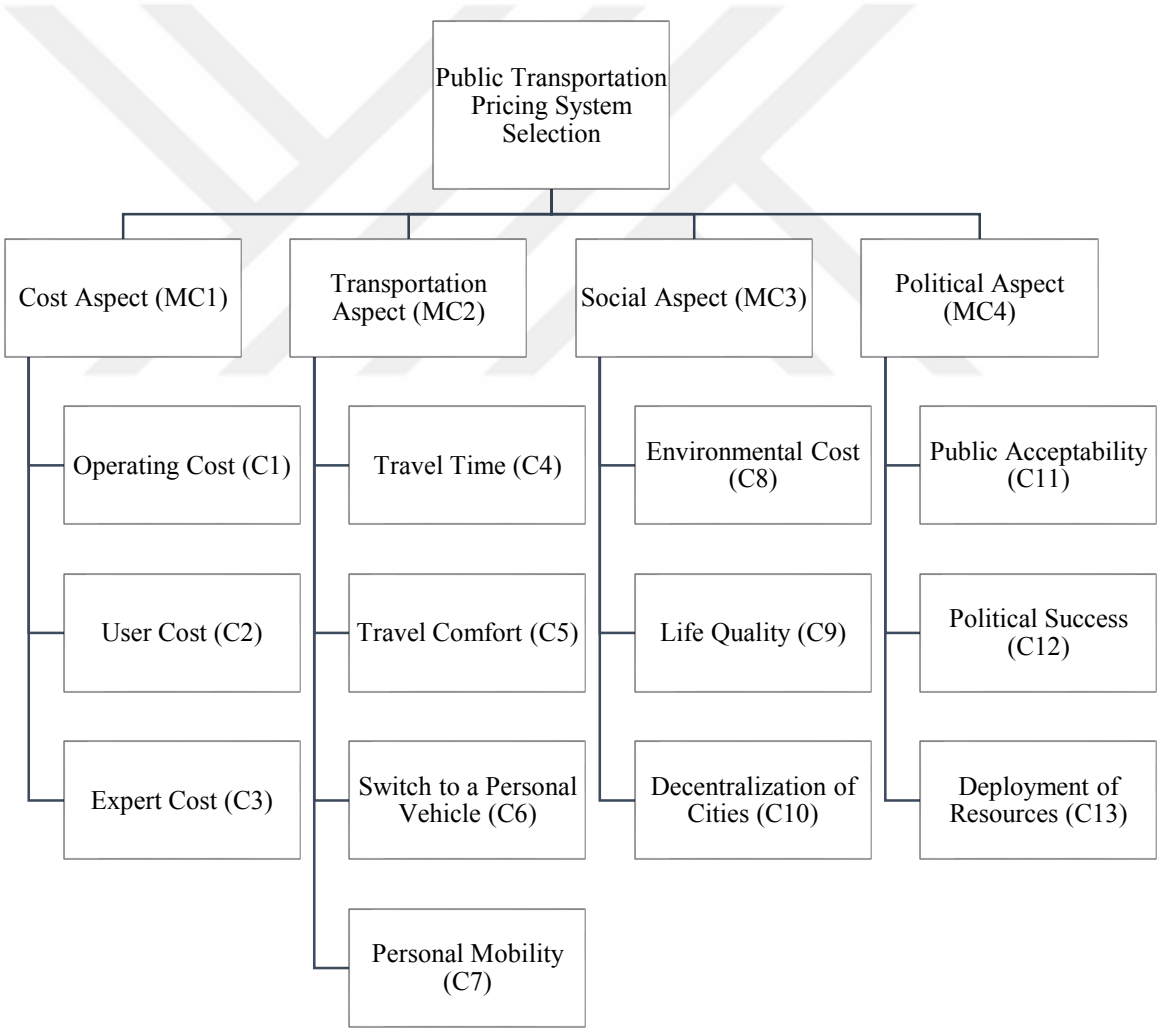

Figure 4.2. The hierarchy between criteria.

Pairwise comparisons are conducted according to the AHP importance scale given in Table 4.4. Comparison matrices are prepared with the geometric mean of the scores given by the 5 experts according to the importance scale. First, an initial matrix is provided. Then, other matrix cells are filled according to the comparison of each criterion with another and normalized. The eigenvectors or Relative Value Vectors (RVV) are calculated with Equation (4.2). Comparison matrices and RVV values are shown in Table 4.4., Table 4.5., Table 4.6., Table 4.7, and Table 4.8.

Table 4.4. Pairwise comparison of main criteria.

Main criteria	**MC1**	**MC2**	**MC3**	**MC4**	**RVV**
Cost aspect (MC1)	1.000	0.431	0.631	0.699	0.154
Transportation aspect (MC2)	2.320	1.000	2.091	1.783	0.400
Social aspect (MC3)	1.585	0.478	1.000	1.644	0.249
Political aspect (MC4)	1.431	0.561	0.608	1.000	0.197

According to the values in Table 4.4., the highest relative importance among the main criteria belongs to Transportation Aspect with a degree of 0.400 followed by Social Aspect with a degree of 0.249, Political Aspect with a degree of 0.197, and Cost Aspect with a degree of 0.154.

Table 4.5. Pairwise comparison of cost criteria.

Cost criteria	**C1**	**C2**	**C3**	**RVV**
Operating cost (C1)	1.000	3.022	0.850	0.386
User cost (C2)	0.331	1.000	0.215	0.117
Expert cost (C3)	1.176	4.644	1.000	0.496

Results in Table 4.5. show that the highest relative importance among the sub-criteria of cost aspect belongs to Expert Cost with a degree of 0.496, followed by Operating Cost with a degree of 0.386, and User Cost with a degree of 0.117.

Table 4.6. Pairwise comparison of transportation criteria.

Transportation criteria	**C4**	**C5**	**C6**	**C7**	**RVV**
Travel time (C4)	1.000	0.922	0.183	0.441	0.103
Travel comfort (C5)	1.084	1.000	0.220	0.488	0.115
Swith to a personal vehicle (C6)	5.471	4.536	1.000	2.426	0.550
Personal mobility (C7)	2.268	2.048	0.412	1.000	0.232

According to Table 4.6., Switch to a Personal Vehicle has the highest importance rate with 0.550 among transportation aspect sub-criteria. Personal Mobility follows with a degree of 0.232 and then, respectively, Travel Comfort with a degree of 0.115 and Travel Time with a degree of 0.103.

Table 4.7. Pairwise comparison of social criteria.

Social criteria	**C8**	**C9**	**C10**	**RVV**
Environmental cost (C8)	1.000	2.460	0.284	0.224
Quality of life (C9)	0.407	1.000	0.184	0.107
Decentralization of cities (C10)	3.519	5.448	1.000	0.669

The sub-criteria of Social Aspect in Table 4.7. are respectively Decentralization of Cities with a degree of 0.669, Environmental Cost with a degree of 0.224, and Quality of Life with a degree of 0.107, according to their relative importance.

Table 4.8. Pairwise comparison of political criteria.

Political criteria	**C11**	**C12**	**C13**	**RVV**
Public acceptability (C11)	1.000	2.605	1.888	0.515
Political success (C12)	0.384	1.000	0.506	0.176
Deployment of resources (C13)	0.530	1.974	1.000	0.308

According to the pairwise comparison Table 4.8. of political sub-criteria, Public Acceptability has the highest degree of importance with a rate of 0.515. It is followed by Deployment of Resources with a rate of 0.308 and Political Success with a rate of 0.176.

To determine the consistency of comparisons, the CR consistency value is calculated with Equation (4.3) for each group of main criteria and sub-criteria. If the CR value is less than 0.1, it is concluded that the judgment is reliable.

Table 4.9. Consistency results.

Factor	**N**	**λmax**	**CI**	**RI**	**CR**
MC1, MC2, MC3, MC4	4	4.04556	0.01519	0.9	0.01687
C1, C2, C3	3	3.00796	0.00398	0.58	0.00758
C4, C5, C6, C7	4	4.00125	0.00042	0.9	0.00046
C8, C9, C10	3	3.02396	0.01198	0.58	0.02066
C11, C12, C13	3	3.0143	0.00715	0.58	0.01232

The decision hierarchy is shown with local and global priorities in Table 4.10. According to 5 transportation authorities, Switch to a personal vehicle is the most important criteria for public transportation pricing system selection with a rate of 22.004%. Decentralization of cities follows with 16.651%, and Public acceptability with 10.157%. Ordering of all criteria is C6>C10>C11>C7>C3>C13>C1>C8>C5>C4>C12>C9>C2.

Table 4.10. Local and global priorities.

Main Criteria	RVV	Sub-Criteria	Local Priorities	Global Priorities
Cost Aspect (MC1)	0.154	Operating cost (C1)	0.386	5.935
		User cost (C2)	0.117	1.800
		Expert cost (C3)	0.496	7.624
Transportation Aspect (MC2)	0.400	Travel time (C4)	0.103	4.126
		Travel comfort (C5)	0.115	4.620
		Switch to a personal vehicle (C6)	0.550	22.004
		Personal mobility (C7)	0.232	9.293
Social Aspect (MC3)	0.249	Environmental cost (C8)	0.224	5.580
		Life quality (C9)	0.107	2.653
		Decentralization of cities (C10)	0.669	16.651
Political Aspect (MC4)	0.197	Public acceptability (C11)	0.515	10.157
		Political success (C12)	0.176	3.476
		Deployment of resources (C13)	0.308	6.080

4.5. Discussion

In the study, 5 public transportation experts are chosen as decision-makers. Because it is important to understand the process from the operators' point of view to ensure sustainable transportation. Many studies have caused transportation pricing systems to impose financial and environmental burdens, considering only the user benefit. However, the priorities of the users and the operators are different. For example, operators place more importance on travel comfort than travel time, according to AHP analysis. However, users give more importance to travel time with a considerable amount than travel comfort, according to passenger data analysis (see Figure 3.6.). Such differences are common, but many criteria should be evaluated together in selecting the pricing system from a wider perspective, as in this study. For this purpose, 4 main criteria and 13 sub-criteria related to transportation pricing systems have been determined.

In the study, the AHP method in determining the priority of the criteria is preferred since it is easy to calculate, understandable, can evaluate qualitative features, provide the opportunity to progress systematically, and control consistency. The expertise of public

transportation experts in the terminology creates an advantage in understanding the criteria and making comparisons, but the inclusion of many sub-criteria for the evaluation makes it difficult to score.

According to the results, it is seen that the experts give the most importance to Transportation Aspect in the selection of public transportation pricing. Social Aspect comes right after, and the Political Aspect and Cost Aspect are close to each other. When global priorities are evaluated, Switch to a Personal Vehicle is the top priority criteria. It is followed by Decentralization of Cities and Public Acceptability. The rankings are substantially parallel with the order of importance achieved by the Criteria Importance Through Intercriteria Correlation (CRITIC) method. Switch to a Personal Vehicle has the highest level of importance since the burden of each vehicle in traffic is a huge cost to the society and cities, and traffic is the most fundamental problem for transportation today. Decentralization of the Cities is significantly ahead of other criteria, since the various disadvantages that growing cities bring to both transportation and life. The results reveal that the public transportation pricing system should be evaluated more broadly and interdisciplinary beyond ticket tariff or user costs.

The limitation of the study is that it was carried out only through IZBAN. Preference differences can be investigated by conducting similar studies for different transportation systems. Other studies can be developed using AHP, CRITIC, or a different Multi-Criteria Decision Making method and inclusion of different criteria.

5. AN INTEGRATED CRITIC AND MABAC BASED TYPE-2 NEUTROSOPHIC MODEL FOR PUBLIC TRANSPORTATION PRICING SYSTEM SELECTION

5.1. Introduction

Public transportation is one of the most effective solutions for dealing with road traffic congestion, which has become a severe problem especially for developing countries all around the world (Jain et al., 2012). The continuing increase in world population has increased and is still increasing the number of private vehicles in traffic. Environmental pollution associated with this increase is a growing problem of humanity overall. To mitigate the increase in private vehicles, the levels of congestion, and the pollution caused by private vehicle usage, the incentivization of public transportation is an important aspect. However, while promoting the usage of public transportation vehicles, there are things that authorities must decide on such as the pricing of the public transportation systems.

While deciding on the pricing system, the decentralization of the cities must be taken into consideration. If the public transportation network is covering the outer-city parts, people work in the inner-city and live at lower rent houses in the outer-city, since transportation between home and work is available via public transportation. This creates a decentralization problem by expanding the city to outer ranges. As the city expands, the lengths of the public transportation lines increase, which puts an additional operating cost on operators due to frequent maintenance needs and increases air pollution because of the larger travel times of the vehicles. However, a distance-based, rent-based, or zone-based pricing system increases the financial burden of transportation on the people traveling for longer lines, which eventually motivates them to choose their residence close to their work and social environment. This mitigates the decentralization of cities and shortens the lines of public transportation trips, which reduces the operating costs of the vehicles and also is an environmentally friendly outcome (Gaigné et al., 2012).

Determination of the pricing system must be dealt with carefully because public acceptance and welfare of the public transportation commuters is an important aspect for municipalities. If a distance-based pricing system is applied and demands are lowered, the frequency of the public transportation lines is to be lowered to compensate for the operating costs. This increases the waiting times of the commuters and reduces the level of satisfaction (Cantwell et al., 2009). If a flat fare pricing system is applied, decentralization of the city is a potential problem to be faced and longer lines are to be increased. This has the potential to increase the crowdedness of the longer lines, which again reduces the satisfaction level of the commuters and also decreases sustainability due to more greenhouse gas emissions.

5.1.1. Objectives of the Study

In this study, the critical worldwide problem of public transportation pricing system selection is for the first time comprehensively addressed and solved in this study. Flat fare, distance-based, zonal, and rent-based pricing systems are defined. To prioritize these alternatives, four aspects are determined, namely cost, transportation, social and political. Thirteen evaluation criteria are identified and briefly defined under these aspects. Studies in the literature were used to determine the criteria. A case scenario is constructed to create an environment for experts to efficiently assess the public transportation pricing systems.

This study aims to help municipalities to compare and improve their public transportation pricing systems by providing a straightforward and flexible decision-making tool. Thus, the study suggests a hybrid two-stage type-2 neutrosophic model is developed to solve the addressed multi-criteria decision-making (MCDM) problem. The first stage determines the reputation of experts under the type-2 neutrosophic number (T2NN) environment by making the trade-off between their experience and expertise. In the second stage, the novel T2NN-based CRiteria Importance Through Intercriteria Correlation (CRITIC) method is employed to evaluate the criteria importance, while the new T2NN-based Multi-Attributive Border Approximation area Comparison (MABAC) method is used to rank the public transportation pricing systems.

5.1.2. The Motivation for Using Type-2 Neutrosophic Numbers

The fuzzy set theory is based on the concept of membership function value by considering linguistic variables. This theory tries to evaluate ambiguous data with expert opinions and matches evaluations with membership function values. However, it is not always the case that expert opinions focus on membership values, especially when there is a lack of experience and expertise. Besides, the experts can be confident about the falsity of their opinions rather than their truthiness (Tiwari and Kumar, 2020). Smarandache (1998, 2003) introduced the neutrosophic set theory to resolve these real-life decision-making situations. Neutrosophic sets are an extension of the fuzzy theory and intuitionistic fuzzy set (IFS). Neutrosophic numbers have proven to be a valid field of study for identifying incompatible and indefinite information. Type-1 neutrosophic numbers are represented in the form of a triplet (T, I, F), where all T, I, and F are from a range [0, 1]. They are called a membership or truth value (T), neutral value or indeterminacy (I), and non-membership or falsehood value (F), respectively. T2NN is represented in the form $<(T_T, T_I, T_F), (I_T, I_I, I_F), (F_T, F_I, F_F)>$; i.e., each neutrosophic component is split into its truth, indeterminacy, and falsehood subparts. T2NN represents an advanced type of neutrosophic technique. It is an efficient tool to deal with experts' impreciseness or incompleteness (Abdel-Basset et al., 2019). Unfortunately, no previous research provided a T2NN-based model to evaluate transportation pricing systems.

5.1.3. The Motivation for Using CRITIC and MABAC Methods

The CRITIC and MABAC methods are extended under the T2NN environment to calculate the importance of evaluation criteria and rank the alternative public transportation pricing systems, respectively. The CRITIC method was developed by Diakoulaki et al. (1995) to determine objective weights considering the differences and correlations among various criteria simultaneously (Lai and Liao, 2021). Although many MCDM approaches used the CRITIC method in recent years, its extension into the T2NN environment is still missing.

On the other hand, the MABAC method is an exceptional MCDM method introduced by Pamučar and Ćirović (2015). The MABAC method is a reliable tool for rational decision-making (Gigović et al., 2017). It comprehensively considers the potential values of gains and losses (Büyüközkan et al., 2021). One of the main principles of the MABAC method is the distance between each alternative and the border approximation area (Büyüközkan et al., 2021; Liu et al., 2020b). The calculation process of this method is forthright, logical, and methodical (Luo and Liang, 2019). The MABAC method has been extended under various uncertain environments, such as interval 2-tuple linguistic (Shi et al., 2017), the hesitant fuzzy linguistic term (Sun et al., 2018), single-valued neutrosophic (Peng and Dai, 2018), single-valued neutrosophic linguistic (Ji et al., 2018), 2-tuple linguistic neutrosophic (Wang et al., 2019b), linguistic neutrosophic (Luo and Liang, 2019; Luo and Xing, 2019), bipolar fuzzy (Liu et al., 2020b), bipolar neutrosophic (Rahim et al., 2020), fuzzy neutrosophic (Pamucar et al., 2020), linguistic distribution assessment (Liang et al., 2020), normal wiggly hesitant fuzzy linguistic term (Liu et al., 2020a), picture 2-tuple linguistic (Zhang et al., 2020), probabilistic single-valued neutrosophic hesitant fuzzy (Şahin and Altun, 2020), the probabilistic uncertain linguistic term (Wei et al., 2020), Z number (Fan et al., 2020; Shen et al., 2020), normal wiggly hesitant fuzzy (Liu and Zhang, 2021), and rough plithogenic (Abdel-Basset et al., 2021). Unfortunately, this innovative MCDM has not been extended before under the T2NN environment.

5.1.4. Contributions of the Study

The contributions of this study to the present body of knowledge are as follows:

(i) Defined alternatives and evaluation criteria offer a practical decision-making framework for municipalities to compare and improve their public transportation pricing systems.

(ii) Unlike other decision-making approaches for transportation pricing, this study uses advanced T2NNs to improve the recognition of information uncertainties in selecting public transportation pricing systems thus providing a more accurate prioritization.

(iii) This is the first study that proposes an integrated methodological framework under T2NNs. Also, the CRITIC and MABAC methods are for the first time extended under the T2NN environment to provide a new perspective as well as an effective tool for researchers and practitioners.

(iv) A case scenario of İzmir, Turkey, confirms the effectiveness of our model in the real-world context. Its findings indicate the rent-based fare system as the most advantageous alternative. This unique pricing system makes cities eventually more compact and solves the problem of unfairness by eliminating the need for long public transportation lines.

(v) Even though this study is devoted to transportation pricing, our integrated CRITIC and MABAC based type-2 neutrosophic model can be used to solve various decision-making problems such as supply chain management, business management, construction management, healthcare management, and so on.

This chapter is structured: Section 2 provides a review of related state-of-the-art research. Section 3 defines the investigated problem. Section 4 presents the developed hybrid type-2 neutrosophic model for public transportation pricing. Section 5 provides the results and discussion.

5.2. Literature Review

The literature review is organized into three sub-sections. The first sub-section overviews decision-making approaches for transportation pricing. The second sub-section surveys the MABAC method. The third sub-section highlights major research gaps.

5.2.1. Decision-Making Approaches for Transportation Pricing

Public transportation is used by many people today. The widespread use of public transportation has been a priority for the administrations for people to have mobility. Today,

global warming threatens the existence of all living things and affects the environment negatively because of the gases and pollutants released into the environment due to transportation activities. Encouraging people to use public transportation will play a role in reducing both the traffic density in cities and the gas emissions that cause global warming and air pollution. Besides these, it is more economical for people who take an active role in transportation to prefer public transportation. Public transportation pricing has different methods such as flat fare, distance-based fare, zonal pricing, and rent-based fare.

A flat fare is one of the most widely implemented pricing in public transportation. There is a fixed price for all users since the fee is not dependent on the duration of use and distance. Nuworsoo et al. (2009) analyzed the five options flat fare proposals of Alameda-Contra Costa Transit Districts including base fare reductions, fare hikes, discontinuation of periodic passes, and eliminations of free transfers. They evaluated the effects of individual flat fare offerings on different subsets of different riders and investigated and estimated likely flat revenues. They found out that the five alternative proposals of Transit Districts that raised the cost of the transfers or removed unlimited-use passes caused inequity on certain riders. Flat fares proposals are found to be least fair since young commuters, minorities, and lower-income riders made more trips. Cheng et al. (2015) examined the unit fare, farebox recovery ratio, and unit cost in terms of indexes of fare equity. They used the Gini coefficient and theory of the Lorenz curve to implement the equity evaluation of unit fares distribution among the public transportation users. They used the established methods and indexes to assess fare equity and observed that flat fare is unfair. Brown (2018) analyzed the frequency of transit use via lower and higher-income transit riders based on six evaluated fare structures in Los Angeles. They found low-income public transportation users pay far higher per-mile transit fares compared to more wealthy users. Jin et al. (2019) examined the relationship between flat fares and the quality of public transport service. They observed that with higher flat fares, operators have more sources to supply a better service focusing on flat fare structure. Rubensson et al. (2020) use the socio-economic statistics of census areas with public transportation modes data from a transport estimation representation to evaluate the distributional and geographical fairness of alternative fare plans which are flat fare, zone-based, and distance-based in Stockholm Public Transportation. They revealed high-income

public transit riders benefit from all three fare schemes reviewed. These riders benefit the least from flat fares.

Distance-based fare determines the relationship between the amount of payment and trip distance. Since the operating costs of public transportation vehicles are directly proportional to the lengths of the routes, this pricing method becomes preferable by the authorities when the lengths of the routes are long, and hence operating costs are high. Tsai et al. (2008) offered an optimization perspective, maximizing total profit depending on fleet size and service capacity, for an intercity transportation system where demand for public transportation is sensitive to fare and travel time. They developed an efficient solution and applied it to the profit maximization problem. Farber et al. (2014) aimed to develop and apply a new procedure for evaluating the social equity effects of distance-based public transit fares. They showed that distance-based fares affect low-wealth, non-white and elderly populations. Hoshino and Beairsto (2018) proposed two-part optimal pricing for changing to distance-based transit fares. The first was to maximize the estimated revenue given a target ridership, and the second was to maximize the estimated ridership given a target revenue. They tested their model successfully on the SkyTrain mass transit network in Metro Vancouver, British Columbia, with over 400.000 public transportation users. Maidi and Schmöcker (2020) exemplified the effects of switching fares from a zonal to a distance-based structure. They took the zonal case as a base model and examined the effects of fare/km and consisting of non-additive fares. Chen et al. (2021) assessed a distance-based preferential fare project for park and ride services in a multichannel transport network. They also examined the choice of passengers that prefer park and ride mode to get a discount. Their analysis proved that the proposed distance-based fare scheme may motivate public transportation travelers to use park-and-ride services and develop the performance of the transport network.

Zonal pricing is one of the public transportation payment methods that can be implemented in big cities like London. The amount of payment is independent of the distance and depends on whether the trip changes a zone boundary. If the user has not changed the zone, he pays the standard fee, but if the user has changed the zone, the user pays a part of the transition fee to that zone beside the standard fee. Rouhani (2018) formulated the three

basic extensions of the analysis of standard optimal road use: maximizing the social welfare outside and inside of the congestion zone, examining the fuel and emissions variable costs, and travel demand variations focusing on zonal pricing. They observed that the effects of emission costs are significant, the examination over predicts the optimal toll rate and may even cause a social income loss, and policymakers should keep away from implementing a flat daily charge. Yuan and Hesamzadeh (2016) offered to design zonal pricing in a dispensation network based on the concept of pricing equivalence. They obtained the rules of zonal pricing and demonstrated the equivalent load move from demand response can be accessible via zonal pricing in case pricing equivalence is positioned. It is seen that zonal pricing planned according to pricing equivalence may attain the same load shift effects and quite close consumer discharges.

Because of high rents in places of work, employees can stay in other locations where rents are lower. Since the places with lower rents are far from workplaces, they can reach their workplaces either by personal vehicles or by using public transportation. Commuters who use public transportation, for this reason, come from outside of the city, causing increased traffic in the city and larger travel time of vehicles. To prevent the city from decentralization, the rent-based fare can be applied and commuters coming from outside of the city are charged with more public transportation fees. Here, the increase in the cost of transportation may cause the person to move from outside of the city to the city, and therefore, the operation cost of public transportation may decrease. In Melbourne, Australia, one study applied a survey of participants with and without travel plans, and propensity score matching to see how their own housing choices could be assessed in the context of trip plans (De Gruyter et al., 2016). According to the findings, residents in settlements with travel plans 213 own fewer cars as well as walk and cycle more frequently than residents in settlements 214 without a travel plan. Zhang (2020) started a housing valuation model to discover the interface relation between transit rail and other transport modes. He also got the family transportation impedance, forming a relationship between the distance of house to city and public transportation. Results showed that users of public transportation who have higher income will choose the residence close to districts. Results also showed that having urban rail transit has a key role effect on the low-income family.

Table 5.1. Survey of the available decision-making approaches for transportation pricing.

Author(s) and year	Research focus	GDM	Discussed pricing types	SA	CA	Method(s)	Application	
							Country	Type
Tsai et al. (2008)	Optimizing distance-based fares and headway of an intercity transportation system	No	DBF	Yes	Yes	Modified Gauss-Southwell method	Taiwan	Real-life
Nuworsoo et al. (2009)	Analyzing equity impacts of transit fare changes	No	FF	Yes	Yes	Alternative price elasticities	California, USA	Real-life
Farber et al. (2014)	Assessing social equity in distance-based transit fares	No	FF, DBF	No	Yes	Joint ordinal/continuous model for trip generation, GIS	Utah, USA	Real-life
Cheng et al. (2015)	Assessing equity of regular public transit fare policy	No	FF	No	No	Lorenz curve, Gini coefficient	-	Literature
De Gruyter et al. (2016)	Measuring self-selection effects	No	RBF	No	No	Case and control sites	Melbourne, Australia	Real-life
Yuan and Hesamzadeh (2016)	Implementing zonal pricing in the distribution network	No	ZF	No	Yes	Long-run incremental cost pricing, Forward cost pricing	-	Literature
Brown (2018)	How flat and variable fares affect transit equity	No	FF, DBF	No	Yes	Bonferroni correction	Los Angeles, USA	Real-life
Hoshino and Beairsto (2018)	Optimal pricing for distance-based transit fares	No	ZF, DBF	No	Yes	Two-part optimal pricing formula	Vancouver, Canada	Real-life
Rouhani (2018)	Standard zonal congestion pricing	No	ZF	Yes	No	Standard optimal road use	California, USA	Real-life

Table 5.1. Survey of the available decision-making approaches for transportation pricing (Cont.).

Author(s) and year	**Research focus**	**GDM**	**Discussed pricing types**	**SA**	**CA**	**Method(s)**	**Application**	
							Country	**Type**
Jin et al. (2019)	The interaction between public transport demand, service quality, and fare for social welfare optimization	No	FF	Yes	Yes	Daganzo's model	-	Literature
Maidi and Schmöcker (2020)	Route choice effects of changes from a zonal to a distance-based fare structure	No	ZF, DBF	No	Yes	Frequency-based assignment approach	-	Literature
Rubensson et al. (2020)	Equity impact of fare scheme change	No	FF, DBF, ZF	No	Yes	Transport forecast model, socio-economics statistics	Stockholm, Sweden	Real-life
Zhang (2020)	Relationship between urban rail transit and residential location	No	RBF	No	No	Housing valuation model	-	Literature
Chen et al. (2021)	Distance-based preferential fare scheme for park-and-ride services in a multimodal transport network	No	DBF	No	Yes	Multimodal transport network equilibrium model, multinomial logit discrete choice model	-	Literature
Our study	*Public transportation pricing system selection*	*Yes*	*FF, DBF, ZF, RBF*	*Yes*	*Yes*	*Hybrid type-2 neutrosophic model, CRITIC, MABAC*	*İzmir, Turkey*	*Real-life*

Comparative Analysis: CA, CRiteria Importance Through Intercriteria Correlation: CRITIC, Distance-Based Fare: DBF, Flat Fare: FF, Geographic Information System: GIS, Group Decision-Making: GDM, Multi-Attributive Border Approximation area Comparison: MABAC, Rent-Based Fare: RB, Sensitivity Analysis: SA, Type-2 Neutrosophic Number: T2NN, Zonal Fare: ZF.

5.2.2. MABAC Method

The MABAC method has become very influential in decision-making. Table 5.2. comprehensively surveys this well-known MCDM method.

Pamučar and Ćirović (2015) prioritized forklift types that are used in logistics centers to make investment decisions. Delice and Can (2017) examined potential failure modes of a high voltage assembly line in electro-mechanic system manufacturing firms. Gigović et al. (2017) ranked locations for the installation of wind farms. Shi et al. (2017) formulated an interval 2-tuple linguistic MABAC method to explore appropriate treatment technologies for healthcare waste management.

Chatterjee et al. (2018) developed a D number-based MABAC method to order construction risk response strategies for construction projects. Ji et al. (2018) provided a single-valued neutrosophic linguistic MABAC method to solve the outsourcing provider selection problem in the information technology (IT) industry. Peng and Dai (2018) introduced a single-valued neutrosophic MABAC method to compare computer books as well as air-conditioning systems. Sun et al. (2018) presented a hesitant fuzzy linguistic term MABAC method to prioritize hospital patients.

Adar and Delice (2019) studied treatment technologies for healthcare waste flow. Luo and Liang (2019) coped with the problem of ranking roadway support schemes in gold mines. Luo and Xing (2019) proposed a linguistic neutrosophic MABAC method to solve the personnel selection problem in IT companies. Wang et al. (2019a) examined collection modes for used parts of construction machinery. Wang et al. (2019b) proposed a 2-tuple linguistic neutrosophic MABAC method to perform the safety assessment of construction projects.

Fan et al. (2020) focused on the selection of the best third-party logistics (3PL) provider. Liang et al. (2020) formulated a linguistic distribution-based MABAC method to

solve the emergency evacuation management problem. Liu et al. (2020a) suggested a normal wiggly hesitant fuzzy linguistic term MABAC method to evaluate the ecological security situation of coastal areas. Liu et al. (2020b) introduced a bipolar fuzzy MABAC method to prioritize occupational health and safety risks on construction sites. Pamucar et al. (2020) developed a fuzzy neutrosophic MABAC method to identify the most resilient supplier for construction companies. Rahim et al. (2020) presented a bipolar neutrosophic MABAC method to solve the sustainable energy management problem. Roy et al. (2020) studied the 3PL provider selection process in the food manufacturing industry. Shen et al. (2020) extended the MABAC method under the Z-information to rank regional development programs related to the circular economy. Şahin and Altun (2020) proposed a probabilistic single-valued neutrosophic hesitant fuzzy MABAC method to select the best investment company. Wei et al. (2020) developed a probabilistic uncertain linguistic term MABAC method to solve the green supplier selection problem in the furniture industry. Zhang et al. (2020) introduced a picture 2-tuple linguistic MABAC method for ranking renewable energy power generation projects.

Recently, Abdel-Basset et al. (2021) formulated the MABAC method based on plithogenic sets and rough numbers to solve the supplier selection problem in the healthcare industry. Büyüközkan et al. (2021) investigated strategies for health tourism development. Hristov et al. (2021) compared automatic cannon weapon systems designed for integration into combat vehicles. Jana and Pal (2021) focused on the selection of road construction companies. Liu and Zhang (2021) stated a normal wiggly hesitant fuzzy MABAC method to assess suppliers for university libraries. Pamučar et al. (2021) compared equipment for disinfecting medical waste flow.

5.2.3. Research Gaps

According to the literature review, the research gaps are as follows:

(i) This is the first work to address and solve the public transportation pricing system selection problem, as can be seen from Table 5.1. Previously, public transportation pricing systems have not been systematically and objectively explored and prioritized. Besides, a practical decision-making framework for municipalities to compare and improve their public transportation pricing systems is still missing since the earlier research efforts failed to comprehensively address and define viable alternatives as well as evaluation aspects and criteria. Also, the available decision-making (Table 5.1.) could generate wrong pricing decisions since they are unable to deal with experts' impreciseness or incompleteness.

(ii) The T2NN-based technique for the order preference by similarity to ideal solution (TOPSIS) method introduced by Abdel-Basset et al. (2019) is the only available decision-making approach under the T2NN environment in the literature. This method is unable to differentiate expert reputation, determine criteria importance, and provide higher flexibility when making decisions.

(iii) The MABAC method has neither been extended under the T2NN environment nor been applied for transportation pricing, as can be seen from Table 5.2. Besides, no earlier work has integrated the CRITIC and MABAC methods into a single methodological framework (Table 5.2).

Table 5.2. Survey of the MABAC method.

Author(s) and year	Research focus	GDM	Parameter type	SA	CA	Combined method(s)	Application		Criteria	Alt.
							Country	Type		
Pamučar and Ćirović (2015)	Machine tool selection	Yes	Crisp	Yes	Yes	DEMATEL	-	IE	10	7
Delice and Can (2017)	Failure mode prioritization	Yes	Random, Crisp	No	Yes	FMEA, Brainstorming	-	IE	6	12
Gigović et al. (2017)	Wind farm location selection	Yes	Crisp, Fuzzy	Yes	Yes	GIS, DEMATEL, ANP	Serbia	Real-life	11	11
Shi et al. (2017)	Waste treatment technology selection	Yes	I2TL	Yes	No	-	China	Real-life	6	4
Chatterjee et al. (2018)	Construction project risk assessment	Yes	D number	Yes	Yes	ANP	-	IE	9	5
Ji et al. (2018)	3PL provider selection	Yes	SVNLT	No	Yes	MSD, ELECTRE	-	From lit.	6	5
Peng and Dai (2018)	-	No	SVN	No	Yes	-	-	IEs	5, 3	10, 5
Sun et al. (2018)	Hospital patient prioritization	No	HFLT	Yes	Yes	-	China	Real-life	6	8
Adar and Delice (2019)	Waste treatment technology selection	Yes	HFLT	Yes	Yes	MAIRCA	Turkey	Real-life	19	4

Table 5.2. Survey of the MABAC method (Cont).

Author(s) and year	Research focus	GDM	Parameter type	SA	CA	Combined method(s)	Application		Criteria	Alt.
							Country	Type		
Luo and Liang (2019)	Roadway support scheme selection	Yes	LN	Yes	Yes	GST, Direct rating	China	Real-life	4	4
Luo and Xing (2019)	Personnel selection	Yes	LN	No	Yes	BWM, PROMETHEE II	-	IE	9	4
Wang et al. (2019a)	Take-back pattern selection	No	Crisp, Grey	Yes	No	AHP, Shannon entropy	China	Real-life	9	3
Wang et al. (2019b)	Construction project selection	Yes	2TLN	No	Yes	-	-	IE	4	5
Fan et al. (2020)	3PL provider selection	No	Z number	No	Yes	Shannon entropy	-	IE	5	4
Liang et al. (2020)	Flood evacuation planning	Yes	LDA	Yes	Yes	-	-	IE	5	4
Liu et al. (2020a)	Ecological security assessment	Yes	NWHFLT	Yes	Yes	Maximizing deviation	-	IE	6	5
Liu et al. (2020b)	Occupational hazard risk assessment	Yes	BF	No	Yes	SWARA	-	IE	3	12
Pamucar et al. (2020)	Resilient supplier selection	Yes	FN	Yes	Yes	Pairwise comparison	Spain	Real-life	12	8

Table 5.2. Survey of the MABAC method (Cont).

Author(s) and year	Research focus	GDM	Parameter type	SA	CA	Combined method(s)	Application		Criteria	Alt.
							Country	Type		
Rahim et al. (2020)	Sustainable energy selection	Yes	BNN	No	Yes	-	Malaysia	Real-life	14	7
Roy et al. (2020)	3PL provider selection	Yes	IVFR	Yes	Yes	FARE	India	Real-life	15	6
Shen et al. (2020)	Development program selection	No	Z number	Yes	Yes	Standard deviation	-	IE	8	5
Şahin and Altun (2020)	Investment project selection	No	PSVNHFS	No	Yes	-	-	From lit.	3	4
Wei et al. (2020)	Supplier selection	Yes	PULT	No	Yes	Shannon entropy	-	IE	5	4
Zhang et al. (2020)	Power generation project selection	Yes	P2TL	No	Yes	-	-	IE	4	5
Abdel-Basset et al. (2021)	Supplier selection	Yes	RP	No	No	BWM	Malaysia	Real-life	9	5
Büyüközkan et al. (2021)	Tourism strategy selection	Yes	HFLT	No	Yes	SWOT, AHP	Turkey	Real-life	24	8
Hristov et al. (2021)	Weapon system selection	Yes	D number	Yes	No	LBWA	-	IE	7	9

Table 5.2. Survey of the MABAC method (Cont).

Author(s) and year	**Research focus**	**GDM**	**Parameter type**	**SA**	**CA**	**Combined method(s)**	**Application**		**Criteria**	**Alt.**
							Country	**Type**		
Jana and Pal (2021)	Construction company selection	No	SVN	Yes	Yes	-	India	Real-life	5	4
Liu and Zhang (2021)	Supplier selection	Yes	NWHF	Yes	Yes	CCSD	China	Real-life	5	4
Pamučar et al. (2021)	Disinfection facility selection	Yes	D number	Yes	No	BWM	B&H	Real-life	18	6
Our study	*Public transportation pricing system selection*	*Yes*	*T2NN*	*Yes*	*Yes*	*CRITIC, MABAC*	*Turkey*	*Real-life*	*13*	*4*

2-Tuple Linguistic Neutrosophic: 2TLN; Analytic Hierarchy Process: AHP; Analytic Network Process: ANP; Best Worst Method: BWM; Bipolar Fuzzy: BF; Bipolar Neutrosophic Number: BNN; Bosnia and Herzegovina: B&H; Comparative Analysis: CA; Correlation Coefficient and Standard Deviation: CCSD; CRiteria Importance Through Intercriteria Correlation: CRITIC; DEcision MAking Trial and Evaluation Laboratory: DEMATEL; ELimination Et Choix Traduisant la Realite: ELECTRE; FActor RElationship: FARE; Failure Mode and Effect Analysis: FMEA; Fuzzy Neutrosophic: FN; Geographic Information System: GIS; Gray System Theory: GST; Group Decision-Making: GDM; Hesitant Fuzzy Linguistic Term: HFLT; Illustrative Example: IE; Interval 2-Tuple Linguistic: I2TL; Interval-Valued Fuzzy-Rough: IVFR; Level Based Weight Assessment: LBWA; Linguistic Distribution Assessment: LDA; Linguistic Neutrosophic LN; Mean-Squared Deviation: MSD; Multi-Attributive Border Approximation area Comparison: MABAC; Multi-Attributive Ideal-Real Comparative Analysis: MAIRCA; Normal Wiggly Hesitant Fuzzy Linguistic Term: NWHFLT; Normal Wiggly Hesitant Fuzzy: NWHF; Picture 2-Tuple Linguistic: P2TL; Preference Ranking Organization METHod for Enrichment of Evaluations: PROMETHEE; Probabilistic Single-Valued Neutrosophic Hesitant Fuzzy: PSVNHFS; Probabilistic Uncertain Linguistic Term: PULT; Rough Plithogenic: RP; Sensitivity Analysis: SA; Single-Valued Neutrosophic Linguistic Term: SVNLT; Single-Valued Neutrosophic: SVN; Step-wise Weight Assessment Ratio Analysis: SWARA; Strengths, Weaknesses, Opportunities, and Threats: SWOT; Third-Party Logistics: 3PL.

5.3. Problem Definition

There are many systems for public transportation pricing. However, each of these systems has certain superiorities to others based on the situation that they are used in. There is still a gap for effectively prioritizing these systems systematically and objectively.

5.3.1. Case Scenario

Pricing of public transportation services needs to be considered regarding various aspects of a city such as mobility, decentralization, and environmental issues. Since this study concentrates on the pricing of public transportation, a case scenario is to be formed to illustrate the conceptual framework, so that solid results and policy implications can be achieved.

In choosing our case scenario, we select a big metropolitan city in a developing country in which a new pricing system for public transportation is planned. The municipality of the city is ready to take action; however, it is required to prioritize the pricing systems. By doing thorough research on the literature, decentralization of cities, compact cities, satisfaction of commuters, improvements of shorter public transportation lines, and environmentally friendly public transportation are seen to be the concepts that should be included in the created case scenario. That is why the alternatives present in the following section are determined as the pricing methods to be assessed on the created case scenario. Experts, whose reputations are also integrated into the analysis, are gathered to observe the relative importance of each criterion and assess the alternatives.

5.3.2. Alternatives

(i) Alternative 1 (A_1): Flat fare pricing.

One of the public transportation pricing systems handled in this study is flat fare pricing. This pricing alternative makes up for all passengers, regardless of distance traveled, zone, and rent, to pay the same price for public transportation. Implementation and control of flat fare pricing are relatively easier and do not create confusion among passengers because of the simplicity of the alternative.

(ii) Alternative 2 (A_2): Distance-based fare pricing.

Implementation of a distance-based fare pricing system aims to make passengers who travel for longer distances pay more since these passengers use the transits more than others. Also, public transportation vehicles, which travel for longer lines, need more frequent maintenance and their operational costs increase. Charging passengers, who travel for longer distances provides equality between public transportation users (Bandegani and Akbarzadeh, 2016).

(iii) Alternative 3 (A_3): Zonal pricing.

In this alternative, public transportation passengers are charged according to the number of zones that they travel through. The application of zonal pricing has the potential to provide equality in terms of meeting the operational expenses accompanied to longer lines by charging passengers of long public transportation lines higher because of more zones traveled. One disadvantage of this alternative is that if the prices of zones are different, decentralization of the city can take place.

(iv) Alternative 4 (A_4): Rent-based fare pricing.

The rent-based fare proposed by this thesis is a rail mass public transit pricing system developed by using a nonlinear optimization model which includes rental costs. Avoiding the decentralization due to people working in cities, but living off-cities to pay less rent is the primary reason behind this pricing system. Decentralization of a city increases the length of public transportation lines, expands the city, and brings more traffic load to urban roads, which is unwanted. By implementing this system, people would live closer to their social or work destinations and travel short distances. Operating costs of public transportation would be less because of having shorter lines. Unlike flat fare, the rent-based fare is based on the distance traveled and the rental prices. Clustered stations in rent-based fare differ from distance-based pricing in that ticket price in clusters is reliant on rent. In contrast to zonal pricing, rent-based pricing considers travel distance and rent.

5.3.3. Definition of Criteria

i) Cost Aspect

Operating cost (C_1): Operating costs are the set of expenses that includes some variable and fixed costs that cover operating the transportation system. Operating costs include a wide range of components from the energy consumption cost to labor, maintenance, and repair costs. Factors such as the frequency of public transportation trips and the lengths of lines directly affect the operating cost. As the number of trips and lengths of these trips increase, operating costs also increase.

User cost (C_2): User cost is defined as the cost to which passengers are exposed. User costs are divided into in-vehicle travel time cost, waiting time cost, access, egress time, and ticket price (Chien and Schonfeld, 1998; Samanta and Jha, 2011; Almujibah and Preston, 2019). User costs and operating costs are always in conflict. Reducing user costs increase operating cost, the acceptance of the fare system, the demand for public transportation, and the life quality of people. However, ensuring this situation entirely with low-ticket prices

may reduce in-vehicle comfort, depending on high demand. The low user cost makes the system more attractive.

Expert cost (C_3): Some of the public transport pricing systems require special research. In this sense, it is necessary to get support from expert teams. Especially complex fare systems are in this scope. Decision-makers can observe which pricing system brings additional costs.

ii) Transportation Aspect

Travel time (C_4): Travel time of public transportation vehicles increases directly proportional to the lengths of the lines. As the travel times increase, operating costs of the vehicles also increase by more frequent maintenance needs and fuel consumption. Travel time of passengers comprises in-vehicle travel time, vehicle waiting time, and access and egress time. High-ticket tariffs can reduce the demand for public transportation. Here, public transportation frequency is reduced to meet the operational costs. Thus, as the waiting time increases, the travel time and the user cost increase. Less travel time is more attractive for users (Lisco, 1968).

Travel comfort (C_5): The travel comfort of passengers is a factor that highly affects the usage of public transportation (İmre and Çelebi, 2017). Travel comfort is affected notably by the demand for public transportation systems. Increasing demand for public transport by reducing ticket prices can negatively affect travel comfort. In systems that charge the passengers more, comfortable travel may become more possible with a decrease in demand. Therefore, the demand sourced by the transportation pricing system is very effective in terms of travel comfort.

Switch to a personal vehicle (C_6): When public transportation is not accessible and ticket prices are high, people switch to personal vehicles. This situation causes an increase in the number of vehicles in traffic and thus an increase in environmental pollution.

Personal mobility (C_7): Mobility is the ability of people to move from one place to another easily and freely. As the ticket prices increase, the demand for commuters towards public transportation decreases, which eventually decreases the frequency of public transportation trips. This will increase waiting times and negatively affect personal mobility. Providing better mobility to passengers provides a positive effect in terms of the preferability of the public transportation systems.

iii) Social Aspect

Environmental cost (C_8): This criterion deals with the environmental pollution associated with the public transportation system. Many factors are affecting pollution, such as public transportation trip frequency and lengths of the trips. As the public transportation trips concentrate on shorter lines, the environmental cost of the system reduces. The pricing system of public transportation is very effective to adjust the traveling behaviors of the commuters by increasing the prices of long lines of travel. A pricing system that causes less environmental pollution is always more attractive.

Life quality (C_9): The quality of life of public transportation commuters is highly affected by accessibility, travel times, travel comfort, and the price that they pay for tickets since it is a constant expense of public transportation users.

Decentralization of cities (C_{10}): The centralization of a city provides a good number of benefits in terms of both public transportation systems and general living conditions. As centralization-sensitive pricing is used in public transportation systems such as distance-based, rent-based, and zonal pricing, people live closer to their work and social environment. This shortens the lengths of transportation lines and reduces the operating costs of vehicles. Therefore, a pricing system that creates centralization in cities is more beneficial.

iv) Political Aspect

Public acceptability (C_{11}): This criterion is about the acceptability of the applied pricing system by the commuters. High prices are viewed negatively by passengers since it increases the financial burden related to transportation. Low pricing of tickets increases the demand, which eventually decreases the level of in-vehicle service, and passengers are most likely to not accept it. Therefore, the pricing system must be selected carefully.

Political success (C_{12}): This criterion refers to the success that municipalities will achieve for the sustainability of the implemented public transportation pricing policy and its acceptance by the public.

Deployment of resources (C_{13}): A system whose operating costs can be covered by the pricing system will no longer be a burden to the municipality and will even provide profit. Thus, both sustainability will be provided and resources for other investments will be created or existing resources will remain sufficient. A system where resources are used properly, and that makes a profit, is more attractive to both the operators and the public.

5.4. Methodology

This section gives some preliminaries and presents the hybrid type-2 neutrosophic model for public transportation pricing.

5.4.1. Preliminaries

Definition 1 (Abdel-Basset et al., 2019). Consider Y as the limited universe of discourse and $D[0, 1]$ as the set of all triangular neutrosophic sets on $D[0, 1]$. A type-2 neutrosophic number set (T2NNS) represented by $\tilde{M}$ can be defined in Y as an object having the form

$$\tilde{M} = \{\langle y, \tilde{T}_{\tilde{M}}(y), \tilde{I}_{\tilde{M}}(y), \tilde{F}_{\tilde{M}}(y) \mid y \in Y\rangle\} \tag{5.1}$$

where $\tilde{T}_{\tilde{M}}(y) : Y \to D[0,1]$, $\tilde{I}_{\tilde{M}}(y) : Y \to D[0,1]$, a$\tilde{F}_{\tilde{M}}(y) : Y \to D[0, 1]$.

A T2NNS $\tilde{T}_{\tilde{M}}(y) = \left(T_{T_{\tilde{M}}}(y), T_{I_{\tilde{M}}}(y), T_{F_{\tilde{M}}}(y)\right)$, $\tilde{I}_{\tilde{M}}(y) = \left(I_{T_{\tilde{M}}}(y), I_{I_{\tilde{M}}}(y), I_{F_{\tilde{M}}}(y)\right)$, and $\tilde{F}_{\tilde{M}}(y) = \left(F_{T_{\tilde{M}}}(y), F_{I_{\tilde{M}}}(y), F_{F_{\tilde{M}}}(y)\right)$, denote the truth, indeterminacy, and falsity memberships of y in $\tilde{M}$, respectively. The membership parameters satisfy the condition

$$0 \le \tilde{T}_{\tilde{M}}(y)^3 + \tilde{I}_{\tilde{M}}(y)^3 + \tilde{F}_{\tilde{M}}(y)^3 \le 3, \quad \forall y \in Y. \tag{5.2}$$

For ease of simplicity, we consider $\tilde{M} = \left\langle \left(T_{T_{\tilde{M}}}(y), T_{I_{\tilde{M}}}(y), T_{F_{\tilde{M}}}(y)\right), \left(I_{T_{\tilde{M}}}(y), I_{I_{\tilde{M}}}(y), I_{F_{\tilde{M}}}(y)\right), \left(F_{T_{\tilde{M}}}(y), F_{I_{\tilde{M}}}(y), F_{F_{\tilde{M}}}(y)\right)\right\rangle$, as a T2NN.

Definition 2 (Abdel-Basset et al., 2019). Let $\tilde{M} = \left\langle \left(T_{T_{\tilde{M}}}(y), T_{I_{\tilde{M}}}(y), T_{F_{\tilde{M}}}(y)\right), \left(I_{T_{\tilde{M}}}(y), I_{I_{\tilde{M}}}(y), I_{F_{\tilde{M}}}(y)\right), \left(F_{T_{\tilde{M}}}(y), F_{I_{\tilde{M}}}(y), F_{F_{\tilde{M}}}(y)\right)\right\rangle$,

$\tilde{M}_1 = \left\langle \left(T_{T_{\tilde{M}_1}}(y), T_{I_{\tilde{M}_1}}(y), T_{F_{\tilde{M}_1}}(y)\right), \left(I_{T_{\tilde{M}_1}}(y), I_{I_{\tilde{M}_1}}(y), I_{F_{\tilde{M}_1}}(y)\right), \left(F_{T_{\tilde{M}_1}}(y), F_{I_{\tilde{M}_1}}(y), F_{F_{\tilde{M}_1}}(y)\right)\right\rangle$, and

$\tilde{M}_2 = \left\langle \left(T_{T_{\tilde{M}_2}}(y), T_{I_{\tilde{M}_2}}(y), T_{F_{\tilde{M}_2}}(y)\right), \left(I_{T_{\tilde{M}_2}}(y), I_{I_{\tilde{M}_2}}(y), I_{F_{\tilde{M}_2}}(y)\right), \left(F_{T_{\tilde{M}_2}}(y), F_{I_{\tilde{M}_2}}(y), F_{F_{\tilde{M}_2}}(y)\right)\right\rangle$ be three T2NNs and λ>0.

Their operations are defined as follows

(a) Addition "⊕"

$$\begin{aligned}\tilde{M}_1 \oplus \tilde{M}_2 = \Big\langle \Big(& T_{T_{\tilde{M}_1}}(y) + T_{T_{\tilde{M}_2}}(y) - T_{T_{\tilde{M}_1}}(y) \times T_{T_{\tilde{M}_2}}(y), T_{I_{\tilde{M}_1}}(y) + T_{I_{\tilde{M}_2}}(y) \\ & - T_{I_{\tilde{M}_1}}(y) \times T_{I_{\tilde{M}_2}}(y), T_{F_{\tilde{M}_1}}(y) + T_{F_{\tilde{M}_2}}(y) - T_{F_{\tilde{M}_1}}(y) \times T_{F_{\tilde{M}_2}}(y) \Big), \\ & \Big(I_{T_{\tilde{M}_1}}(y) \times I_{T_{\tilde{M}_2}}(y), I_{I_{\tilde{M}_1}}(y) \times I_{I_{\tilde{M}_2}}(y), I_{F_{\tilde{M}_1}}(y) \times I_{F_{\tilde{M}_2}}(y) \Big), \\ & \Big(F_{T_{\tilde{M}_1}}(y) \times F_{T_{\tilde{M}_2}}(y), F_{I_{\tilde{M}_1}}(y) \times F_{I_{\tilde{M}_2}}(y), F_{F_{\tilde{M}_1}}(y) \times F_{F_{\tilde{M}_2}}(y) \Big) \Big\rangle, \end{aligned} \tag{5.3}$$

(b) Multiplication "⊗"

$$\begin{aligned}\tilde{M}_1 \otimes \tilde{M}_2 = \Big\langle & \Big(T_{T_{\tilde{M}_1}}(y) \times T_{T_{\tilde{M}_2}}(y), T_{I_{\tilde{M}_1}}(y) \times T_{I_{\tilde{M}_2}}(y), T_{F_{\tilde{M}_1}}(y) \times T_{F_{\tilde{M}_2}}(y) \Big), \\ & \Big(T_{T_{\tilde{M}_1}}(y) + T_{T_{\tilde{M}_2}}(y) - T_{T_{\tilde{M}_1}}(y) \times T_{T_{\tilde{M}_2}}(y), T_{I_{\tilde{M}_1}}(y) + T_{I_{\tilde{M}_2}}(y) \\ & - T_{I_{\tilde{M}_1}}(y) \times T_{I_{\tilde{M}_2}}(y), T_{F_{\tilde{M}_1}}(y) + T_{F_{\tilde{M}_2}}(y) - T_{F_{\tilde{M}_1}}(y) \times T_{F_{\tilde{M}_2}}(y) \Big), \\ & \Big(T_{T_{\tilde{M}_1}}(y) + T_{T_{\tilde{M}_2}}(y) - T_{T_{\tilde{M}_1}}(y) \times T_{T_{\tilde{M}_2}}(y), T_{I_{\tilde{M}_1}}(y) + T_{I_{\tilde{M}_2}}(y) \\ & - T_{I_{\tilde{M}_1}}(y) \times T_{I_{\tilde{M}_2}}(y), T_{F_{\tilde{M}_1}}(y) + T_{F_{\tilde{M}_2}}(y) - T_{F_{\tilde{M}_1}}(y) \times T_{F_{\tilde{M}_2}}(y) \Big) \Big\rangle, \end{aligned} \tag{5.4}$$

(c) Scalar multiplication

$$\begin{aligned}\lambda\tilde{M} = \Big\langle & \Big(1 - \big(1 - T_{T_{\tilde{M}}}(y)\big)^{\lambda}, 1 - \big(1 - T_{I_{\tilde{M}}}(y)\big)^{\lambda}, 1 - \big(1 - T_{F_{\tilde{M}}}(y)\big)^{\lambda} \Big), \\ & \Big(\big(I_{T_{\tilde{M}}}(y)\big)^{\lambda}, \big(I_{I_{\tilde{M}}}(y)\big)^{\lambda}, \big(I_{F_{\tilde{M}}}(y)\big)^{\lambda} \Big), \\ & \Big(\big(F_{T_{\tilde{M}}}(y)\big)^{\lambda}, \big(F_{I_{\tilde{M}}}(y)\big)^{\lambda}, \big(F_{F_{\tilde{M}}}(y)\big)^{\lambda} \Big) \Big\rangle, \end{aligned} \tag{5.5}$$

(d) Power

$$\tilde{M}^{\lambda}=\left\langle\left(\left(T_{T_{\tilde{M}}}(y)\right)^{\lambda},\left(T_{I_{\tilde{M}}}(y)\right)^{\lambda},\left(T_{F_{\tilde{M}}}(y)\right)^{\lambda}\right),\right.$$
$$\left(1-\left(1-I_{T_{\tilde{M}}}(y)\right)^{\lambda},1-\left(1-I_{I_{\tilde{M}}}(y)\right)^{\lambda},1-\left(1-I_{F_{\tilde{M}}}(y)\right)^{\lambda}\right), \tag{5.6}$$
$$\left.\left(1-\left(1-F_{T_{\tilde{M}}}(y)\right)^{\lambda},1-\left(1-F_{I_{\tilde{M}}}(y)\right)^{\lambda},1-\left(1-F_{F_{\tilde{M}}}(y)\right)^{\lambda}\right)\right\rangle.$$

Definition 3 (Abdel-Basset et al., 2019). Suppose that $\tilde{M}_l=\left\langle\left(T_{T_{\tilde{M}_l}}(y),T_{I_{\tilde{M}_l}}(y),T_{F_{\tilde{M}_l}}(y)\right),\right.$ $\left.\left(I_{T_{\tilde{M}_l}}(y),I_{I_{\tilde{M}_l}}(y),I_{F_{\tilde{M}_l}}(y)\right),\left(F_{T_{\tilde{M}_l}}(y),F_{I_{\tilde{M}_l}}(y),F_{F_{\tilde{M}_l}}(y)\right)\right\rangle$ l=1, …, p is a collection of T2NNs, and $\gamma=(\gamma_1,\ ...,\ \gamma_p)^T$ be the weight vector of them, with $\gamma_l\in[0,\ 1]$ and $\sum_{l=1}^{p}\gamma_l=1$. A type-2 neutrosophic number weighted averaging (T2NNWA) operator is defined as follows

$$T2NNWA_{\gamma}(\tilde{M}_1,...,\tilde{M}_l,...,\tilde{M}_p)=\gamma_1\tilde{M}_1\oplus\cdots\oplus\gamma_l\tilde{M}_l\oplus\cdots\oplus\gamma_p\tilde{M}_p=\bigoplus_{l=1}^{p}\gamma_l\tilde{M}_l$$
$$=\left\langle\left(1-\prod_{l=1}^{p}\left(1-T_{T_{\tilde{M}_l}}(y)\right)^{\gamma_l},1-\prod_{l=1}^{p}\left(1-T_{I_{\tilde{M}_l}}(y)\right)^{\gamma_l},1-\prod_{l=1}^{p}\left(1-T_{F_{\tilde{M}_l}}(y)\right)^{\gamma_l}\right),\right.$$
$$\left(\prod_{l=1}^{p}\left(I_{T_{\tilde{M}_l}}(y)\right)^{\gamma_l},\prod_{l=1}^{p}\left(I_{I_{\tilde{M}_l}}(y)\right)^{\gamma_l},\prod_{l=1}^{p}\left(I_{F_{\tilde{M}_l}}(y)\right)^{\gamma_l}\right), \tag{5.7}$$
$$\left.\left(\prod_{l=1}^{p}\left(F_{T_{\tilde{M}_l}}(y)\right)^{\gamma_l},\prod_{l=1}^{p}\left(F_{I_{\tilde{M}_l}}(y)\right)^{\gamma_l},\prod_{l=1}^{p}\left(F_{F_{\tilde{M}_l}}(y)\right)^{\gamma_l}\right)\right\rangle.$$

Definition 4 (Abdel-Basset et al., 2019). Let $\tilde{M}=\left\langle\left(T_{T_{\tilde{M}}}(y),T_{I_{\tilde{M}}}(y),T_{F_{\tilde{M}}}(y)\right),\right.$ $\left.\left(I_{T_{\tilde{M}}}(y),I_{I_{\tilde{M}}}(y),I_{F_{\tilde{M}}}(y)\right),\left(F_{T_{\tilde{M}}}(y),F_{I_{\tilde{M}}}(y),F_{F_{\tilde{M}}}(y)\right)\right\rangle$ be a T2NN. The score function $\tilde{M}$ is defined as follows

$$S(\tilde{M}) = \frac{1}{12}\Big\langle 8 + \Big(T_{T_{\tilde{M}}}(y) + 2\Big(T_{I_{\tilde{M}}}(y)\Big) + T_{F_{\tilde{M}}}(y)\Big) - \Big(I_{T_{\tilde{M}}}(y) + 2\Big(I_{I_{\tilde{M}}}(y)\Big) + I_{F_{\tilde{M}}}(y)\Big) - \Big(F_{T_{\tilde{M}}}(y) + 2\Big(F_{I_{\tilde{M}}}(y)\Big) + F_{F_{\tilde{M}}}(y)\Big)\Big\rangle. \quad (5.8)$$

5.4.2. The Hybrid Type-2 Neutrosophic Model for Public Transportation Pricing

Figure 5.1. presents the flowchart of the hybrid type-2 neutrosophic model for public transportation pricing. The model has two stages. In the first stage, the reputation of the invited experts is determined under the T2NN environment by making the trade-off between their experience and expertise. In the second stage, the T2NN-CRITIC-MABAC approach is formulated to solve the investigated MCDM problem. More detailed, the novel T2NN-CRITIC method is employed to evaluate the criteria importance, while the new T2NN-MABAC method is used to rank the alternatives.

Let A=$\{A_1, \ldots, A_i, \ldots, A_m\}$ ($m\geq 2$) be a finite set of alternatives, C=$\{C_1, \ldots, C_j, \ldots, C_n\}$ ($n\geq 2$) be a finite set of criteria, and D=$\{D_1, \ldots, D_e, \ldots, D_k\}$ ($k\geq 2$) is a set of invited experts. The stages and encompassed steps of the introduced hybrid type-2 neutrosophic model for public transportation pricing are given in the following:

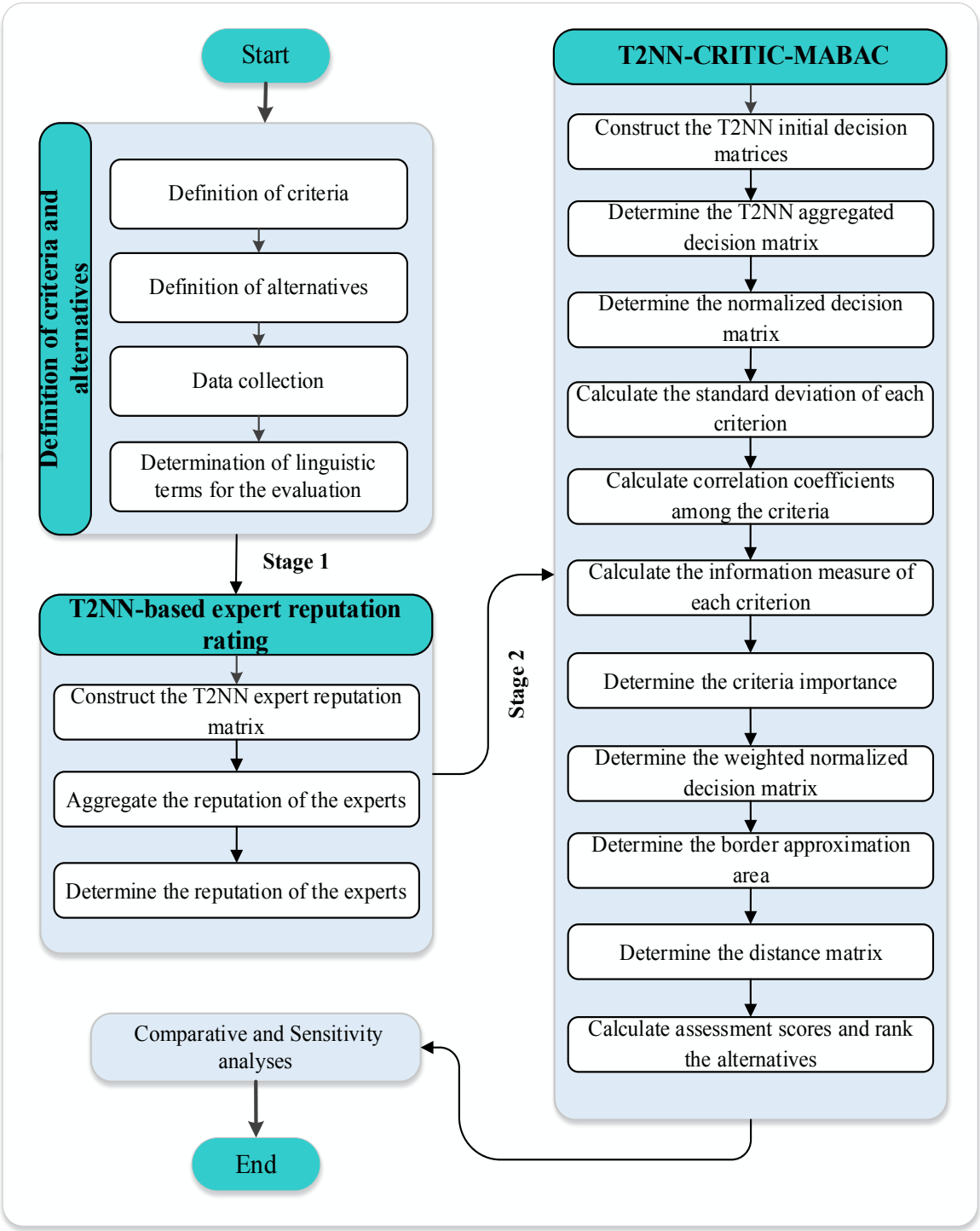

Figure 5.1. The flowchart of the hybrid type-2 neutrosophic model for public transportation pricing.

Stage 1: T2NN-based expert reputation rating.

Step 1.1. Construct the T2NN expert reputation matrix $\tilde{\mathrm{V}} = \left[\tilde{V}_e^{(l)}\right]_{2\times k}$

$$\tilde{\mathrm{V}} = \begin{array}{c} \begin{matrix} D_1 & \cdots & D_k \end{matrix} \\ \begin{bmatrix} \left\langle \begin{matrix} \left(T_{T_{\tilde{V}_1^{(1)}}}(y), T_{I_{\tilde{V}_1^{(1)}}}(y), T_{F_{\tilde{V}_1^{(1)}}}(y)\right), \\ \left(I_{T_{\tilde{V}_1^{(1)}}}(y), I_{I_{\tilde{V}_1^{(1)}}}(y), I_{F_{\tilde{V}_1^{(1)}}}(y)\right), \\ \left(F_{T_{\tilde{V}_1^{(1)}}}(y), F_{I_{\tilde{V}_1^{(1)}}}(y), F_{F_{\tilde{V}_1^{(1)}}}(y)\right) \end{matrix} \right\rangle & \cdots & \left\langle \begin{matrix} \left(T_{T_{\tilde{V}_k^{(1)}}}(y), T_{I_{\tilde{V}_k^{(1)}}}(y), T_{F_{\tilde{V}_k^{(1)}}}(y)\right), \\ \left(I_{T_{\tilde{V}_k^{(1)}}}(y), I_{I_{\tilde{V}_k^{(1)}}}(y), I_{F_{\tilde{V}_k^{(1)}}}(y)\right), \\ \left(F_{T_{\tilde{V}_k^{(1)}}}(y), F_{I_{\tilde{V}_k^{(1)}}}(y), F_{F_{\tilde{V}_k^{(1)}}}(y)\right) \end{matrix} \right\rangle \\ \left\langle \begin{matrix} \left(T_{T_{\tilde{V}_1^{(2)}}}(y), T_{I_{\tilde{V}_1^{(2)}}}(y), T_{F_{\tilde{V}_1^{(2)}}}(y)\right), \\ \left(I_{T_{\tilde{V}_1^{(2)}}}(y), I_{I_{\tilde{V}_1^{(2)}}}(y), I_{F_{\tilde{V}_1^{(2)}}}(y)\right), \\ \left(F_{T_{\tilde{V}_1^{(2)}}}(y), F_{I_{\tilde{V}_1^{(2)}}}(y), F_{F_{\tilde{V}_1^{(2)}}}(y)\right) \end{matrix} \right\rangle & \cdots & \left\langle \begin{matrix} \left(T_{T_{\tilde{V}_k^{(2)}}}(y), T_{I_{\tilde{V}_k^{(2)}}}(y), T_{F_{\tilde{V}_k^{(2)}}}(y)\right), \\ \left(I_{T_{\tilde{V}_k^{(2)}}}(y), I_{I_{\tilde{V}_k^{(2)}}}(y), I_{F_{\tilde{V}_k^{(2)}}}(y)\right), \\ \left(F_{T_{\tilde{V}_k^{(2)}}}(y), F_{I_{\tilde{V}_k^{(2)}}}(y), F_{F_{\tilde{V}_k^{(2)}}}(y)\right) \end{matrix} \right\rangle \end{bmatrix} \end{array}, \quad (5.9)$$

where

$$\tilde{V}_e^{(1)} = \left\langle \left(T_{T_{\tilde{V}_e^{(1)}}}(y), T_{I_{\tilde{V}_e^{(1)}}}(y), T_{F_{\tilde{V}_e^{(1)}}}(y)\right), \left(I_{T_{\tilde{V}_e^{(1)}}}(y), I_{I_{\tilde{V}_e^{(1)}}}(y), I_{F_{\tilde{V}_e^{(1)}}}(y)\right), \left(F_{T_{\tilde{V}_e^{(1)}}}(y), F_{I_{\tilde{V}_e^{(1)}}}(y), F_{F_{\tilde{V}_e^{(1)}}}(y)\right) \right\rangle$$

and

$$\tilde{V}_e^{(2)} = \left\langle \left(T_{T_{\tilde{V}_e^{(2)}}}(y), T_{I_{\tilde{V}_e^{(2)}}}(y), T_{F_{\tilde{V}_e^{(2)}}}(y)\right), \left(I_{T_{\tilde{V}_e^{(2)}}}(y), I_{I_{\tilde{V}_e^{(2)}}}(y), I_{F_{\tilde{V}_e^{(2)}}}(y)\right), \left(F_{T_{\tilde{V}_e^{(2)}}}(y), F_{I_{\tilde{V}_e^{(2)}}}(y), F_{F_{\tilde{V}_e^{(2)}}}(y)\right) \right\rangle,$$

are T2NNs that represent the (self-)appraisal of the experience and the expertise of the invited expert D_e, e= 1, ..., k, respectively. The seven-point T2NN linguistic scale is presented in Table 5.3. can be used to distinguish experts following their experience and expertise.

Table 5.3. T2NN linguistic variables to distinct experts.

Experience (years)	**Expertise**	**Type-2 neutrosophic number**
5<	Very poor	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>
[5, 10)	Poor	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>
[10, 15)	Medium poor	<(0.40, 0.30, 0.35), (0.50, 0.45, 0.60), (0.45, 0.40, 0.60)>
[15, 20)	Medium	<(0.50, 0.45, 0.50), (0.40, 0.35, 0.50), (0.35, 0.30, 0.45)>
[20, 25)	Medium good	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
[25, 30)	Good	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
≥30	Very good	<(0.95, 0.90, 0.95), (0.10, 0.10, 0.05), (0.05, 0.05, 0.05)>

Step 1.2. Aggregate the reputation of the experts

$$\begin{aligned}\tilde{Q}_e &= T2NNWA_{\xi}(\tilde{V}_e^{(1)}, \tilde{V}_e^{(2)}) = \xi_1\tilde{V}_e^{(1)} \oplus \xi_2\tilde{V}_e^{(2)} = \bigoplus_{l=1}^{2} \xi_l\tilde{V}_e^{(l)} \\ &= \left\langle \left(1-\prod_{l=1}^{2}\left(1-T_{\tilde{V}_e^{(l)}}(y)\right)^{\xi_l}, 1-\prod_{l=1}^{2}\left(1-T_{I_{\tilde{V}_e^{(l)}}}(y)\right)^{\xi_l}, 1-\prod_{l=1}^{2}\left(1-T_{F_{\tilde{V}_e^{(l)}}}(y)\right)^{\xi_l} \right), \right. \\ &\quad \left(\prod_{l=1}^{2}\left(I_{T_{\tilde{V}_e^{(l)}}}(y)\right)^{\xi_l}, \prod_{l=1}^{2}\left(I_{I_{\tilde{V}_e^{(l)}}}(y)\right)^{\xi_l}, \prod_{l=1}^{2}\left(I_{F_{\tilde{V}_e^{(l)}}}(y)\right)^{\xi_l} \right), \\ &\quad \left. \left(\prod_{l=1}^{2}\left(F_{T_{\tilde{V}_e^{(l)}}}(y)\right)^{\xi_l}, \prod_{l=1}^{2}\left(F_{I_{\tilde{V}_e^{(l)}}}(y)\right)^{\xi_l}, \prod_{l=1}^{2}\left(F_{F_{\tilde{V}_e^{(l)}}}(y)\right)^{\xi_l} \right) \right\rangle, \ e=1,\ldots,k,\end{aligned} \tag{5.10}$$

where

$$\tilde{Q}_e = \left\langle \left(T_{T_{\tilde{Q}_e}}(y), T_{I_{\tilde{Q}_e}}(y), T_{F_{\tilde{Q}_e}}(y)\right), \left(I_{T_{\tilde{Q}_e}}(y), I_{I_{\tilde{Q}_e}}(y), I_{F_{\tilde{Q}_e}}(y)\right), \left(F_{T_{\tilde{Q}_e}}(y), F_{I_{\tilde{Q}_e}}(y), F_{F_{\tilde{Q}_e}}(y)\right) \right\rangle$$

is the T2NN aggregated reputation of the invited expert D_e based on the T2NNWA operator. In Equation (5.10), ξ_1 and ξ_2 denotes the trade-off parameters of the reputation of the invited experts, with $\xi_1, \xi_2 \in [0,1]$ and $\xi_1 + \xi_2 = 1$. If the trade-off parameter ξ_1 is 1 (i.e., ξ_2=0), then the reputation of the invited experts is determined according to their experience. If the value of ξ_2 is set to 1, then the reputation of the invited experts is in line with their expertise.

If $\xi_1 = \xi_2 = 0.5,$ then the experience and expertise of the invited experts are equally appraised in the hybrid type-2 neutrosophic model.

Step 1.3. Determine the reputation of the experts

$$\delta_e = \frac{S\left(\tilde{Q}_e\right)}{\sum_{l=1}^{k} S\left(\tilde{Q}_l\right)}, \quad e = 1, \ldots, k \tag{5.11}$$

where $\delta = (\delta_1, \ldots, \delta_e, \ldots, \delta_k)^T$ is the reputation vector of the invited experts, with $\delta_e \in [0, 1],$ $e = 1, \ldots, k,$ and $\sum_{e=1}^{k} \delta_e = 1.$ The score function of the T2NN aggregated reputation for each invited expert is computed as follows

$$S\left(\tilde{Q}_e\right) = \frac{1}{12}\left\langle \begin{array}{l} 8 + \left(T_{T_{\tilde{Q}_e}}(y) + 2\left(T_{I_{\tilde{Q}_e}}(y)\right) + T_{F_{\tilde{Q}_e}}(y)\right) - \\ \left(I_{T_{\tilde{Q}_e}}(y) + 2\left(I_{I_{\tilde{Q}_e}}(y)\right) + I_{F_{\tilde{Q}_e}}(y)\right) \\ -\left(F_{T_{\tilde{Q}_e}}(y) + 2\left(F_{I_{\tilde{Q}_e}}(y)\right) + F_{F_{\tilde{Q}_e}}(y)\right) \end{array} \right\rangle, \; e = 1, \ldots, k. \tag{5.12}$$

Stage 2: T2NN-CRITIC-MABAC.

Step 2.1. Construct the T2NN initial decision matrices $\tilde{\mathrm{B}}^e = \left[\tilde{B}_{ij}^e\right]_{m \times n}$

$$\tilde{\mathrm{B}}^{e} = \begin{array}{c} \\ A_1 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & \cdots & C_n \end{array} \\ \begin{bmatrix} \left\langle \begin{pmatrix} T_{\tilde{B}^{e}_{11}}(y), T_{I_{\tilde{B}^{e}_{11}}}(y), T_{F_{\tilde{B}^{e}_{11}}}(y) \end{pmatrix}, \\ \begin{pmatrix} I_{T_{\tilde{B}^{e}_{11}}}(y), I_{I_{\tilde{B}^{e}_{11}}}(y), I_{F_{\tilde{B}^{e}_{11}}}(y) \end{pmatrix}, \\ \begin{pmatrix} F_{T_{\tilde{B}^{e}_{11}}}(y), F_{I_{\tilde{B}^{e}_{11}}}(y), F_{F_{\tilde{B}^{e}_{11}}}(y) \end{pmatrix} \end{array} \right\rangle & \cdots & \left\langle \begin{pmatrix} T_{\tilde{B}^{e}_{1n}}(y), T_{I_{\tilde{B}^{e}_{1n}}}(y), T_{F_{\tilde{B}^{e}_{1n}}}(y) \end{pmatrix}, \\ \begin{pmatrix} I_{T_{\tilde{B}^{e}_{1n}}}(y), I_{I_{\tilde{B}^{e}_{1n}}}(y), I_{F_{\tilde{B}^{e}_{1n}}}(y) \end{pmatrix}, \\ \begin{pmatrix} F_{T_{\tilde{B}^{e}_{1n}}}(y), F_{I_{\tilde{B}^{e}_{1n}}}(y), F_{F_{\tilde{B}^{e}_{1n}}}(y) \end{pmatrix} \end{array} \right\rangle \\ \vdots & \ddots & \vdots \\ \left\langle \begin{pmatrix} T_{\tilde{B}^{e}_{m1}}(y), T_{I_{\tilde{B}^{e}_{m1}}}(y), T_{F_{\tilde{B}^{e}_{m1}}}(y) \end{pmatrix}, \\ \begin{pmatrix} I_{T_{\tilde{B}^{e}_{m1}}}(y), I_{I_{\tilde{B}^{e}_{m1}}}(y), I_{F_{\tilde{B}^{e}_{m1}}}(y) \end{pmatrix}, \\ \begin{pmatrix} F_{T_{\tilde{B}^{e}_{m1}}}(y), F_{I_{\tilde{B}^{e}_{m1}}}(y), F_{F_{\tilde{B}^{e}_{m1}}}(y) \end{pmatrix} \end{array} \right\rangle & \cdots & \left\langle \begin{pmatrix} T_{\tilde{B}^{e}_{mn}}(y), T_{I_{\tilde{B}^{e}_{mn}}}(y), T_{F_{\tilde{B}^{e}_{mn}}}(y) \end{pmatrix}, \\ \begin{pmatrix} I_{T_{\tilde{B}^{e}_{mn}}}(y), I_{I_{\tilde{B}^{e}_{mn}}}(y), I_{F_{\tilde{B}^{e}_{mn}}}(y) \end{pmatrix}, \\ \begin{pmatrix} F_{T_{\tilde{B}^{e}_{mn}}}(y), F_{I_{\tilde{B}^{e}_{mn}}}(y), F_{F_{\tilde{B}^{e}_{mn}}}(y) \end{pmatrix} \end{array} \right\rangle \end{bmatrix} \end{array}, \quad (5.13)$$

$e = 1, \ldots, k,$

where

$$\tilde{B}^{e}_{ij} = \left\langle \left(T_{\tilde{B}^{e}_{ij}}(y), T_{I_{\tilde{B}^{e}_{ij}}}(y), T_{F_{\tilde{B}^{e}_{ij}}}(y) \right), \left(I_{T_{\tilde{B}^{e}_{ij}}}(y), I_{I_{\tilde{B}^{e}_{ij}}}(y), I_{F_{\tilde{B}^{e}_{ij}}}(y) \right), \left(F_{T_{\tilde{B}^{e}_{ij}}}(y), F_{I_{\tilde{B}^{e}_{ij}}}(y), F_{F_{\tilde{B}^{e}_{ij}}}(y) \right) \right\rangle,$$

i=1, ..., m; j=1, ..., n; e=1, ..., k is a T2NN that represents the evaluation of the alternative A_i under the criterion C_j given by the invited expert D_e.

The initial decision matrices are structured by using a T2NN linguistic scale. The seven-point T2NN linguistic scale is presented in Table 5.4. can be used to present alternative evaluation preferences of the invited experts. In this study, T2NN linguistic scales are utilized to help experts to express their opinions, since some of them may not have sufficient experience with neutrosophic numbers. As a result, the experts do not give direct values of truth, indeterminacy, and falsity memberships. Instead, they provide linguistic evaluations to make this approach more practical in real-life applications.

Table 5.4. T2NN linguistic variables for evaluating alternatives.

Linguistic variable	**Type-2 neutrosophic number**
Very low	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>
Low	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>
Medium low	<(0.40, 0.30, 0.35), (0.50, 0.45, 0.60), (0.45, 0.40, 0.60)>
Medium	<(0.50, 0.45, 0.50), (0.40, 0.35, 0.50), (0.35, 0.30, 0.45)>
Medium high	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
High	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
Very high	<(0.95, 0.90, 0.95), (0.10, 0.10, 0.05), (0.05, 0.05, 0.05)>

Step 2.2. Determine the T2NN aggregated decision matrix $\tilde{Z} = \left[\tilde{Z}_{ij}\right]_{m\times n}$

$$\tilde{Z}_{ij} = T2NNWA_{\delta}(\tilde{B}_{ij}^{1}, ..., \tilde{B}_{ij}^{e}, ..., \tilde{B}_{ij}^{k}) = \overset{k}{\underset{e=1}{\oplus}} \delta_e \tilde{B}_{ij}^{e}$$

$$= \left\langle \left(1 - \prod_{e=1}^{k} \left(1 - T_{\tilde{B}_{ij}^{e}}(y) \right)^{\delta_e}, 1 - \prod_{e=1}^{k} \left(1 - T_{I_{\tilde{B}_{ij}^{e}}}(y) \right)^{\delta_e}, 1 - \prod_{e=1}^{k} \left(1 - T_{F_{\tilde{B}_{ij}^{e}}}(y) \right)^{\delta_e} \right), \right.$$

$$\left(\prod_{e=1}^{k} \left(I_{T_{\tilde{B}_{ij}^{e}}}(y) \right)^{\delta_e}, \prod_{e=1}^{k} \left(I_{I_{\tilde{B}_{ij}^{e}}}(y) \right)^{\delta_e}, \prod_{e=1}^{k} \left(I_{F_{\tilde{B}_{ij}^{e}}}(y) \right)^{\delta_e} \right), \tag{5.14}$$

$$\left. \left(\prod_{e=1}^{k} \left(F_{T_{\tilde{B}_{ij}^{e}}}(y) \right)^{\delta_e}, \prod_{e=1}^{k} \left(F_{I_{\tilde{B}_{ij}^{e}}}(y) \right)^{\delta_e}, \prod_{e=1}^{k} \left(F_{F_{\tilde{B}_{ij}^{e}}}(y) \right)^{\delta_e} \right) \right\rangle,$$

$i = 1, \ldots, m;\ j = 1, \ldots, n.$

where the aggregation is determined by applying the T2NNWA operator (Definition 3),

$$\tilde{Z}_{ij} = \left\langle \left(T_{T_{\tilde{Z}_{ij}}}(y), T_{I_{\tilde{Z}_{ij}}}(y), T_{F_{\tilde{Z}_{ij}}}(y) \right), \left(I_{T_{\tilde{Z}_{ij}}}(y), I_{I_{\tilde{Z}_{ij}}}(y), I_{F_{\tilde{Z}_{ij}}}(y) \right), \left(F_{T_{\tilde{Z}_{ij}}}(y), F_{I_{\tilde{Z}_{ij}}}(y), F_{F_{\tilde{Z}_{ij}}}(y) \right) \right\rangle$$

is the T2NN aggregated evaluation of the alternative A_i under the criterion C_j given by the experts.

Step 2.3. Determine the normalized decision matrix $\mathrm{R} = [R_{ij}]_{m\times n}$

$$R_{ij} = \begin{cases} \dfrac{S\left(\tilde{Z}_{ij}\right) - \min\limits_{1\le l\le m} S\left(\tilde{Z}_{lj}\right)}{\max\limits_{1\le l\le m} S\left(\tilde{Z}_{lj}\right) - \min\limits_{1\le l\le m} S\left(\tilde{Z}_{lj}\right)} \;\Big|\; C_j \in \mathrm{C}^{+} \\ \dfrac{\max\limits_{1\le l\le m} S\left(\tilde{Z}_{lj}\right) - S\left(\tilde{Z}_{ij}\right)}{\max\limits_{1\le l\le m} S\left(\tilde{Z}_{lj}\right) - \min\limits_{1\le l\le m} S\left(\tilde{Z}_{lj}\right)} \;\Big|\; C_j \in \mathrm{C}^{-} \end{cases}, \; i = 1, \ldots, m;\; j = 1, \ldots, n \tag{5.15}$$

where R_{ij} denotes a normalized evaluation of the alternative A_i under the criterion C_j given by the experts, $\mathrm{C}^{+} \subseteq \mathrm{C}$ is the set of benefit criteria, $\mathrm{C}^{-} \subseteq \mathrm{C}$ is the set of cost criteria, and $\mathrm{C}^{+} \cup \mathrm{C}^{-} = \mathrm{C}$. The score function of the T2NN aggregated evaluation of the alternative A_i under the criterion C_j given by the experts is calculated as follows

$$S\left(\tilde{Z}_{ij}\right) = \frac{1}{12}\Bigg\langle 8 + \left(T_{T_{\tilde{Z}_{ij}}}(y) + 2\left(T_{I_{\tilde{Z}_{ij}}}(y)\right) + T_{F_{\tilde{Z}_{ij}}}(y)\right) - \left(I_{T_{\tilde{Z}_{ij}}}(y) + 2\left(I_{I_{\tilde{Z}_{ij}}}(y)\right) + I_{F_{\tilde{Z}_{ij}}}(y)\right) - \left(F_{T_{\tilde{Z}_{ij}}}(y) + 2\left(F_{I_{\tilde{Z}_{ij}}}(y)\right) + F_{F_{\tilde{Z}_{ij}}}(y)\right)\Bigg\rangle, \; i = 1, \ldots, m;\; j = 1, \ldots, n. \tag{5.16}$$

Step 2.4. Calculate the standard deviation of each criterion

$$\sigma_j = \sqrt{\frac{\sum\limits_{i=1}^{m}\left(R_{ij} - \bar{R}_j\right)^2}{m}}, \; j = 1, \ldots, n \tag{5.17}$$

where $\bar{R}_j = \frac{1}{m}\sum_{i=1}^{m} R_{ij}$, j=1, …, n presents an average normalized evaluation of the alternatives under the criterion C_j given by the experts.

Step 2.5. Calculate correlation coefficients among the criteria

$$\rho_{jk} = \frac{\sum_{i=1}^{m}\left[\left(R_{ij} - \bar{R}_j\right)\left(R_{ik} - \bar{R}_k\right)\right]}{\sqrt{\sum_{i=1}^{m}\left(R_{ij} - \bar{R}_j\right)^2 \sum_{i=1}^{m}\left(R_{ik} - \bar{R}_k\right)^2}},\ j,k = 1, \ldots, n. \tag{5.18}$$

Step 2.6. Calculate the information measure of each criterion

$$U_j = \sigma_j \sum_{l=1}^{n}\left(1 - \rho_{jl}\right),\ j = 1, \ldots, n \tag{5.19}$$

where criteria of greater importance have higher values of the information measure and vice versa.

Step 2.7. Determine the criteria importance

$$\omega_j = \frac{U_j}{\sum_{l=1}^{n} U_l},\ \ j = 1, \ldots, n \tag{5.20}$$

where $\omega = \left(\omega_1, \ldots, \omega_j, \ldots, \omega_n\right)^T$ is the importance vector of the criteria, with $\omega_j \in [0, 1]$, j=1, …, n, and $\sum_{j=1}^{n} \omega_j = 1$.

Step 2.8. Determine the weighted normalized decision matrix $\mathrm{G} = \left[G_{ij} \right]_{m \times n}$

$$G_{ij} = \omega_j \left(R_{ij} + 1 \right),\ i = 1, \ldots, m;\ j = 1, \ldots, n \tag{5.21}$$

where G_{ij} denotes a weighted normalized evaluation of the alternative A_i under the criterion C_j given by the experts.

Step 2.9. Determine the border approximation area

$$O_j = \left(\prod_{i=1}^{m} G_{ij} \right)^{1/m},\ j = 1, \ldots, n \tag{5.22}$$

where $\mathrm{O} = \left\{ O_1, \ldots, O_j, \ldots, O_n \right\}$ represents the border approximation area given by the experts.

Step 2.10. Determine the distance matrix $\mathrm{P} = \left[P_{ij} \right]_{m \times n}$

$$P_{ij} = G_{ij} - O_j,\ i = 1, \ldots, m;\ j = 1, \ldots, n \tag{5.23}$$

where P_{ij} presents a distance of the alternative A_i from the border approximation area under the criterion C_j given by the experts. The alternative A_i under the criterion C_j can belong to the border approximation area O, an upper approximation area O^+, or a lower approximation area O^-. If $P_{ij}>0$ then it belongs to O^+, if $P_{ij}=0$ then it belongs to O, and if $P_{ij}<0$ then it belongs to O^-.

Step 2.11. Calculate assessment scores and rank the alternatives

$$B_i = \sum_{j=1}^{n} P_{ij}, \ \ i = 1, \ldots, m \tag{5.24}$$

where B_i represents the assessment score of the alternative A_i. The alternatives are ranked according to the decreasing values of their assessment score. The best alternative has the highest assessment score. The detailed nomenclatures for the indices, parameters, sets, matrices, and variables are provided in the list of symbols section.

5.5. Results and Discussion

5.5.1. Experimental Results

Stage 1: T2NN-based expert reputation rating.

Step 1.1. Five experts are invited to participate in the investigated real-life case study (Table 5.5.). Due to the COVID-19 outbreak, the online questionnaire approach via Google Forms is used to collect information about the experts and their evaluations of the pricing systems for IZBAN.

Table 5.5. The information about the experts.

Expert	Experience (years)	Expertise	Occupation	Profession	Gender
D_1	6	Medium	Industry	Urban management	Male
D_2	13	Good	Industry	Transportation engineering	Male
D_3	9	Medium	Industry	Urban planning	Male
D_4	4	Very good	Industry	Transportation engineering	Male
D_5	10	Medium good	Industry	Urban planning	Male

The T2NN expert reputation matrix is constructed with the help of Equation (5.9) and presented in Table 5.6. It is based on the experts' self-appraisal of their experience and expertise (Table 5.5.) as well as the seven-point T2NN linguistic scale (Table 5.3.).

Table 5.6. The T2NN expert reputation matrix.

Expert	Experience	Expertise
D_1	<(0.35, 0.35, 0.1), (0.5, 0.75, 0.8), (0.5, 0.75, 0.65)>	<(0.5, 0.45, 0.5), (0.4, 0.35, 0.5), (0.35, 0.3, 0.45)>
D_2	<(0.4, 0.3, 0.35), (0.5, 0.45, 0.6), (0.45, 0.4, 0.6)>	<(0.7, 0.75, 0.8), (0.15, 0.2, 0.25), (0.1, 0.15, 0.2)>
D_3	<(0.35, 0.35, 0.1), (0.5, 0.75, 0.8), (0.5, 0.75, 0.65)>	<(0.5, 0.45, 0.5), (0.4, 0.35, 0.5), (0.35, 0.3, 0.45)>
D_4	<(0.2, 0.2, 0.1), (0.65, 0.8, 0.85), (0.45, 0.8, 0.7)>	<(0.95, 0.9, 0.95), (0.1, 0.1, 0.05), (0.05, 0.05, 0.05)>
D_5	<(0.4, 0.3, 0.35), (0.5, 0.45, 0.6), (0.45, 0.4, 0.6)>	<(0.6, 0.45, 0.5), (0.2, 0.15, 0.25), (0.1, 0.25, 0.15)>

Step 1.2. In the base case scenario, the experience and expertise are equally appraised; i.e., the trade-off parameters ξ_1 and ξ_2 are 0.5. T2NNs that represent the experience and the expertise of the invited experts from Table 5.6. are aggregated with the help of the T2NNWA operator defined in Equation (5.10). As a result, aggregated reputations of the experts are given in Table 5.7. For example, the T2NN aggregated reputation of the first expert is calculated as follows:

$$\tilde{Q}_1 = \left\langle \left(1-(1-0.35)^{0.5}\cdot(1-0.5)^{0.5}, 1-(1-0.35)^{0.5}\cdot(1-0.45)^{0.5}, 1-(1-0.1)^{0.5}\cdot(1-0.5)^{0.5}\right),\right.$$

$$\left.\left(0.5^{0.5}\cdot 0.4^{0.5}, 0.75^{0.5}\cdot 0.35^{0.5}, 0.8^{0.5}\cdot 0.5^{0.5}\right), \left(0.5^{0.5}\cdot 0.35^{0.5}, 0.75^{0.5}\cdot 0.3^{0.5}, 0.65^{0.5}\cdot 0.45^{0.5}\right)\right\rangle$$

=<(0.430, 0.402, 0.329), (0.447, 0.512, 0.632), (0.418, 0.474, 0.541)>.

Step 1.3. Score function values of the T2NN aggregated reputations are obtained by using Equation (5.12). For example, the score function of the T2NN aggregated reputation of the first expert is computed as follows

$$S(\tilde{Q}_1)=\frac{1}{12}\langle 8+(0.430+2\cdot 0.402+0.329)-(0.447+2\cdot 0.512+0.632)-(0.418+2\cdot 0.474+0.541)\rangle=0.463.$$

The score function values (see Table 5.7., Column 3) are normalized with the help of Equation (5.11) to determine the reputation of the invited experts. The obtained reputation vector is $\delta=(0.155, 0.226, 0.155, 0.259, 0.205)^T$.

Table 5.7. The reputation of the experts.

Expert	T2NN aggregated	Score function	Reputation
D_1	<(0.430, 0.402, 0.329), (0.447, 0.512, 0.632), (0.418, 0.474, 0.541)>	0.463	0.155
D_2	<(0.576, 0.582, 0.639), (0.274, 0.300, 0.387), (0.212, 0.245, 0.346)>	0.672	0.226
D_3	<(0.430, 0.402, 0.329), (0.447, 0.512, 0.632), (0.418, 0.474, 0.541)>	0.463	0.155
D_4	<(0.800, 0.717, 0.788), (0.255, 0.283, 0.206), (0.150, 0.200, 0.187)>	0.772	0.259
D_5	<(0.510, 0.380, 0.430), (0.316, 0.260, 0.387), (0.212, 0.316, 0.300)>	0.611	0.205

Stage 2: T2NN-CRITIC-MABAC.

Step 2.1. Five invited experts used T2NN linguistic variables from Table 5.4. to evaluate four public transportation pricing systems under 13 criteria. Their evaluations of the pricing systems for IZBAN are provided in Table 5.8. The T2NN initial decision matrices are constructed based on the experts' input and with the help of Equation (5.13). They are given in Table B.1.

Table 5.8. Experts' evaluations of the public transportation pricing systems under the criteria.

Alternative	Expert	Criterion												
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
A_1: Flat fare	D_1	M	M	ML	MH	L	L	H	H	M	L	MH	M	L
	D_2	MH	L	L	H	L	L	H	ML	M	VH	H	H	ML
	D_3	H	ML	VL	H	L	M	VH	VH	ML	L	MH	M	L
	D_4	MH	M	ML	H	L	ML	H	H	VL	L	ML	L	VL
	D_5	MH	M	L	H	L	M	H	H	ML	L	MH	M	ML
A_2: Distance-based fare	D_1	M	M	M	M	L	ML	MH	MH	M	L	MH	MH	ML
	D_2	L	MH	H	ML	MH	VH	L	VH	MH	L	ML	M	VH
	D_3	VL	ML	M	L	H	L	H	ML	H	M	MH	MH	VH
	D_4	ML	L	M	ML	M	M	M	MH	M	M	MH	M	MH
	D_5	ML	M	M	M	MH	MH	M	M	MH	H	MH	MH	MH
A_3: Zonal pricing	D_1	L	MH	MH	M	MH	MH	M	ML	MH	H	L	L	H
	D_2	M	H	ML	ML	M	MH	VH	M	M	VH	L	L	M
	D_3	L	MH	H	M	MH	H	M	MH	MH	H	L	ML	MH
	D_4	ML	ML	H	ML	H	MH	ML	M	MH	VH	VL	L	H
	D_5	M	MH	MH	M	M	MH	ML	M	M	VH	L	ML	M
A_4: Rent-based fare	D_1	VL	MH	MH	ML	MH	MH	M	ML	MH	H	L	ML	VH
	D_2	L	VL	VL	M	ML	MH	VH	VL	VH	L	M	H	H
	D_3	VL	ML	VH	VL	VH	L	H	ML	H	M	L	M	H
	D_4	L	ML	H	L	VH	M	ML	M	MH	VH	L	L	H
	D_5	ML	ML	MH	L	H	VL	MH	M	H	VH	M	MH	MH

Very Low: VL, Low: L, Medium Low: ML, Medium: M, Medium High: MH, High: H, Very High: VH.

Step 2.2. The T2NN aggregated decision matrix is presented in Table B.2. It is determined with the help of Equation (5.14) by taking into account the reputation of the experts (Table 5.7., Column 4) and four T2NN initial decision matrices (Table B.1). For example, the T2NN evaluations of the public transportation pricing system "flat fare" (A_1) under the criterion "operation cost" (C_1) are (see Table B.1):

• expert 1 – $\tilde{B}_{11}^1 =$<(0.50, 0.45, 0.50), (0.40, 0.35, 0.50), (0.35, 0.30, 0.45)>,

• expert 2 – $\tilde{B}_{11}^2 =$<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>,

• expert 3 – $\tilde{B}_{11}^{3}$ =<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>,

• expert 4 – $\tilde{B}_{11}^{4}$ =<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>, and

• expert 5 – $\tilde{B}_{11}^{5}$ =<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>.

The T2NN aggregated evaluation of A_1 under C_1 given by five experts is computed as follows

$$\tilde{Z}_{11}=\left\langle\begin{pmatrix}1-(1-0.50)^{0.155}\cdot(1-0.60)^{0.226}\cdot(1-0.70)^{0.155}\cdot(1-0.60)^{0.259}\cdot(1-0.60)^{0.205},\\ 1-(1-0.45)^{0.155}\cdot(1-0.45)^{0.226}\cdot(1-0.75)^{0.155}\cdot(1-0.45)^{0.259}\cdot(1-0.45)^{0.205},\\ 1-(1-0.50)^{0.155}\cdot(1-0.50)^{0.226}\cdot(1-0.80)^{0.155}\cdot(1-0.50)^{0.259}\cdot(1-0.50)^{0.205}\end{pmatrix},\right.$$
$$\left.\begin{pmatrix}0.40^{0.155}\cdot0.20^{0.226}\cdot0.15^{0.155}\cdot0.20^{0.259}\cdot0.20^{0.205},\\ 0.35^{0.155}\cdot0.15^{0.226}\cdot0.20^{0.155}\cdot0.15^{0.259}\cdot0.15^{0.205},\\ 0.50^{0.155}\cdot0.25^{0.226}\cdot0.25^{0.155}\cdot0.25^{0.259}\cdot0.25^{0.205}\end{pmatrix},\begin{pmatrix}0.35^{0.155}\cdot0.10^{0.226}\cdot0.10^{0.155}\cdot0.10^{0.259}\cdot0.10^{0.205},\\ 0.30^{0.155}\cdot0.25^{0.226}\cdot0.15^{0.155}\cdot0.25^{0.259}\cdot0.25^{0.205},\\ 0.45^{0.155}\cdot0.15^{0.226}\cdot0.20^{0.155}\cdot0.15^{0.259}\cdot0.15^{0.205}\end{pmatrix}\right\rangle$$

=<(0.604, 0.513, 0.566), (0.213, 0.179, 0.278), (0.121, 0.238, 0.186)>.

Step 2.3. Firstly, score function values of the T2NN aggregated evaluations (Table B.3) are calculated by using Equation (5.16). Then, the normalized decision matrix (Table 5.9.) is determined with the help of Equation (5.15) by taking into account the score decision matrix, the extreme values (i.e., minimum and maximum), and the types of evaluation criteria (Table B.3). Cost criteria are "operation cost" (C_1), "user cost" (C_2), "expert cost" (C_3), "travel time" (C_4), "switch to a personal vehicle" (C_6), "environmental cost" (C_8), and "decentralization of cities" (C_{10}). The other six criteria are in the set of benefit criteria; i.e., C^{+}={C_5, C_7, C_9, C_{11}, C_{12}, C_{13}}.

Table 5.9. The normalized decision matrix and average normalized evaluations.

Alternative	**Criterion**												
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
A_1	0.0	0.844	1.0	0.0	0.0	1.0	1.0	0.0	0.0	0.921	1.0	0.789	0.0
A_2	0.749	0.658	0.274	0.776	0.676	0.048	0.0	0.106	0.620	1.0	0.942	1.0	0.999
A_3	0.609	0.0	0.069	0.686	0.738	0.0	0.346	0.648	0.560	0.0	0.0	0.0	0.758
A_4	1.0	1.0	0.0	1.0	1.0	0.609	0.671	1.0	1.0	0.247	0.381	0.862	1.0
Average	0.590	0.626	0.336	0.615	0.603	0.414	0.504	0.439	0.545	0.542	0.581	0.663	0.689

Steps 2.4–2.7. Firstly, the standard deviations and the correlation coefficients among the criteria are calculated by employing Equation (5.17) and Equation (5.18), respectively. They are determined based on the normalized decision matrix and the average normalized evaluations (Table 5.9.). Secondly, the information measures are computed to simultaneously consider the differences and correlations among the criteria by using Eq. (5.19). Lastly, Equation (5.20) is applied to normalize the information measure of each criterion and elucidate its objective importance. The obtained importance vector of the evaluation criteria is presented in Table 5.10.

Table 5.10. The correlation coefficient matrix, standard deviations, information measures, and criteria importance.

Criterion	C_1	C_2	C_3	C_4	C_5	···	C_{13}	**Standard deviation**	**Information measure**	**Importance**
C_1	1.000	0.033	–0.932	0.997	0.980	···	0.969	0.368	3.741	0.067
C_2	0.033	1.000	0.305	–0.051	–0.115	···	–0.107	0.381	3.326	0.059
C_3	–0.932	0.305	1.000	–0.957	–0.981	···	–0.922	0.397	5.644	0.100
C_4	0.997	–0.051	–0.957	1.000	0.989	···	0.977	0.373	3.927	0.070
C_5	0.980	–0.115	–0.981	0.989	1.000	···	0.943	0.369	4.003	0.071
C_6	–0.544	0.709	0.695	–0.604	–0.586	···	–0.714	0.414	4.786	0.085
C_7	–0.562	0.446	0.588	–0.600	–0.530	···	–0.750	0.372	4.730	0.084
C_8	0.734	–0.044	–0.798	0.736	0.818	···	0.581	0.407	4.586	0.082
C_9	0.990	0.081	–0.924	0.982	0.981	···	0.925	0.357	3.570	0.064
C_{10}	–0.447	0.500	0.687	–0.487	–0.610	···	–0.353	0.428	5.159	0.092
C_{11}	–0.464	0.622	0.729	–0.515	–0.630	···	–0.412	0.413	4.793	0.085
C_{12}	0.085	0.888	0.279	0.012	–0.107	···	0.053	0.390	3.515	0.063
C_{13}	0.969	–0.107	–0.922	0.977	0.943	···	1.000	0.410	4.433	0.079

Steps 2.8–2.9. Firstly, the normalized evaluations of the public transportation pricing systems (Table 5.9.) and the criteria importance (Table 5.10.) are taken into account to determine the weighted normalized decision matrix by employing Equation (5.21). This matrix is given in Table 5.11. Then, the border approximation area (Table 5.11., Column 6) is determined with the help of Equation (5.22).

Table 5.11. The weighted normalized decision matrix and the border approximation area.

Criterion	**Alternative**				**Border approximation area**
	A_1: Flat fare	A_2: Distance-based fare	A_3: Zonal pricing	A_4: Rent-based fare	
C_1: Operation cost	0.067	0.116	0.107	0.133	0.103
C_2: User cost	0.109	0.098	0.059	0.118	0.093
C_3: Expert cost	0.201	0.128	0.107	0.100	0.129
C_4: Travel time	0.070	0.124	0.118	0.140	0.109
C_5: Travel comfort	0.071	0.119	0.124	0.142	0.111
C_6: Switch to a personal veh.	0.170	0.089	0.085	0.137	0.115
C_7: Personal mobility	0.168	0.084	0.113	0.141	0.123
C_8: Environmental cost	0.082	0.090	0.134	0.163	0.113
C_9: Life quality	0.064	0.103	0.099	0.127	0.095
C_{10}: Decentralization of cities	0.176	0.184	0.092	0.114	0.136
C_{11}: Public acceptability	0.171	0.166	0.085	0.118	0.130
C_{12}: Political success	0.112	0.125	0.063	0.116	0.100
C_{13}: Deployment of resources	0.079	0.158	0.139	0.158	0.128

Step 2.10. The distance matrix is provided in Table 5.12. It is constructed based on the weighted normalized decision matrix and the border approximation area (Table 5.11.) with the help of Equation (5.23).

Step 2.11. The assessment scores of the investigated public transportation pricing systems for IZBAN are calculated by employing Equation (5.24) and presented in Table 5.12. Four pricing systems are ranked according to the decreasing values of their assessment scores. The obtained ordering is $A_4 \succ A_2 \succ A_1 \succ A_3$. Based on the results from Table 5.12., the most appropriate pricing system for the analyzed suburban system in İzmir Province is "rent-based fare" (A_4) since it has the highest assessment score.

Table 5.12. The distance matrix, assessment scores, and ranks of the public transportation pricing systems.

Alternative	Criterion								Assessment score	Rank
	C_1	C_2	C_3	C_4	C_5	C_6	···	C_{13}		
A_1: Flat fare	–0.036	0.016	0.072	–0.039	–0.039	0.055	···	–0.050	0.054	3
A_2: Distance-based fare	0.014	0.005	–0.001	0.015	0.009	–0.026	···	0.029	0.099	2
A_3: Zonal pricing	0.005	–0.034	–0.022	0.008	0.013	–0.030	···	0.010	–0.159	4
A_4: Rent-based fare	0.031	0.025	–0.029	0.030	0.032	0.022	···	0.029	0.223	1

5.5.2. Ranking Discussion

After each alternative and criteria are defined, experts are consulted to gather their scorings of each alternative under each criterion. Gathered results from the experts are then used to sort the alternatives. According to the prioritization results, zonal pricing is seen to be the least advantageous alternative. A flat fare is observed to be the second least advantageous pricing system, and distance-based pricing is the third. According to the experts, a rent-based fare pricing alternative, which is a public transportation fare system proposed in this thesis is seen to be the most advantageous alternative.

The zonal pricing is the least advantageous alternative since the price increases as commuters change the zone, aiming to make this pricing alternative travel distance sensitive and providing equity among the short-distance and long-distance travelers. However, a notable unfairness aspect is still present in this alternative. The price difference between traveling for long distances in a zone and traveling a short distance, but changing zones is an issue that creates unfairness in pricing. Zonal fees being different creates zonal distinctions. These distinctions have the potential to eventually create decentralization in terms of lower public transportation zone fees. Two highly interconnected choice problems must be handled when developing a zone-based tariff: the zone and the pricing (Otto and Boysen, 2017). Expert labor may be required to establish the boundaries fairly. All these reasons have made this alternative the least advantageous one.

Flat fare pricing is the second least advantageous method. The fact that all commuters are charged the same amount regardless of the distance and time traveled creates unfairness for commuters. The public frequently rejects flat fare that charges the same for a short trip between two nearby stations as it would for a long trip throughout the entire system (Hamacher and Schöbel, 2004). Even though some commuters travel for very short distances using public transportation vehicles, they must meet the operating costs of the public transportation vehicles at the same rate compared to the commuters, who travel for longer distances. The flat fare usually cannot meet the long-haul operating costs (Yamada, 1985). Short-haul customers heavily subsidize long-haul passengers (Cervero, 1981). Therefore, a flat fare system is suitable for compact cities and short travel distances. Implementing a flat fare price has the potential to create a decentralization problem. As the price of public transportation is fixed regardless of the distance, low- and medium-income residents live in the outer parts of the city since rents are lower in those regions. This increases the lengths of the public transportation lines, which eventually increases the operating costs because of the more frequent maintenance needs of the vehicles. The unfairness aspect of the flat fare pricing alternative and the potential of creating a decentralization issue has made this alternative a disadvantageous one. However, compared to the zonal pricing method, the unfairness issues in the pricing mechanism of the zonal pricing alternative such as the mentioned price difference in traveling for long distances in a zone and short distances, but changing a zone makes the flat fare pricing system the second least advantageous alternative.

Distance-based fare pricing alternative is the second most advantageous pricing method. In this pricing alternative, commuters pay as much as they travel. Therefore, the unfair aspect of the public transportation pricing methods is eliminated. However, it may require the use of specialized equipment since it is complex to implement and manage (Fleishman et al., 1996). The fact that passengers pay for the distance that they travel also removes the decentralization possibility faced in flat fare and zonal pricing alternatives, which puts distance-based fare pricing in front as means of advantage. Therefore, the two reasons specified have made the distance-based fare pricing alternative the second most advantageous one.

A rent-based fare system is selected to be the most advantageous alternative among all other alternatives. The most significant reason for the decentralization of the cities is the lower rent accommodation present in outer regions of the cities. Low- and medium-income residents of the city pay lower rents and use public transportation to travel to their work, which is in inner-city regions. The rent-based fare method aims to eliminate the decentralization possibility by charging commuters, which pay lower rents the more. As this pricing method is implemented, people live in inner-city regions, which shortens the public transportation lines. This also reduces the operating costs of the vehicles because of less frequent maintenance needs. As people move their homes closer to their work and social environment, long traveling needs are mitigated, which removes the unfairness aspect from the beginning. All these reasons have made this alternative the most advantageous one.

5.5.3. Comparative Analysis

The T2NN-TOPSIS method introduced by Abdel-Basset et al. (2019) is the only available decision-making approach under the T2NN environment in the literature. It computes a positive-ideal solution (PIS) and a negative ideal solution (NIS) to find an alternative with the shortest Euclidean distance from PIS and the farthest Euclidean distance from NIS. The differences between our hybrid type-2 neutrosophic model and T2NN-TOPSIS are as follows: (Table 5.13.)

(i) Our model can not only take into account the experience and expertise of experts that contribute to the MCDM process but also make a trade-off between these important reputation indicators.

(ii) The only available T2NN-based approach ranks alternatives with the help of the TOPSIS method while our model assesses public transportation pricing systems by using the new T2NN-MABAC method.

(iii) The only available T2NN-based decision-making approach assumes that criteria weights are known in advance while our model utilizes the novel T2NN-CRITIC method to determine the objective importance of the evaluation criteria.

(iv) Our model has two build-in parameters that provide higher flexibility when selecting public transportation pricing systems while the T2NN-based TOPSIS method has no intrinsic parameters.

Table 5.13. The characteristic of different type-2 neutrosophic approaches.

Characteristic	**Approach**	
	Our study	T2NN-TOPSIS
Uncertain environment	Type-2 neutrosophic	Type-2 neutrosophic
Group decision-making	Yes	Yes
Expert reputation rating	Yes	No
Criteria weighting	CRITIC	No
Alternative ranking	MABAC	TOPSIS
Build-in parameter(s)	Two	No
Flexibility	High	Low

CRiteria Importance Through Intercriteria Correlation: CRITIC, Multi-Attributive Border Approximation area Comparison: MABAC, Technique for the Order Preference by Similarity to Ideal Solution: TOPSIS, Type-2 Neutrosophic Number: T2NN.

The comparative analysis with the T2NN-based TOPSIS method is performed to investigate the reliability of the hybrid type-2 neutrosophic model for public transportation pricing. Table 5.14. gives the comparison results. According to this table, both T2NN-based approaches identify “rent-based fare” (A_4) as the best public transportation pricing system for the investigated suburban system. Moreover, our model and the T2NN-based TOPSIS method generate the same ordering of four evaluated pricing systems for IZBAN. As a result, it can be concluded that the hybrid type-2 neutrosophic model for public transportation pricing is highly reliable.

Table 5.14. The comparison of different T2NN-based approaches.

Alternative	Our study		T2NN-TOPSIS	
	Assessment score	Rank	Closeness coefficient	Rank
A_1: Flat fare	0.054	3	0.484	3
A_2: Distance-based fare	0.099	2	0.610	2
A_3: Zonal pricing	–0.159	4	0.410	4
A_4: Rent-based fare	0.223	1	0.615	1

5.5.4. Sensitivity Analysis

The sensitivity analysis to changes in the trade-off parameter ξ_1 is performed to check the robustness of the hybrid type-2 neutrosophic model for public transportation pricing (Figure 5.2.). The values of ξ_1 are varied in the interval [0, 1] with an increment value of 0.1 to comprehensively analyze its influence as well as the quality of the proposed pricing system for IZBAN; i.e., switching from the distance-based to rent-based fare system.

In the base case scenario, the trade-off parameter ξ_1 is set to 0.5 to equally appraise the experience and expertise of the invited experts (Figure 5.2.). In real-life applications, such an assumption may not be reasonable since the municipal body (IZBAN) in charge of selecting a public transportation pricing system may decide to have more trust in experienced experts or prefer those with greater expertise. Values of the trade-off parameter ξ_1 that are in the interval $0.5<\xi_1\leq 1$ favor the experience. They present scenarios when the municipal body has more trust in experienced experts. On the other hand, values of the parameter ξ_1 that are in the interval $0\leq\xi_1<0.5$ favor the expertise. These values represent scenarios when the municipal body prefers expertise in the pricing system selection process for IZBAN. Also, only the experience or expertise of the invited experts may be taken into account in some specific conditions. The reputation is determined according to the experience of the invited experts when $\xi_1=1$ (denoted as “experience only” in Figure 5.2.). On the other hand, the expert reputation rating is fully in line with the expertise when $\xi_1=0$ (denoted as “expertise only” in Figure 5.2.).

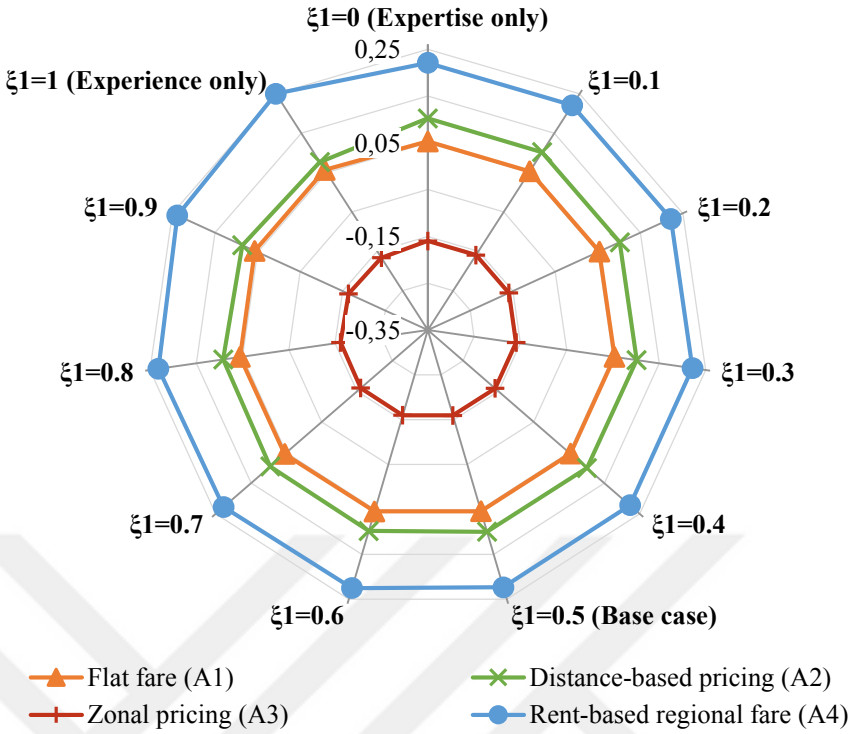

Figure 5.2. The sensitivity analysis of the integrated neutrosophic decision-making model.

As can be seen from Figure 5.2., in both extreme cases (i.e., for $\xi_1 \in \{0, 1\}$) the order of the investigated public transportation pricing systems is $A_4 \succ A_2 \succ A_1 \succ A_3$. From Figure 5.2. it can be outlined that alternative A_4 (i.e., rent-based fare) is the best pricing system for IZBAN. The current distance-based fare system (A_2) holds the second position in all investigated scenarios. The second worst pricing system is "flat fare" (A_1) which was applied till 2018, while by far the worst solution is "zonal pricing" (A_3). From the sensitivity analysis, it can be concluded that the introduced model for public transportation pricing is highly robust. Besides, switching IZBAN pricing to the rent-based regional fare system is strongly suggested.

5.5.5. Managerial Implications

There are various advantages and disadvantages to each alternative present in this study. Zonal pricing is the most disadvantageous in means of decentralization of the city and the issues regarding the pricing mechanism. Flat fare pricing is the second least disadvantageous regarding both fairness aspects because of fixing the price of public transportation and creating decentralization problems in the city. Distance-based fare pricing alternative is seen to be an advantageous pricing alternative in means of both fairness and decentralization by making commuters pay as much as they travel. However, the rent-based pricing method is the most advantageous one since it attacks the idea of decentralization. It makes the cities eventually more compact and so the need for long lines of public transportation becomes eliminated, which also solves the problem of unfairness.

This chapter fills a gap concerning public transportation pricing methods. Rent-based fare pricing is a unique public transportation pricing method and a rent-based fare pricing alternative is evaluated by the experts as a successful method. This paper also creates a consensus for municipalities to compare different transportation pricing systems. Municipalities have the chance to use transportation and rent cost dates, to confirm the need for rent-based fare pricing and implement it easily.

6. A PROPOSED RAIL TRANSPORTATION PRICING: RENT-BASED PRICING

This chapter addresses a sustainable approach to regional rail system pricing by considering rental costs. The growth of cities increases passengers' travel distances and it brings a variety of costs associated with this. Also, flat fare, distance-based fare, and zonal pricing neglect the decentralization problem of the cities. This chapter aims to develop a sustainable regional rail system pricing by encouraging people to rent houses in regions that will shorten their travel distances and to fill a gap in the literature on regional rail system pricing by dealing with the decentralization of the cities. A non-linear optimization model is developed based on face-to-face surveys with regional rail system passengers. For various clusters of stations, rent per income rates and rental-based ticket prices were obtained. The findings are compared to flat and distance-based fare models.

6.1. Introduction

The value of public transportation in a successful transportation system is universally acknowledged (Nash, 1982; May & Roberts, 1995; Murray et al., 1998). Development within public transportation systems is required to limit major problems in urban transportation such as traffic congestion, environmental pollution, energy consumption (Anh et al., 2022). Rail transportation is an important mode of passenger transportation (Assad, 1980). Regional and urban rail transportation not only reduces commuting times for city dwellers but also changes urban spatial patterns such as population and employment distributions (Zhang et al., 2017). Also, rail transportation contributes to meeting global climate targets since it is characterized by low emissions (Lindenmaier et al., 2021). Incentivizing rail transportation is a key part of reducing the number of private automobiles on the road, traffic congestion, and pollution. However, while increasing the use of the regional rail system, effective ticket pricing should be considered.

Decentralization of cities is an important criterion for selecting an urban rail transportation pricing system. If the urban rail transportation network covers the outer of the city, people work in the city center and live in lower-rent houses outside the city. By expanding the city to the outer, a decentralization issue is created. As the city grows, so do the lengths of public transportation lines, which adds to operators' operating costs due to frequent maintenance requirements and increases air pollution due to longer vehicle travel times. A rent-based pricing system, on the other hand, increases the financial burden on people traveling for longer distances, motivating them to live close to their work and social environment. This reduces city decentralization and shortens urban rail transportation lines, lowering vehicle operating costs while also being environmentally friendly (Gaigné et al., 2012).

6.2. Background

Pricing structures are usually categorized as flat fare, distance-based fare, and zonal pricing (Batarce & Mulley, 2016). A flat fare is the application of a fixed price regardless of the distance and time traveled. Researchers have criticized that flat fare is unfair (Liu et al., 2017; Cheng et al., 2015). Because, short-haul customers heavily subsidize long-haul passengers (Cervero, 1981). Therefore, a flat fare system is suitable for small cities and short travel distances. In a study, a Sectional Fare System price for the New York City subway is established and its impact on the financial situation of the New York City Transit Authority is investigated (Yamada, 1985). Results show that in the flat fare, total operating revenue did not cover total operating expenses. Increasing ticket prices in the flat fare ignored the equity problem between short-distance and long-distance riders. Besides, substantial loss in ridership occurred. A study offered a fare selection for rail transport systems based on an operating plan with elastic demand (Deng et al., 2014). An optimization model was built in terms of the operators' interests, system efficiency, system control goals, and system expenses. The results reveal that a low-cost policy in the flat fare may be implemented only if the government provides sufficient financial assistance. Nuworsoo et al. (2009) examined the Alameda Contra Costa Transit Districts' five flat fare proposals, which included base fare reductions, fare hikes, the discontinuation of periodic passes, and the elimination of free

transfers. In the study, it is estimated likely flat revenues, as well as the effects of individual flat fare offerings on different subsets of different riders. It was concluded that the five alternative Transit District proposals that raised the cost of transfers or removed unlimited-use passes caused inequity for some riders. Flat-fare was found to be the least equitable since young commuters, minorities, and lower-income riders made more trips. Rubensson et al. (2020) compare the distributional and geographical fairness of flat fare, zone-based, and distance-based fare plans in Stockholm Public Transportation using socio-economic statistics from census areas and data from 78 public transportation modes from a transport estimation representation. High-income public transit customers gain from all three fare structures studies, although flat fares provide the least advantage. The theoretical studies in the literature are limited compared to the practical studies. Cheng et al. (2015) evaluated the unit fare, farebox recovery ratio, and unit cost in terms of fare equity indexes. To perform the equitable evaluation of unit fares distribution among public transportation passengers, the Gini coefficient and the Lorenz curve theory were used. They assessed fare equity using recognized methods and indexes, concluding that a flat fare is unfair.

In zonal pricing, the ticket price depends on the start and end zone of the journey. In a study, a multinomial logit mode choice model is developed to measure the monetary value of transit users' travel time and the effect of such fare change on passengers' accessibility is investigated (Ma et al., 2017). It was found that the most adequate structure in terms of accessibility is the one that minimizes monetary cost for users. The findings of this paper suggest applying a zone-based fare structure as opposed to the flat fare structure available, to ensure equity for all users. Zonal pricing is easier to implement than distance-based fare. The limited variety of fare combinations between zones creates less confusion for passengers. In zonal pricing, a different pricing method is applied within and between each zone by making regional distinctions (Otto & Boysen, 2017). These distinctions can cause decentralization of the cities and hardness in managing the public transportation system. Also, it may seem unfair to pay less for a long distance within a zone than for short-distance travel between two zones. Another problem of this system is the difficulty of determining the zone boundaries. Expert labor may be required to establish the boundaries fairly.

Distance-based fare changes according to the number of kilometers traveled (Borndörfer et al., 2012). In this system, passengers traveling long distances pay more, while the ones traveling short distances pay less (Maadi & Schmöcker, 2018). Deng et al. (2014) created an optimization model that provides operator benefit by taking flat fare and distance-based fare into account. It was stated that the flat fare is applicable only when the government provides sufficient financial subsidies or economic support for a low price policy and the distance-based fare structure had better be taken to attract more short-haul passengers. A study using detailed travel log data from California investigated the equity outputs of low- and high-income public transit passengers under different fare structures (Brown, 2018). It has been observed that using a distance-based pricing system instead of a flat fare has greatly increased the fairness and transport ridership (Daskin et al., 1988; Tsai et al., 2008). Similarly, in some studies that prioritize social benefits and fairness, flat fare systems are criticized and distance-based pricing is recommended. (Liu et al., 2017; Ma et al., 2017). Farber et al. (2014) create and test a new method for assessing the social equity effects of distance-based public transportation fares. It is noted that distance-based fares disproportionately affect low-income, non-white, and elderly people.

The efficiency of the public transportation pricing system benefits many aspects such as cost, transportation, and the environment. Besides these, the decentralization of cities is an essential but often ignored consequence of the rail transportation pricing system. Regular commuters who live in low-density residential areas outside of the big cities frequently use suburban public transportation (Hörcher et al., 2017). When the public transportation network extends to the edges of the city, people can work in the inner city and live in lower-cost housing on the outside, as public transit provides transportation between home and work. By expanding the city to the outside, it creates a decentralization problem. Decentralization is simpler when a service's externality is low; nevertheless, services with significant network effects or spillovers are difficult to decentralize (Prud'Homme, 1995). As the city grows, the lengths of public transportation lines grow, resulting in higher operating costs for operators due to frequent maintenance needs and increased air pollution due to longer vehicle travel times. Public transportation can reduce greenhouse gas emissions by facilitating compact land use, reducing the need to travel long distances, and minimizing the carbon footprint of transit operations, according to data from the Federal Transit

Administration and other academic, government, and industry sources (Hodges, 2010). The paper by Bloch and Pignataro (1982) discusses the role of public transportation in a decentralized urban setting. The authors point out that while public transportation in decentralized areas is less efficient than in high-density areas, public transportation operating costs in decentralized areas are substantially higher. However, a system that raises the cost burden of transportation on those who must travel in longer lines may eventually encourage them to pick a home that is close to their workplace and social surroundings. This lessens the decentralization of cities and shortens the lines of public transportation trips, which lowers vehicle operating costs and is also good for the environment (Gaigné et al., 2012).

To the best of the authors' knowledge, there is no previously published research on public transportation pricing based on rent prices. The majority of the research is focused on transportation and housing. Households with easy access to public transport may spend less on transportation and therefore more on housing (Kilpatrick et al., 2007). Economic theory says that house prices should be influenced by the value of travel time savings (Hess and Almeida 2007). Transport and housing costs are bonded, and theories and models of urban form, suburbanization, and housing markets are built on this bond (Alonso 1960, 1964, Muth 1969, Mills 1972, Brueckner 1987). Households should plan their financial costs properly and make affordable choices in their housing and transportation choices. Otherwise, there is a danger of not being able to meet other essential needs, which can cause financial stress on individuals. Recently, an essential method for measuring total housing and transportation costs called Housing and Transportation (H+T) affordability index has been developed for various locations within cities (Isalou et al., 2014). According to Litman (2013), the transportation expenditure should not exceed more than 20% of the total income and the combination with a housing expenditure should be less than 45% of the total income for affordable life. By establishing a bridge between rent prices and transportation costs, this paper develops a rent-based pricing system that can be a solution to the problems mentioned in the literature.

6.3. A Proposed Rail Transportation Pricing

Distance to the city's single-center largely explains real estate prices in the monocentric city model (Free and Free, 2010). The city is assumed to be a uniform space with a single-center, known as the central business district (CBD), in such models (Huriot and Thisse, 2000). Closed-form solutions describing the falloff in population density, land prices, and house prices as residents live increasingly far from a CBD are obtained using only a few general assumptions in stripped-down models (Rappaport, 2014). Workers commute to a central location to work and choose a residential location based on the trade-off between lost wages due to travel time and their preference for space in the monocentric city model (Baum-Snow, 2007). In recent years, the development of transportation networks and low rental prices in areas outside of the city center have pressured people to live edge of the city. According to TUIK population growth rate data for 2020, the population growth rate of districts such as Aliağa and Torbalı located on the IZBAN route and outside the city is 43.1 percent and 44.1 percent, respectively, while the Konak district located in the city center has a population growth rate of -19.8 percent (DIE, 2020). Rental prices in İzmir are also falling from the city center to the edge of the city. The table shows the average rent prices per square meter in the districts along the IZBAN route of the clusters created within the scope of rent-based pricing. Rents outside of the city are lower than those in the city center. Rent per m^2 in the districts along the IZBAN route is presented in Table 6.1.

Table 6.1. Rent per m^2 in the districts along the IZBAN route.

Clusters	**District**	**Rent per m^2**	**Mean prices**
Cluster-1	Aliağa	13 TL	13 TL
Cluster-2	Menemen	14 TL	17 TL
	Çiğli	18 TL	
	Karşıyaka	20 TL	
	Bayraklı	15 TL	
	Konak	18 TL	
Cluster-3			16,5 TL
	Buca	16 TL	
	Gaziemir	18 TL	
	Menderes	14 TL	
Cluster-4	Torbalı	10 TL	10 TL
	Selçuk	10 TL	

Source: Endeksa

All of these data demonstrate that existing public transit pricing schemes encourage people to select based on rent rather than transportation prices. Rent-based pricing, on the other hand, attempts to encourage travelers to rent a house in the regions where they travel, such as near their jobs or schools, by allowing them to directly consider the rent when deciding where to live. Figure 6.1. illustrates the different types of public transportation pricing systems and how rent-based pricing works. In a flat fare, passengers pay the same fare at x km distance and 2x km distance. Also, the fare for arrivals from outside the city to the central area of the city is the same price. Even if x km departing and 2x km departing pay different costs under distance-based pricing, there is no difference in fares for arrivals from outside and inside the city. The transportation price for x km in a zone in the city center is half of the distance x km in the zone outside the city, according to zonal pricing. The x km distance outside the city and the 2x km distance from this zone to the city center are charged at the same price. All of these pricing structures encourage individuals to relocate outside of cities, causing cities to decentralize. The person who travels x km distance outside the city pays more than the one who travels x km distance inside the city in rent-based pricing. At the same time, the 2x km distance from outside the city to inside the city incurs the largest cost. As a result, many who live outside of the city will contemplate moving to the city center, taking into consideration transport costs.

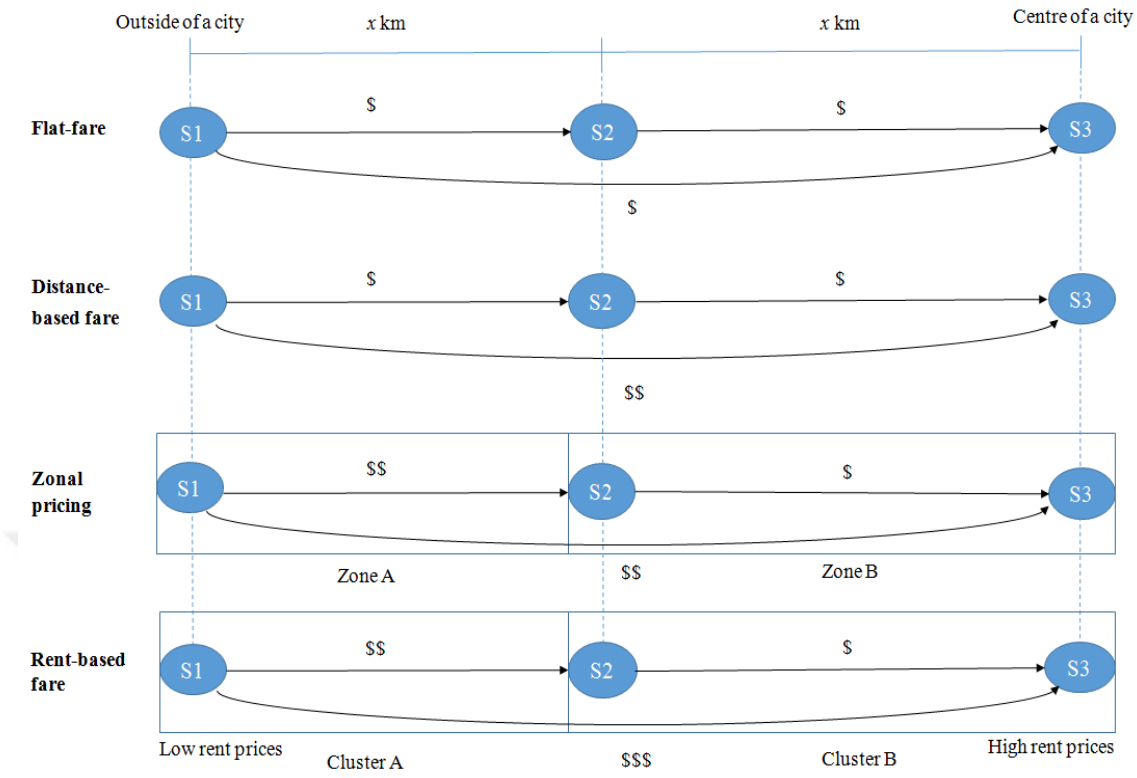

Figure 6.1. Public transportation pricing types.

6.4. Methodology

The study's methodology is divided into three sections. The first step is the case study. The second step is to collect data that will be used to create rent-based pricing. The cluster analysis is the third stage, which is used to classify the data based on stations. The non-linear optimization method is the final stage and then ticket prices are calculated. A flowchart of the rent-based pricing process is shown in Figure 6.2.

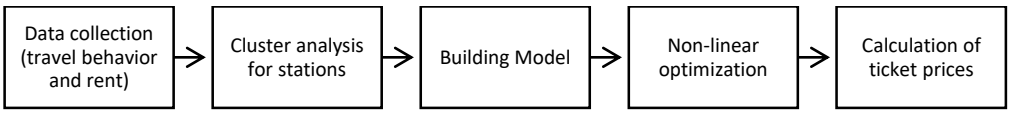

Figure 6.2. Flowchart of the rent-based pricing process.

6.4.1. Case Study

İzmir is Turkey's third-largest city, with public transit available by land, sea, and rail. İzmir Urban Rail Mass Transit System (IZBAN), which has been in operation since 2010 and has a line length of 136 kilometers, is one of the city's most major public transportation systems. IZBAN, which operates 40 stations in the city center and beyond, began with a flat fare until switching to a distance-based pricing system in 2018. IZBAN is a suitable example for the application of rent-based pricing since both pricing systems are implemented and it hosts stations with different rental prices. Figure 3.1. shows the IZBAN route, which begins with Aliağa station on the north axis and Selçuk station on the south axis.

6.4.2. Data

The number of IZBAN passengers is 84,450,567 according to 2018 IZBAN data. This number is 231,371 for a day. The sample size is calculated as 400 with Equation (3.2) of Yamane (1967) by taking population size as 231,371 and assuming 95% confidence level and $P=0.5$. However, 606 surveys were conducted.

6.4.3. Cluster Analysis

Cluster analysis is associated with grouping or segmentation. Each data object is defined by its features and connection with others. Cluster analysis, one of the multivariate statistical techniques, classifies non-predefined objects and an unknown number of sets. It examines the similarity within the same cluster and the dissimilarity between the clusters. That is, cluster analysis is based on two basic principles; maximizing the distances between intercluster and minimizing distances within the cluster. The clustering methods are classified as hierarchical and non-hierarchical. K-means is the most widely used non-hierarchical cluster algorithm.

In the k-means algorithm, the k parameter specifies the number of clusters that will divide the data, and the number of clusters must be determined beforehand. The algorithm

randomly selects the number of *k* centroids. Each cluster is compatible with the centroid, which is the mean value of the points in the cluster, and each point is assigned to the closest cluster. Proximity is determined by "Euclidean distance", cosine similarity, correlation, etc. Then, the centroid is calculated again for each cluster and reclustering is performed. Clusters can change from one run to the next. The aim is to keep the *J* function as low as possible, that is, to minimize the sum of the intracluster distances. K-means will aggregate the similarity measures at a point where the *J* function will decrease as the clusters become more compact. Calculations continue until the centroid remains constant (Norusis, 1993)

$$J = \sum_{x_i \in D} \min_{c_i \in C} \|c_i - x_i\|^2 \qquad (6.1)$$

where c_i is the data point, x_i is the centroid of c_i's cluster.

The k-means algorithm may not give good results if the data groups are of different sizes, the densities of the data groups are different, the shape of the data groups is not spherical, and there are outliers in the data. The number of clusters must be specified in advance. Unfortunately, there is no way to find the optimal number of clusters. The final clusters are very sensitive to random initialization and do not guarantee convergence. If *k* is large, the error is probably reduced but the risk of overfitting increases.

The clustering structure consists of all data points at one end and clusters equal to the data points at the other end in hierarchical clustering. It is not possible to rearrange previously created clusters. Hierarchical clustering can be agglomerative or divisive clustering. The divisive clustering technique is a top-down approach, starting from a single cluster to the maximum number of clusters. Agglomerative is a bottom-up approach. Each observation starts in its cluster, and as it moves up the hierarchy, groups of clusters are combined into a single cluster. Clusters with the nearest measure of cluster similarity are merged continuously until the last cluster or a predefined number of clusters remains.

If the number of clusters k is unknown, the Silhouette method is used to find the k value. The silhouette value demonstrates the consistency of the clustering technique by

measuring how similar an object is to its cluster in comparison to other clusters (Wang et al., 2016). This value changes in the range of [-1,1]. The higher the value, the better the object matches its cluster and the better it differentiates from other clusters. Values close to 0 are an indication of overlapping clusters. Negative values typically indicate that a sample is incorrectly assigned to a cluster (Lefranc et al., 2016). The calculation of the silhouette coefficient is as shown (Dinh et al., 2019)

$$s_i = \frac{b_i - a_i}{\max(b_i, a_i)} \tag{6.2}$$

where a_i is the mean intra-cluster distance, b_i is the mean nearest-cluster distance, s_i is silhouette coefficient.

The basic algorithm of Agglomerative Nesting clustering, the most popular hierarchical clustering technique, is simple. There is no need to determine the number of clusters. It produces nested clusters organized in a hierarchical tree. Algorithms use a similarity or distance matrix. It can be visualized as a dendrogram. Any number of clusters can be found by cutting the dendrogram at an appropriate level.

Data should be prepared as a numerical matrix consisting of rows representing observations and columns representing variables. In the algorithm, each point is considered a cluster, and one cluster less is generated at each of the *(N-1)* steps. The proximity between all cluster pairs is calculated and the two closest clusters are combined. There are three most commonly used methods of identifying intergroup dissimilarity. The difference *d(Z, V)* between *Z* and *V* is derived from the binary set of observation differences where one member of the pair *i* is in *Z* and the other *i* is in *V* if *Z* and *V* represent two such groups (Hastie et al., 2009). The Nearest-neighbor approach, also known as single-linkage (SL) agglomerative clustering, considers the difference between groups as the nearest one as shown

$$d_{SL}(Z,V) = \min d_{ii'} \qquad i \in Z,\ i' \in V. \tag{6.3}$$

Complete linkage (CL) agglomerative clustering, also called the furthest-neighbor technique, takes the difference between groups as that of the furthest pair as shown (Hastie et al., 2009)

$$d_{CL}(Z,V)=max\ d_{ii'} \qquad i \in Z,\ i' \in V. \tag{6.4}$$

Group Average (GA) Clustering uses the average difference between the group as shown (Hastie et al., 2009)

$$d_{GA}(Z,V) = \frac{1}{N_Z N_V} \sum_{i \in Z} \sum_{i' \in V} d_{ii'} \tag{6.5}$$

where N_Z and N_V are the numbers of relevant observations in each group.

The pairwise similarity between the new cluster and the original clusters is reflected by updating the similarity matrix (Farjo et al., 2013). The process of combining the two nearest clusters and updating the similarity matrix is repeated until only one last single cluster or predefined cluster remains.

6.4.4. Model Building

Many studies use optimization techniques to determine public transportation prices (Tsai, 2008; Jin et al., 2019; Samanta & Jha, 2011; Zhu et al., 2017; Deng et al., 2014). The non-linear optimization method is preferred in this study since the data to be used in rent-based pricing is non-linear. Optimization models can be classified according to the decision variables, objective function, and system constraints. In the nonlinear optimization model, the objective function or some of the constraints are nonlinear. In the study, a set of objectives and constraints are formulated and the resulting models are resolved by non-linear optimization techniques concerning public transportation fare and rent. Model 1 is established as

$$
\begin{aligned}
&\max z_1 = \sum_i \left[\left(\frac{p_i}{s_i . n_i} \right) \left(f_i + r_i \right) \right] \\
&g_i = c_i + d_i . r_i \\
&g_i . \alpha_i \le f_i \le g_i . \beta_i \\
&l_i \le r_i \le v_i \\
&g_i \ge 0 \\
&f_i \ge 0 \\
&r_i \ge 0.
\end{aligned} \tag{6.6}
$$

The cluster in which the stop is located is represented by i in all models. In the study, four clusters were formed according to cluster analysis. While p_i represents the number of passengers in cluster i, n_i represents the population in cluster i. Together, p_i and n_i, and the number of stations in the cluster s_i, represent the population's public transportation usage rate. The objective function allows for higher total rent and transportation costs at stations with high ridership, and lower total rent and transportation costs at stations with low ridership to encourage travelers. f_i, represents the average household public transportation cost in cluster i. r_i, is the average rental price in the cluster. g_i refers to monthly household income and is calculated using regression analysis of survey data, and c_i represents constants for income forecasting in Equation (6.7), while d_i is the variable coefficient for income estimation. f_i is constrained by g_i's lower α_i and upper β_i public transportation affordability index limits. r_i is constrained by the lower limit of rent l_i and upper limit of rent v_i.

Model 2 is established as

$$\begin{aligned} &\max z_2 = \sum_i f_i.r_i \\ &g_i = c_i + d_i.r_i \\ &g_i.\alpha_i \le f_i \le g_i.\beta_i \\ &l_i \le r_i \le v_i \\ &g_i \ge 0 \\ &f_i \ge 0 \\ &r_i \ge 0. \end{aligned} \tag{6.7}$$

The objective function in the second model is based on the inversely proportional variation of the rental and transportation costs. The rest of the constraints are the same as in model 1. Model 3 is established as

$$\begin{aligned} &\min z_3 = \sum_i \left(\frac{f_i + r_i}{g_i} \right) \\ &g_i = c_i + d_i.r_i \\ &g_i.\alpha_i \le f_i \le g_i.\beta_i \\ &l_i \le r_i \le v_i \\ &g_i \ge 0 \\ &f_i \ge 0 \\ &r_i \ge 0. \end{aligned} \tag{6.8}$$

The objective function of the third model minimizes the ratio of total rental and transportation costs to monthly household income. All other constraints are the same as in previous models.

Model goal programming is established as

$$
\begin{aligned}
&\min z = \frac{s_1^-}{z_1^*} + \frac{s_2^-}{z_2^*} + \frac{s_3^+}{z_3^*} \\
&\sum_i \left[\left(\frac{p_i}{s_i.n_i} \right) \left(f_i + r_i \right) \right] - z_1^* = s_1^+ - s_1^- \\
&\sum_i (f_i.r_i) - z_2^* = s_2^+ - s_2^- \\
&\sum_i \left(\frac{f_i + r_i}{g_i} \right) - z_3^* = s_3^+ - s_3^- \\
&s_1^+, s_1, s_2^+, s_2^-, s_3^+, s_3^- \geq 0 \\
&g_i = c_i + d_i.r_i \\
&g_i.\alpha_i \leq f_i \leq g_i.\beta_i \\
&l_i \leq r_i \leq v_i \\
&g_i \geq 0 \\
&f_i \geq 0 \\
&r_i \geq 0.
\end{aligned}
\tag{6.9}
$$

In the goal programming model, s_1^+ and s_1^- represent the positive and negative deviation from the primary objective, s_2^+ and s_2^- positive and negative deviation from the secondary objective, s_3^+ and s_3^- positive and negative deviation from the third objective. The goal here is to minimize the sum of the ratios of deviations and the optimal values of the objective functions. So the goal is to minimize the optimal value *z* of the objective function of the goal programming model. z_1^*, z_2^* and z_3^* represent optimal values of objective functions.

Solving Constraint Integer Programs (SCIP) are used to resolve the model. SCIP is a constraint integer programming (CIP) software platform (Achterberg, 2009). Modeling and resolution strategies based on mixed-integer programming (MIP) and satisfiability (SAT) are included. All of the algorithms involved work on a single search tree, allowing for close collaboration between them.

6.5. Results

K-value is found by using k-means and AGNES (*Agglomerative* Nesting) clustering methods. The cluster methods consider the distance between the stations. Cluster type is selected according to the best value of silhouette coefficient. Comparison of silhouette coefficients by AGNES and k-means clustering is given in Figure 6.3. The highest silhouette value is obtained with 0.539 in 4 clusters with the K-means method, and with 0.536 in 5 clusters with AGNES. Therefore, the k-value is 4 and the K-means clustering method is suitable.

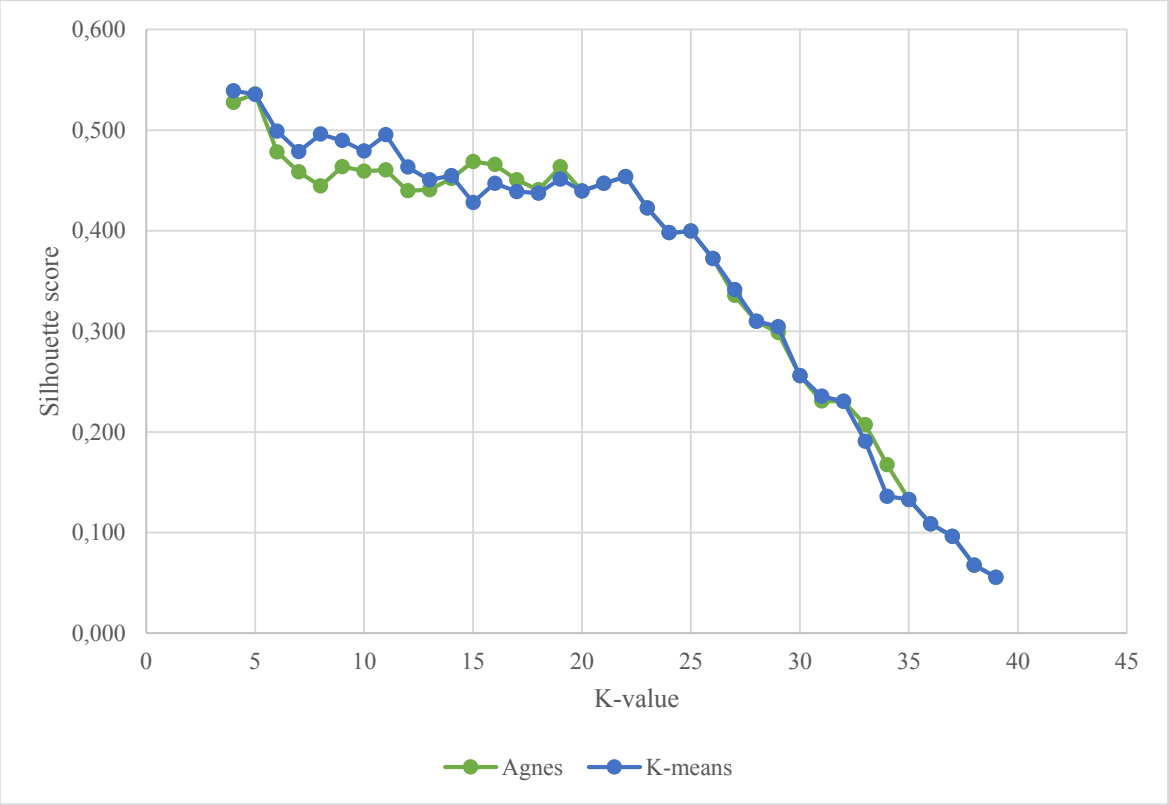

Figure 6.3. Silhouette scores by K-means and Agnes methods.

One of the purposes of establishing a rent-based pricing system is to reduce the number of trips from outside to the city center and to encourage those passengers to rent houses in the areas where they travel constantly. Therefore, rent-based pricing also takes into account

the distance between stations, just like distance-based pricing. Clusters, average rent, average income, average travel frequency, and average household size are shown in Table 6.2. The cost of renting a home outside of the city center is slightly greater than in the city center. Because there are many slums and many old residences in the city center. Planned and luxury housing projects are located outside of the city at affordable prices. Those who live outside of the city have a greater average income than those who live in the city center. In terms of the rent-to-income ratio, people who live outside the city have an advantage over those who live in the city center due to the modest difference in rents. Travel distances fluctuate significantly. Passengers who travel far from the city center travel an average of 41.16 km and 42.08 km, while those who live in the city center travel an average of 11.97 km and 15.71 km. That is, people who live far from the city center can meet the living conditions in the city center. However, they live outside of the city and burden enormous operational, environmental, and user costs.

Table 6.2. Cluster characteristics.

Features	Clusters			
	Aliağa-Hatundere	Menemen-Halkapınar	Alsancak-Tekeli	Pancar-Selçuk
Rental price	1385	1262	1161	1297
Household income	6333	5755	5163	6375
Travel distance	41.16	15.71	11.97	42.08
Journey frequency	24.33	25.55	21.59	24.44
Household size	2.79	3.56	3.46	3.06
Rent per income	0.2188	0.2193	0.2248	0.2034

The public transportation affordability index is calculated over the averages of household income, household size, travel frequency, and ticket price with the formulation used by Gomez-Lobo (2011). The minimum value is calculated over the current ticket tariff since it is considered that operators define the current ticket price depending on operating costs. As result, the public transportation affordability index is a minimum of 3.2% and a maximum of 4.9%.

Income and rent relationships within the clusters are defined by Regression Analysis. Household income is assigned as the dependent variable, and rent is the estimator. The model summary is given in Table 6.3., the values show that the model is significant.

Table 6.3. Regression analysis of income and rent price.

Departure station		Unstandardized Coefficients	R	R Square	Durbin-Watson	Anova	
		B				F	Sig
Aliağa-Hatundere	(Constant)	272.344	0.858	0.735	1.361	61.146	0.000
	Rent price	4.375					
Menemen-Halkapınar	(Constant)	1,533.52	0.638	0.407	1.469	209.588	0.000
	Rent price	3.345					
Alsancak-Tekeli	(Constant)	1,811.87	0.574	0.330	1.408	126.116	0.000
	Rent price	2.887					
Pancar-Selçuk	(Constant)	-739.92	0.823	0.677	2.298	29.396	0.000
	Rent price	5.486					

For each cluster, the objective function results of transportation and rent costs derived from solving the nonlinear optimization problem are shown in Table 6.4. The public transportation goal and rent goal ratios for Pancar-Selçuk and Aliağa-Hatundere, which are the clusters furthest from the city center, are 25% and 22%, respectively. In the city center, however, it is 19 percent for the Menemen-Halkapınar cluster and 17 percent for the Alsancak-Tekeli cluster.

Table 6.4. Non-linear optimization results.

Cluster	Results								
	f-1	f-2	f-3	f-goal	r-1	r-2	r-3	r-goal	f/r
Aliağa-Hatundere	576.079	576.079	96.215	576.079	2625	2625	625	2625	0.22
Menemen-Halkapınar	587.346	587.346	89.213	587.346	3125	3125	375	3125	0.19
Alsancak-Tekeli	495.488	495.488	92.624	495.488	2875	2875	375	2875	0.17
Pancar-Selçuk	467.77	467.77	305.483	467.77	1875	1875	1875	1875	0.25

The new pricing is based on the transportation cost-to-rent ratio and the clusters' average rental value. The flat fare is applied up to 25 km and the distance-based fare is applied after 25 km, the same as the current system. Tariffs for full, student and teacher transportation cards are shown in Table 6.5. The prices for students and teachers are different. The full fare for up to 25 km is 2.86 TL, and the same pricing is applied to all stations in distance-based pricing. In rent-based fare, a passenger in the Aliağa-Hatundere cluster pays 4.49 TL up to 25 km. Another in the Pancar-Selçuk cluster pays 4.34 TL. Passengers in the Menemen-Halkapınar and Alsancak-Tekeli clusters pay 2.64 TL. After 25 km, 0.07 TL per km is charged to the flat fare at all stops for distance-based pricing. In rent-based pricing, on the other hand, 0.07 TL per kilometer is charged in addition to each cluster's flat fare. For all stops and travel distances, the full price is 2.86 TL at the flat fare. Flat fare, which does not account for travel distances, imposes a substantial burden on operating costs in this respect. Distance-based pricing, on the other hand, is incapable of preventing long-distance travel from outside the city, and it imposes a financial and environmental cost.

Table 6.5. Rent-based fare, distance-based fare, and flat fare comparison.

			Cluster			
			Aliağa-Hatundere	**Menemen-Halkapınar**	**Alsancak-Tekeli**	**Pancar-Selçuk**
Rent-based fare scheme (According to 2018)	**Full fare**	**FF**	4.49 TL	2.64 TL	2.64 TL	4.34 TL
		DBF	4.49+0.07x(TD-25)	2.64+0.07x(TD-25)	2.64+0.07x(TD-25)	4.34+0.07x(TD-25)
	Student	**FF**	2.59 TL	1.52 TL	1.52 TL	2.5 TL
		DBF	2.59+0.04x(TD-25)	1.52+0.04x(TD-25)	1.52+0.04x(TD-25)	2.50+0.04x(TD-25)
	Teacher	**FF**	3.45 TL	2.03 TL	2.03 TL	3.34 TL
		DBF	3.45+0.05x(TD-25)	2.03+0.05x(TD-25)	2.03+0.05x(TD-25)	3.34+0.05x(TD-25)
Current pricing scheme (in 2018)	**Full fare**	**FF**	2.86 TL			
		DBF	TP=2.86+0.07x(TD-25)			
	Student	**FF**	1.65 TL			
		DBF	TP=1,65+0.04x(TD-25)			
	Teacher	**FF**	2.2 TL			
		DBF	TP=2.20+0.05x(TD-25)			
Previous pricing scheme (Flat fare according to 2018)	**Full fare**		2.86 TL			
	Student		1.65 TL			
	Teacher		2.2 TL			

Ticket revenues were computed using two different ways. First, the number of passengers and the maximum journey distance based on stations were used. Second, the distribution ratio of departure stations to arrival stations obtained from the survey data, as well as the number of passengers based on stations, were used in the ticket revenue computations. The rent-based fare reduces ticket revenues by 2.77 percent and 1.18 percent, respectively, under the distance-based fare. However, passengers will soon begin to travel short distances as the implications of rent-based pricing play out over time. As a result, because operating expenses would be lower, more revenue will be generated than the current system. Also, there is a significant revenue increase in rent-based fare compared to the flat fare system.

Table 6.6. Ticket revenue comparison.

	Ticket Revenues (TL)				
	Rent-based fare	Distance-based fare	Change (%)	Flat fare	Change (%)
Based on the survey	243,448,705.12	250,383,852.28	2.77	234,248,780.48	-6.44
Based on the max. distance	590,985,998.45	598,044,839.72	1.18	241,527,892.32	-59.61

Municipalities may not want to lose ticket revenues in the first stage since the reduction of operating costs in rent-based fare spreads over time. As a result, they can use the current pricing system in city center clusters and the rent-based pricing system outside the city. Compared to the current pricing system, ticket revenues increase by 3.88 percent and 1.68 percent in the alternative scenario.

Table 6.7. Alternative ticket revenue comparison.

	Ticket Revenues (TL)		
	Distance-based fare	Alternative	Change (%)
Based on the survey	250,383,852.28	260,106,095.54	3.88
Based on the max. distance	598,044,839.72	608,107,494.77	1.68

6.6. Managerial Implications

There is a large gap in the literature about the relationship between rent price and public transportation pricing. Rent-based fare is determined using a Nonlinear Optimization model and data on rent and travel behavior. It encourages people to spend more on rent rather than transportation. That is, people prefer to live close to their social or work areas and travel short distances. This system has many positive outcomes. Rent-based fare solves the decentralization problem since it encourages people to rent a house in regions that will shorten their travel distances and decrease transportation costs. The system provides many benefits besides building compact and central cities. Operating costs are reduced due to reduced travel distances, and financial resources are used more effectively. Travel comfort and service quality are increased by increasing vehicle travel frequencies through reduced operating costs; thus, personal vehicle use reduces. In terms of users, beyond the reduction of transportation cost, it offers more comfortable travel with more efficient use of the time allocated for transportation, reducing user cost, increasing the quality of life, and improving the public transportation service quality. Rent-based fare, which can be an alternative to existing pricing systems, is sustainable and fair for operators and users. For this purpose, an interpretive approach is presented to better capture the strategic actions of public transport actors and all stakeholders within their context, with the example of rent-based pricing offered through IZBAN. While the proposed pricing method is exemplary for commuter rail systems, it can also lead to empirical examples in long-distance buses, trams, and other public transportation modes. Municipalities can access transportation and rent data without any problems, making it easier to implement a rent-based fare system for operators.

6.7. Conclusion

This chapter fills an important gap in public transportation pricing systems by presenting a new pricing system based on rental prices. To determine the rent-based fare, the survey data was subjected to a k-means clustering technique based on the distances between the stops. A non-linear optimization model was created and rent-based fares were determined for each cluster to leverage the clusters' rent and income information in the objective functions. Rent-based pricing generates more ticket revenues than flat fare, but not as much as distance-based fare. The consequences of rent-based pricing may become apparent over time because the goal is to encourage travelers to rent homes in places where they travel shorter distances. When travel distances are reduced, travel frequencies for longer distances can be reduced, and operational expenses can be reduced. As a result, an effective and fair pricing structure is established.

Further research can establish rent-based pricing for each station using more extensive passenger data. Also, the engagement of a larger number of experts and the using real-time data can be provided in future research. The proposed pricing method can also be applied in long-distance buses, trams, and other public transportation modes. Municipalities can access transportation and rent data without any problems, making it easier to implement a rent-based fare system for operators.

7. CONCLUSION AND RECOMMENDATIONS

Public transport pricing is a multifaceted issue and requires an interdisciplinary perspective that embraces various fields such as economics, urban planning, engineering, sociology, and traffic management. While there are different approaches for public transportation pricing, such as optimizing the existing pricing system and the user or operator profit, there is no systematic and concise analysis and review of the public transportation pricing in the literature in terms of its impact on other key issues such as decentralization of cities, traffic, and political aspect. This thesis aims to fill this gap. In this context, this thesis provides an overview of the relevant literature but also fills an important gap in public transportation pricing systems by presenting a new pricing system based on rental prices. Hence, the basis for future rent-based public transport fare studies is prepared. This document also establishes a consensus for municipalities to compare different transport pricing systems. Hence, the study proposes the integrated CRITIC and MABAC based type-2 neutrosophic model for public transportation pricing system selection. This hybrid model has two straightforward stages. The first stage determines the reputation of invited experts under the T2NN environment. In the second stage, the T2NN-CRITIC-MABAC approach is formulated to solve the addressed MCDM problem. According to the proposed methodology, the rent-based fare is the most advantageous pricing system for public transportation. This unique pricing system makes cities eventually more compact and solves the problem of unfairness by eliminating the need for long public transportation lines.

Operating and user costs are more visible in urban transportation pricing assessments because of conflict between the interests of operators and users. However, the costs of public transportation pricing are very diverse, and some have huge impacts. These are the increase in transportation operating and user costs as a result of the growth of cities, the decrease in comfort levels and social acceptability due to overcrowding, switching to use personal vehicles, long travel times, environmental pollution, the substantial financial burden on municipal budget and political failure. In this study, a rent-based pricing model is proposed to reduce these multifaceted costs by aligning the interests of the transport authority and

operators. Rent-based pricing is a beneficial pricing method for both users and the environment.

İzmir is a city where the study's findings can be applied to developed and developing cities due to its high population, having different transportation systems, and spreading its borders over a wide area. There are also examples of the urban rail mass transit system used in İzmir in world cities such as Paris (Réseau Express Régional-RER), Istanbul (Marmaray), and Berlin (S-Bahn). Therefore, this thesis provides a deeper understanding of the problems posed by such transportation modes. Developing cities suffering from a shortage of adequate public transport specialists may also benefit from the findings presented in this study. However, contextual factors such as diversity of geographical conditions, integration between modes of transport, and demographics of cities should be considered before using the findings. The findings do not directly apply to cities where transportation systems operate over short distances and have low operational, environmental, and user costs.

What can holistically improve the performance of the transportation pricing system is not only the benefit of users or operators but the ability to settle down applications that can reduce personal vehicle use and prevent the decentralization of cities. One of the claims put forward by this thesis is that a systematic improvement can be achieved, and public acceptance is increased by providing better urban public transport through the many benefits of a pricing system that can be seen as a disadvantage in terms of public acceptability.

There is a large gap in the literature about the relationship between rent price and public transportation pricing. Rent-based fare is determined using a Nonlinear Optimization model and data on rent and travel behavior. It encourages people to spend more on rent rather than transportation. That is, people prefer to live close to their social or work areas and travel short distances. This system has many positive outcomes. Rent-based fare solves the decentralization problem since it encourages people to rent a house in regions that will shorten their travel distances and decrease transportation costs. The system provides many benefits besides building compact and central cities. Operating costs are reduced due to reduced travel distances, and financial resources are used more effectively. Travel comfort

and service quality are increased by increasing vehicle travel frequencies through reduced operating costs; thus, personal vehicle use reduces. In terms of users, beyond the reduction of transportation cost, it offers more comfortable travel with more efficient use of the time allocated for transportation, reducing user cost, increasing the quality of life, and improving the public transportation service quality. Rent-based fare, which can be an alternative to existing pricing systems, is sustainable and fair for operators and users. It ensures political success as its public acceptability increases over time, and its benefits become evident. For this purpose, an interpretive approach is presented to better capture the strategic actions of public transport actors and all stakeholders within their context, with the example of rent-based pricing offered through IZBAN. While the proposed pricing method is exemplary for commuter rail systems, it can also lead to empirical examples in long-distance buses, trams, and other public transportation modes. Municipalities can access transportation and rent data without any problems, making it easier to implement a rent-based fare system for operators.

IZBAN, the most basic passenger transportation system in İzmir, has been examined in this thesis to emphasize the above claims. IZBAN was established with a 50% partnership of Turkish Republic State Railways and İzmir Metropolitan Municipality. IZBAN's first stop in the north is Aliağa, and the first stop in the south is Selçuk. With a total line length of 136 km, IZBAN switched to using the distance-based pricing system in 2018. However, discussions about the sustainability of the new pricing system continue. In the past years, the public's reaction to the distance-based pricing system and the signature campaigns initiated, the strikes that took place due to the failure of the operators to meet the financial burden, and the service disruptions that lasted for weeks are some of the problems experienced in the system. These problems are evaluated, and a new public transportation pricing system is proposed as a solution.

Face-to-face surveys of 606 passengers are used to demonstrate travel behaviors in the thesis. A rent-based fare system is offered by a Nonlinear Optimization model that includes various data. Criteria with which public transportation pricing interacts are defined under 4 main headings for comparing the new system with other pricing systems and selecting the best system. These are cost aspect, transportation aspect, social aspect, and political aspect.

The cost aspect represents the financial expenses of operators and users. The expert cost has been included in this set since it is one of the main points where some transportation pricing systems differ from each other. The transportation aspect evaluates travel time, travel comfort, switch to a personal vehicle, and personal mobility. Another main criterion affecting public transport pricing selection is the social aspect, including environmental cost, quality of life, and decentralization of cities. Finally, the political aspect in which public transportation pricing is discussed in terms of transportation authorities creates a big gap in the literature and has never been mentioned. The political aspect includes the sub-criteria of public acceptability, political success, and deployment of resources. To determine the order of importance of these criteria in the selection of the public transportation pricing system, detailed surveys are conducted with public transportation experts. Two different methods are used to determine the ordering of importance of the criteria. First, local and global priorities of the criteria are determined through the Analytical Hierarchy Process. Accordingly, among the criteria, switch to a personal vehicle, decentralization of cities and public acceptability stood out as the three highest prior criteria. Later, the reputation of the experts is determined under the T2NN environment, and the novel T2NN-based CRiteria Importance Through Intercriteria Correlation (CRITIC) method is employed to evaluate the criteria importance.

The introduced hybrid type-2 neutrosophic model for public transportation pricing provides a new perspective as well as an effective tool for researchers and practitioners. Its advantages are as follows:

- Real-life preferences of municipal bodies (i.e., public transportation pricing actors) to favor experience over expertise and vice versa can be successfully represented.

- Differences and correlations among evaluation criteria can be simultaneously considered to elucidate their objective importance.

- Two build-in parameters provide higher flexibility when selecting public transportation pricing systems.

The AHP and T2NN-based CRITIC results are largely parallel. Alternative public transportation pricing systems to be evaluated by the criteria are selected as flat fare, distance-based fare, zonal pricing, and rent-based fare. The T2NN-CRITIC-MABAC approach is to solve the addressed MCDM problem. Results show that zonal pricing is the most disadvantageous in means of decentralization of the city and the issues regarding the pricing mechanism. Flat fare pricing is the second least disadvantageous regarding both fairness aspects because of fixing the price of public transportation and creating decentralization problems in the city. Distance-based fare pricing alternative is seen to be an advantageous pricing alternative in means of both fairness and decentralization by making commuters pay as much as they travel. According to the proposed methodology, the rent-based fare is the most advantageous pricing system for public transportation. This unique pricing system makes cities eventually more compact and solves the problem of unfairness by eliminating the need for long public transportation lines. However, the rent-based pricing method is the most advantageous one since it attacks the idea of decentralization. It makes the cities eventually more compact, so the need for long lines of public transportation becomes eliminated, which also solves the problem of unfairness. Rent-based fare is a unique public transport pricing method, and this alternative is considered a successful method by experts.

Alongside the advantages, there are also some limitations of this study. One of the main limitations of the study is the limited data available on IZBAN. It is barely difficult to get real data on transportation pricing systems since many authorities have considered transportation pricing to be a sensitive issue. One of the most important difficulties at the data collection point was that it coincided with the Covid-19 epidemic period. Further research should be directed towards the engagement of a larger number of experts in the research and analysis of the possibility of using real-time data. The other limiting effect is that the ridership at IZBAN stops in rural areas is very low, and there is no rent data in the catchment areas. Another limitation is the attractive areas locating schools, hospitals, bazaars, and shopping centers, apart from rent price and transportation factor, among the factors affecting the choice of living area. It must be admitted that considering these factors requires a very large amount of data. Pricing alternatives have been evaluated from a general perspective since real-time data are not used. Besides, the lack of an existing example of a

rent-based pricing system is a prejudiced issue. Four alternatives prioritized according to the advantages in this study may yield different results specific to the implemented region. For example, implementing flat fare may provide more benefits for smaller cities. Therefore, in future studies, geographical conditions can be taken into account. The proposed type-2 neutrosophic model can be focused on different aggregation operators to increase its flexibility, such as t-norm and t-conorm based Dombi or Einstein operators. The T2NN-CRITIC method is developed and solely employed to assign weights to the criteria. The integration of some other weight assigning method (e.g., Shannon entropy (Shannon, 1948), cross-entropy (Kullback and Leibler, 1951), Tsallis-Havrda Charvát entropy (Havdra and Charvat, 1967; Tsallis, 1988), nonprobabilistic entropy (De Luca and Termini, 1972), R-norm entropy (Boekee and Van der Lubbe, 1980), exponential entropy (Pal and Pal, 1989), etc.) into the proposed methodological framework can generate hybrid criteria weights and additionally improve its robustness. However, extensions of the aforementioned entropy-based methods under the T2NN environment are not yet available. This can be seen as another important avenue for future research. There are also some disadvantages associated with the new fare system such as the complexity of the system and the need for experts in its application. However, we believe that these problems can be solved with widespread use.

REFERENCES

Abdel-Basset, M., M. Saleh, A. Gamal and F. Smarandache, 2019, "An Approach of TOPSIS Technique for Developing Supplier Selection with Group Decision Making under Type-2 Neutrosophic Number", *Applied Soft Computing*, 77, 438-452.

Abdel-Basset, M., R. Mohamed, F. Smarandache and M. Elhoseny, 2021, "A New Decision Making Model Based on Plithogenic Set for Supplier Selection", *Computers, Materials & Continua*, 66(3), 2751-2769.

Achterberg, T., 2009, "SCIP: Solving Constraint Integer Programs", *Mathematical Programming Computation*, *1*(1), 1-41.

Adar, T. and E. K. Delice, 2019, "New Integrated Approaches Based on MC-HFLTS for Healthcare Waste Treatment Technology Selection", *Journal of Enterprise Information Management*, 32(4), 688-711.

Aggarwala, R. T., 2012, *Why Higher Fares Would Be Good for Public Transit*, http://www.citylab.com/commute/2014/07/why-higher-fares-would-be-good-for-public-transit/374314, accessed in March 2019.

Almujibah, H. and J. Preston, 2019, "The Total Social Costs of Constructing and Operating an High-Speed Rail Line Using a Case Study of the Riyadh-Dammam Corridor, Saudi Arabia", *Frontiers in Built Environment*, vol 5, 1-18.

Alonso, W., 1960, "A Theory of the Urban Land Market", *Papers in Regional Science*, 6 (1), 149–157.

Alonso, W., 1964, "Location and Land Use. Toward A General Theory of Land Rent", Cambridge, MA: Harvard University Press.

Anh, T. N., E. Kozemko and G. T. Cirella, 2022, "Research and Development Within Public Transport Systems", *In Human Settlements,* 59-76, Springer, Singapore.

Assad, A. A., 1980, "Models for Rail Transportation", *Transportation Research Part A: General*, 14(3), 205-220.

Aulia, P. L., H. M. Taki and A. S. Wartaman, 2021, "Impact of Transportation on Urban Compactness Index in South Tangerang City, Indonesia", *In IOP Conference Series: Earth and Environmental Science,* Vol. 737, No. 1, P. 012052, IOP Publishing.

Bandegani, M. and M. Akbarzadeh, 2016, "Evaluation of Horizontal Equity under a Distance-Based Transit Fare Structure", *Journal of Public Transportation*, 19(3), 161-172.

Bartley, B., 1995, "Mobility Impacts, Reactions and Opinions: Traffic Demand Management Options in Europe: The MIRO Project", *Traffic Engineering & Control*, *36*(11), 596-602.

Batarce, M. and C. Mulley, 2016, "Fare Structures", *Restructuring Public Transport Through Bus Rapid Transit: An International and Interdisciplinary Perspective*, 145-160, Policy Press.

Baum-Snow, N., 2007, "Suburbanization and Transportation in the Monocentric Model", *Journal of Urban Economics*, 62(3), 405-423.

Bloch, A. J. and L. J. Pignataro, 1982, *Public Transportation and Urban Decentralization: Conflict or Accord?*, Transportation Training and Research Center, Polytechnic Institute of New York.

Boekee, D.E. and J.C.A. Van Der Lubbe, 1980, "The R-Norm Information Measure", *Information Control*, 45(2), 136-155.

Borndörfer, R., M. Karbstein and M. E. Pfetsch, 2012, "Models for Fare Planning in Public Transport", *Discrete Applied Mathematics*, 160(18), 2591-2605.

Borndörfer, R., M. Neumann and M. E. Pfetsch, 2006, "Optimal Fares for Public Transport", *In Operations Research Proceedings 2005*, 591-596, Springer, Berlin, Heidelberg.

Brown, A.E., 2018, "Fair Fares? How Flat and Variable Fares Affect Transit Equity in Los Angeles", *Case Studies on Transport Policy*, 6(4), 765-773.

Brueckner, J.K., 1987, "The Structure of Urban Equilibria: A Unified Treatment of the Muth-Mills Model", *In: E.S. Mills, Ed. Handbook of Regional and Urban Economics*, New York: Elsevier, 821–845.

Buehler, R. and J. Pucher, 2011, "Making Public Transport Financially Sustainable", *Transport Policy*, *18*(1), 126-138.

Büyüközkan, G., E. Mukul and E. Kongar, 2021, "Health Tourism Strategy Selection via SWOT Analysis and Integrated Hesitant Fuzzy Linguistic AHP-MABAC Approach", *Socio-Economic Planning Sciences*, 74, 1-14.

Cantwell, M., B. Caulfield and M. O'Mahony, 2009, "Examining the Factors That Impact Public Transport Commuting Satisfaction", *Journal of Public Transportation*, 12(2), 1-21.

Carruthers, R., M. Dick and A. Saurkar, 2005, *Affordability of Public Transport In Developing Countries (Transport Paper TP-3)*, The World Bank, Washington, DC.

Cervero, R., 1981, "Flat Versus Differentiated Transit Pricing: What's a Fair Fare?", *Transportation*, *10*(3), 211-232.

Cervero, R., 2004, "Transit-Oriented Development in The United States: Experiences, Challenges, and Prospects", *Transportation Research Board*, Vol. 102.

Chatterjee, K., E.K. Zavadskas, J. Tamošaitienė, Adhikary, K. and Kar, S., 2018, "A Hybrid MCDM Technique for Risk Management in Construction Projects", *Symmetry*, 10(2), 7-34.

Chau, K. W. and F. F. Ng, 1998, "The Effects of Improvement in Public Transportation Capacity on Residential Price Gradient in Hong Kong", *Journal of Property Valuation and Investment*.

Chen, P. W. and Y. M. Nie, 2017, "Connecting E-Hailing to Mass Transit Platform: Analysis of Relative Spatial Position", *Transportation Research Part C: Emerging Technologies*, *77*, 444-461.

Chen, X., R. Yin, Q. An and Y. Zhang, 2021, "Modeling A Distance-Based Preferential Fare Scheme for Park-and-Ride Services in A Multimodal Transport Network", *Sustainability*, 13(5), 1-14.

Cheng, S., Q. Gao and Y. Zhang, 2015, "Assessing Equity of Regular Public Transit Fare Policy Based on Gini Coefficient", *In CICTP,* 2015, 1121-1131.

Chiarazzo, V., L. Dell'olio, Á. Ibeas and M. Ottomanelli, 2014, "Modeling The Effects of Environmental Impacts and Accessibility on Real Estate Prices in Industrial Cities", *Procedia-Social and Behavioral Sciences*, *111*, 460-469.

Chien, S. and P. Schonfeld, 1998, "Joint Optimization of a Rail Transit Line and Its Feeder Bus System", *Journal of Advanced Transportation*, 32(3), 253-284.

Chien, S. I. J. and C. F. Tsai, 2007, "Optimization of Fare Structure and Service Frequency for Maximum Profitability of Transit Systems", *Transportation Planning and Technology*, *30*(5), 477-500.

Chin, A., A. Lai and J. Y. Chow, 2016, "Nonadditive Public Transit Fare Pricing under Congestion with Policy Lessons from A Case Study in Toronto, Ontario, Canada", *Transportation Research Record*, *2544*(1), 28-37.

Chowdhury, S. M. and S. I-Jy Chien, 2002, "Intermodal Transit System Coordination", *Transportation Planning and Technology*, *25*(4), 257-287.

Chowdhury, S., A. A. Ceder and B. Schwalger, 2015, "The Effects of Travel Time and Cost Savings on Commuters' Decision to Travel on Public Transport Routes Involving Transfers", *Journal of Transport Geography*, *43*, 151-159.

Christiansen, P., 2020, "The Effects of Transportation Priority Congruence for Political Legitimacy", *Transportation Research Part A: Policy and Practice*, *132*, 61-76.

CIRIT, F., 2016, *Sürdürülebilir Kentiçi Ulaşım Politikaları ve Toplu Taşıma Sistemlerinin Karşılaştırılması*, Expertise Thesis, The Ministry of Development, Turkey.

CNT, 2012, *Housing & Transportation Affordability Index, Center for Neighborhood Technology*, http://Htaindex.Cnt.Org, accessed in September 2020.

Curtis, C., J. L. Renne and L. Bertolini, (Eds.), 2016, *Transit Oriented Development: Making It Happen*, Routledge.

Daskin, M. S., J. L. Schofer and A. E. Haghani, 1988, "A Quadratic Programming Model for Designing and Evaluating Distance-Based and Zone Fares for Urban Transit", *Transportation Research Part B: Methodological*, *22*(1), 25-44.

De Borger, B., I. Mayeres, S. Proost and S. Wouters, 1996, "Optimal Pricing of Urban Passenger Transport: A Simulation Exercise for Belgium", *Journal of Transport Economics and Policy*, 31-54.

De Gruyter, C., G. Rose and G. Currie, 2016, "Travel Plans for New Residential Developments: Measuring Self-Selection Effects to Better Understand Travel Behavior Impacts", *Transportation Research Record: Journal of the Transportation Research Board*, 2564(1), 60-69.

De Luca, A. and S. Termini, 1972, "A Definition of a Nonprobabilistic Entropy in the Setting of Fuzzy Sets Theory", *Information and Control*, 20(4), 301-312.

Delice, E.K. and G.F. Can, 2017, "A Stochastic Approach for Failure Mode and Effect Analysis", *RAIRO-Operations Research*, 51(4), 1077-1100.

Deng, L., K. Liu, Z. Zhang and T. Lai, 2014, "Fare Optimization for Changsha Metro Line 2", *In CICTP 2014: Safe, Smart, and Sustainable Multimodal Transportation Systems*, 1602-1612.

Deng, L., Z. Zhang, K. Liu, W. Zhou and J. Ma, 2014, "Fare Optimality Analysis of Urban Rail Transit under Various Objective Functions", *Discrete Dynamics in Nature and Society*, *2014*.

Diakoulaki, D., G. Mavrotas and L. Papayannakis, 1995, "Determining Objective Weights in Multiple Criteria Problems: The Critic Method", *Computers & Operations Research*, 22(7), 763-770.

Diaz, R. B. and V. A. Mclean, 1999, "Impacts of Rail Transit on Property Values", *In American Public Transit Association Rapid Transit Conference Proceedings*, 1-8.

DİE., 2020, *İl ve İlçelere Göre İl/İlçe Merkezi, Belde/Köy Nüfusu ve Yıllık Nüfus Artış Hızı*, https://data.tuik.gov.tr/Bulten/Index?p=Adrese-Dayali-Nufus-Kayit-Sistemi-Sonuclari-2020-37210, accessed in January 2021.

Dinh, D. T., T. Fujinami and V. N. Huynh, 2019, "Estimating the Optimal Number of Clusters in Categorical Data Clustering by Silhouette Coefficient", *In International Symposium on Knowledge and Systems Sciences*, 1-17, Springer, Singapore.

Dirgahayani, P., 2013, "Environmental Co-Benefits of Public Transportation Improvement Initiative: The Case of Trans-Jogja Bus System in Yogyakarta, Indonesia", *Journal of Cleaner Production*, 58, 74-81.

Dubé, J., M. Thériault and F. Des Rosiers, 2013, "Commuter Rail Accessibility and House Values: The Case of the Montreal South Shore, Canada, 1992–2009", *Transportation Research Part A: Policy and Practice*, 54, 49-66.

Duncan, M., 2008, "Comparing Rail Transit Capitalization Benefits for Single-Family and Condominium Units in San Diego, California", *Transportation Research Record*, 2067(1), 120-130.

Eboli, L. and G. Mazzulla, 2009, "A New Customer Satisfaction Index for Evaluating Transit Service Quality", *Journal of Public Transportation*, 12, 21-37.

Edvardson, B., 1998, "Causes of Customer Dissatisfaction-Studies of Public Transport by the Critical-Incident Method", *Journal of Service Theory and Practice*, 8, 189-197.

Endeksa, 2021, *Türkiye Konut Kiraları*, https://www.endeksa.com/tr/analiz/izmir/endeks/kiralik, accessed in April 2021.

Evans, S. C., 2016, "Property Value Changes from Public Transportation: How the Greenbush Commuter Line Affected Property Values", *Journal of Environmental and Resource Economics at Colby*, 3(1), 1-13.

Fan, J., R. Guan and M. Wu, 2020, "Z-MABAC Method for the Selection of Third-Party Logistics Suppliers in Fuzzy Environment", *the Institute of Electrical and Electronics Engineers Access*, 8, 199111-199119.

Farber, S., K. Bartholomew, X. Li, A. Páez and K. M. N. Habib, 2014, "Assessing Social Equity in Distance Based Transit Fares Using a Model of Travel Behavior", *Transportation Research Part A: Policy and Practice*, 67, 291-303.

Farjo, J., W. Masri and H. Hajj, 2013, "Isolating Failing Test Cases: A Comparative Experimental Study of Clustering Techniques", *In 2013 Third International Conference on Communications and Information Technology (ICCIT)*, 73-77.

Fearnley, N., 2013, "Free Fares Policies: Impact on Public Transport Mode Share and Other Transport Policy Goals", *Int. J. Transp*, 1(1), 75–90.

Feifei, Q. I. N. and J. I. A. Haicheng, 2013, "Modeling Optimal Fare and Service Provisions for a Crowded Rail Transit Line", *Journal of Transportation Systems Engineering and Information Technology*, 13(2), 69-80.

Flath, C. M., J. P. Ilg, S. Gottwalt, H. Schmeck and C. Weinhardt, 2014, "Improving Electric Vehicle Charging Coordination through Area Pricing", *Transportation Science*, 48(4), 619-634.

Fleishman, D., N. Shaw, A. Joshi, R. Freeze and R. Oram, 1996, *TCRP Report 10, Fare Policies, Structures, and Technologies*, National Academy Press, Washington, D.C.

Foth, N., K. Manaugh and A. M. El-Geneidy, 2013, "Towards Equitable Transit: Examining Transit Accessibility and Social Need in Toronto, Canada, 1996–2006", *Journal of Transport Geography*, 29, 1-10.

Free, R. C. and R. C. Free, (Eds.), 2010, *21st Century Economics: A Reference Handbook*, Vol. 1, Sage.

Gaigné, C., S. Riou and J.F. Thisse, 2012, "Are Compact Cities Environmentally Friendly?", *Journal of Urban Economics*, 72(2-3), 123-136.

Galindez, A. A. and R. Mireles-Córdova, 2001, "Visualization of Transit Mobility and Performance", *Journal of Public Transportation*, *3*(4), 61-72.

Gärling, T. and G. Schuitema, 2007, "Travel Demand Management Targeting Reduced Private Car Use: Effectiveness, Public Acceptability and Political Feasibility", *Journal of Social Issues*, 63(1), 139-153.

Gigović, L., D. Pamučar, D. Božanić and S. Ljubojević, 2017, "Application of the GIS-DANP-MABAC Multi-Criteria Model for Selecting the Location of Wind Farms: A Case Study of Vojvodina, Serbia", *Renewable Energy*, 103, 501-521.

Giuliano, G., 2005, "Low Income, Public Transit, and Mobility", *Transportation Research Record*, 1927(1), 63-70.

Gomez-Lobo, A., 2011, "Affordability of Public Transport a Methodological Clarification", *Journal of Transport Economics and Policy (JTEP)*, 45(3), 437-456.

Goodwin, P. B., 1992, "A Review of New Demand Elasticities with Special Reference to Short and Long Run Effects of Price Changes", *Journal of Transport Economics and Policy*, 155-169.

Guerra E. and M. Kirschen, 2016, "Housing Plus Transportation Affordability Indices: Uses, Opportunities, And Challenges", *OECD Round-Table On Income Inequality, Social Inclusion, And Mobility*, Paris, April 2016.

Guzman, L. A., C. A. Moncada and S. Gómez, 2018, "Fare Discrimination and Daily Demand Distribution in The BRT System in Bogotá", *Public Transport*, 10(2), 191-216.

Guzman, L. A., D. De La Hoz and G. Circella, 2015, "Evaluation of Synergies from Transportation Policy Packages Using a Social Welfare Maximization Approach: A Case Study for Madrid, Spain", *Case Studies on Transport Policy*, 3(1), 99-110.

Haig, R. M., 1927, *Major Economic Factors in Metropolitan Growth and Arrangement Regional Survey of New York*, Regional Plan of New York.

Hamacher, H.W. and A. Schöbel, 2004, "Design of Zone Tariff Systems in Public Transportation", *Operations Research*, 52(6), 897-908.

Hastie, T., R. Tibshirani and J. Friedman, 2009, *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*, Springer Science & Business Media.

Havdra, J.H. and F. Charvat, 1967, "Quantification Method Classification Process: Concept of Structral A-Entropy", *Kybernetika*, 3, 30-35.

Hendrickson, C. T., 1981, "Travel Time and Volume Relationships in Scheduled, Fixed-Route Public Transportation", *Transportation Research Part A: General*, 15(2), 173-182.

Herbert, C., A. Hermann and D. Mccue, 2018, *Measuring Housing Affordability: Assessing the 30-Percent of Income Standard*, Joint Center for Housing Studies of Harvard University, Cambridge, MA, USA.

Hess, D. B. and T. M. Almeida, 2007, "Impact of Proximity to Light Rail Rapid Transit on Station-Area Property Values in Buffalo, New York", *Urban Studies*, 44(5-6), 1041-1068.

Hodges, T., 2010, *Public Transportation's Role in Responding to Climate Change*, Diane Publishing.

Holmes, J. and J. Van Hemert, 2008, *Transit Oriented Development*, The Rocky Mountain Land Use Institute, Denver, CO.

Hörcher, D., W. Seifu, B. De Borger and D. J. Graham, 2017, "Decentralisation and Its Efficiency Implications in Suburban Public Transport", *6th Symposium of the European Association for Research in Transportation*.

Hoshino, R. and J. Beairsto, 2018, "Optimal Pricing for Distance-Based Transit Fares", *Proceedings of the AAAI Conference on Artificial Intelligence*, 32(1), 7765-7770.

Hristov, N., D. Pamucar and M.S.M.E. Amine, 2021, "Application of a D Number Based LBWA Model and an Interval MABAC Model in Selection of an Automatic Cannon for Integration into Combat Vehicles", *Defence Science Journal*, 71(1), 34-45.

Huang, D., Z. Liu and D. Hua, 2016, "An Optimization Decision Model of Urban Public Transit Fare Structures", *In CICTP 2016*, 658-669.

Huriot, J. M. and J. F. Thisse (Eds.), 2000, *Economics of Cities: Theoretical Perspectives*, Cambridge University Press.

İmre, Ş. and D. Çelebi, 2017, "Measuring Comfort in Public Transport: A Case Study for İstanbul", *Transportation Research Procedia*, 25, 2441-2449.

Isalou, A. A., T. Litman and B. Shahmoradi, 2014, "Testing The Housing and Transportation Affordability Index in a Developing World Context: A Sustainability Comparison of Central and Suburban Districts in Qom, Iran", *Transport Policy*, 33, 33-39.

İzmir Banliyö Sistemi, 2019, *İZBAN A.Ş.,* https://www.izban.com.tr/sayfalar, accessed in February 2019.

Jain, V., A. Sharma and L. Subramanian, 2012, "Road Traffic Congestion in The Developing World", *Proceedings of The 2nd Association for Computing Machinery Symposium On Computing for Development*, 1-10.

Jana, C. and M. Pal, 2021, "Multi-Criteria Decision Making Process Based on Some Single-Valued Neutrosophic Dombi Power Aggregation Operators", *Soft Computing*, 25, 5055-5072.

Jansson, J. O., J. Holmgren, and A. Ljungberg, 2015, "Pricing Public Transport Services", *In Handbook of Research Methods and Applications in Transport Economics and Policy*, Edward Elgar Publishing.

Jenks, M., 2019, "Compact City", *The Wiley Blackwell Encyclopedia of Urban and Regional Studies*, 1-4.

Jha, M. K. and C. Oluokun, 2004, "Optimizing Station Locations Along Transit Rail Lines with Geographic Information Systems and Artificial Intelligence", *WIT Transactions on the Built Environment*, 74, 11-20.

Jha, M. K., P. Schonfeld and S. Samanta, 2007, "Optimizing Rail Transit Routes with Genetic Algorithms and Geographic Information System", *Journal of Urban Planning and Development*, 133(3), 161-171.

Ji, P., H.Y. Zhang and J.Q. Wang, 2018, "Selecting an Outsourcing Provider Based on the Combined MABAC–ELECTRE Method Using Single-Valued Neutrosophic Linguistic Sets", *Computers & Industrial Engineering*, 120, 429-441.

Jin, Z., J.D. Schmöcker and S. Maadi, 2019, "On the Interaction Between Public Transport Demand, Service Quality and Fare for Social Welfare Optimisation", *Research in Transportation Economics*, 76, 1-12.

Jones, P. M., 1995, "Road Pricing: The Public Viewpoint", *In Road Pricing: Theory, Empirical Assessment and Policy*, 159-179, Springer, Dordrecht.

Kaddoura, I., B. Kickhöfer, A. Neumann and A. Tirachini, 2015, "Optimal Public Transport Pricing: Towards an Agent-Based Marginal Social Cost Approach", *Journal of Transport Economics and Policy (JTEP)*, 49(2), 200-218.

Kallbekken, S., 2013, "Public Acceptability of Incentive-Based Mechanisms", *In: Shogren, J. (Ed.), Encyclopedia of Energy, Natural Resource and Environmental Economics*, Elsevier Inc., ISBN 978-0-08-096452-2, 306-312.

Kilpatrick, J., R. Throupe, J. Carruthers and A. Krause, 2007, "The Impact of Transit Corridors on Residential Property Values", *Journal of Real Estate Research*, 29(3), 303-320.

Kim, M., P. Schonfeld and E. Kim, 2012, "Comparison of Vertical Alignments for Rail Transit", *Journal of Transportation Engineering*, 139(2), 230-238.

King, D., M. Manville and D. Shoup, 2007, "The Political Calculus of Congestion Pricing", *Transport Policy*, 14(2), 111-123.

Kotulla, T., J. M. Denstadli, A. Oust and E. Beusker, 2019, "What Does It Take to Make the Compact City Liveable for Wider Groups? Identifying Key Neighbourhood and Dwelling Features", *Sustainability*, 11(12), 1-18.

Kullback, S. and R.A. Leibler, 1951, "On Information and Sufficiency", *The Annals of Mathematical Statistics*, 22(1), 79-86.

Lai, H. and H. Liao, 2021, "A Multi-Criteria Decision Making Method Based on DNMA and CRITIC with Linguistic D Numbers for Blockchain Platform Evaluation", *Engineering Applications of Artificial Intelligence*, 101, 1-10.

Lai, X. and P. Schonfeld, 2012, "Optimization of Rail Transit Alignments Considering Vehicle Dynamics", *Transportation Research Record*, 2275(1), 77-87.

Lam, W. H. and J. Zhou, 2000, "Optimal Fare Structure for Transit Networks with Elastic Demand", *Transportation Research Record*, 1733(1), 8-14.

Leao, S. and H. Elkadi, 2012, "The Use of Public Transport in Coastal Australia: Modes of Travel to Work and Greenhouse Emissions", *In Advanced Materials Research*, Vol. 347, 4034-4044, Trans Tech Publications Ltd.

Lefranc, S., P. Roca, M. Perrot, C. Poupon, D. Le Bihan, J. F. Mangin and D. Rivière, 2016, "Groupwise Connectivity-Based Parcellation of the Whole Human Cortical Surface Using Watershed-Driven Dimension Reduction", *Medical Image Analysis*, 30, 11-29.

Li, C., J. Ma, T. H. Luan, X. Zhou and L. Xiong, 2018, "An Incentive-Based Optimizing Strategy of Service Frequency for an Urban Rail Transit System", *Transportation Research Part E: Logistics and Transportation Review*, 118, 106-122.

Li, Z. C., W. H. Lam and S. C. Wong, 2009, "The Optimal Transit Fare Structure under Different Market Regimes with Uncertainty in The Network", *Networks and Spatial Economics*, 9(2), 191-216.

Li, Z. C., W. H. Lam, S. C. Wong and A. Sumalee, 2012, "Design of a Rail Transit Line for Profit Maximization in a Linear Transportation Corridor", *Transportation Research Part E: Logistics and Transportation Review*, 48(1), 50-70.

Liang, X., F. Teng and Y. Sun, 2020, "Multiple Group Decision Making for Selecting Emergency Alternatives: A Novel Method Based on the LDWPA Operator and LD-MABAC", *International Journal of Environmental Research and Public Health*, 17(8), 1-20.

Lindenmaier, L., I. F. Lövétei, G. Lukács and S. Aradi, 2021, "Infrastructure Modeling and Optimization to Solve Real-Time Railway Traffic Management Problems", *Periodica Polytechnica Transportation Engineering*, 49(3), 270-282.

Lisco, T.E., 1968, “Value of Commuters Travel Time - A Study in Urban Transportation”, *Highway Research Board*, 245, 1-36.

Litman, T., 2004, “Transit Price Elasticities and Cross-Elasticities”, *Journal of Public Transportation*, *7*(2), 37-58.

Litman, T., 2013, *Transportation Affordability: Evaluation and Improvement Strategies*, Victoria Transport Policy Institute.

Liu, B. Z., Y. E. Ge, K. Cao, X. Jiang, L. Meng, D. Liu and Y. Gao, 2017, “Optimizing a Desirable Fare Structure for A Bus-Subway Corridor”, *Plos One*, 12(10), 1-21.

Liu, G., G. Quain and S. C. Wirasinghe, 1996, “Rail Line Length in a Crosstown Corridor With Many-to-Many Demand”, *Journal of Advanced Transportation*, 30(1), 95-114.

Liu, P. and P. Zhang, 2021, “A Normal Wiggly Hesitant Fuzzy MABAC Method Based on CCSD and Prospect Theory for Multiple Attribute Decision Making”, *International Journal of Intelligent Systems*, 36(1), 447-477.

Liu, P., H. Xu and W. Pedrycz, 2020, “A Normal Wiggly Hesitant Fuzzy Linguistic Projection-Based Multiattributive Border Approximation Area Comparison Method”, *International Journal of Intelligent Systems*, 35(3), 432-469.

Liu, R., L.X. Hou, H.C. Liu and W. Lin, 2020, “Occupational Health and Safety Risk Assessment Using an Integrated SWARA-MABAC Model under Bipolar Fuzzy Environment”, *Computational and Applied Mathematics*, 39, 1-17.

Luo, S.Z. and L.N. Xing, 2019, “A Hybrid Decision Making Framework for Personnel Selection Using BWM, MABAC and PROMETHEE”, *International Journal of Fuzzy Systems*, 21(8), 2421-2434.

Luo, S.Z. and W.Z. Liang, 2019, "Optimization of Roadway Support Schemes with Likelihood-Based MABAC Method", *Applied Soft Computing*, 80, 80-92.

Ma, J., C. Li, W. Dong, Z. Liu, T. H. Luan and L. Xiong, 2017, "Optimizing Service Frequency for Urban Rail Transit: A Game-Theoretical Methodology", *In 2017 the Institute of Electrical and Electronics Engineers 86th Vehicular Technology Conference (VTC-Fall)*, 1-5.

Ma, Z., A. R. Masoud and A. O. Idris, 2017, "Modeling the Impact of Transit Fare Change on Passengers' Accessibility", *Transportation Research Record*, *2652*(1), 78-86.

Maadi, S. and J. D. Schmöcker, 2018, "Theoretical Evaluation on the Effects Of Changes From a Zonal to a Distance-Based Fare Structure", *In 14th International Conference on Advanced Systems in Public Transport (CASPT),* 23-25 July, Brisbane, Australia.

Maadi, S. and J.D. Schmöcker, 2020, "Route Choice Effects of Changes from a Zonal to a Distance-Based Fare Structure in a Regional Public Transport Network", *Public Transport*, 12(3), 535-555.

Mackett, R. L. and M. Edwards, 1998, "The Impact of New Urban Public Transport Systems: Will the Expectations Be Met?", *Transportation Research Part A: Policy and Practice*, 32(4), 231-245.

Manaugh, K. and A. El-Geneidy, 2012, "Who Benefits from New Transportation Infrastructure? Using Accessibility Measures to Evaluate Social Equity in Public Transport Provision", *In Accessibility Analysis and Transport Planning*, Edward Elgar Publishing.

Martinez, M. J., 2009, "Calculation of Benefits of Advanced Integrated Rail Service: Application of Intelligent Transportation Systems to the Developing City of Lima, Peru", *Transportation Research Record*, 2112(1), 26-33.

Mattson, J. W., 2012, *Travel Behavior and Mobility of Transportation-Disadvantaged Populations: Evidence from the National Household Travel Survey*, No. DP-258, Fargo, ND: Upper Great Plains Transportation Institute.

May, A. D. and M. Roberts, 1995, "The Design of Integrated Transport Strategies", *Transport Policy*, 2(2), 97-105.

Mills, E.S., 1972, *Studies in the Structure of the Urban Economy*, Baltimore: The Johns Hopkins Press.

MIRO, 1995, *MIRO Final Report*, Deliverable to Commission of the European Communities, DG XIII DRIVE Programme, Brussels.

Murray, A. T., R. Davis, R. J. Stimson and L. Ferreira, 1998, "Public Transportation Access", *Transportation Research Part D: Transport and Environment*, 3(5), 319-328.

Muth, R.F., 1969, *Cities and Housing; the Spatial Pattern of Urban Residential Land Use*, Chicago: University of Chicago Press.

Nash, C. A., 1982, *Economics of Public Transport*, Longman, New York.

Nassi, C. D. and F. C. D. C. Da Costa, 2012, "Use of the Analytic Hierarchy Process to Evaluate Transit Fare System", *Research in Transportation Economics*, 36(1), 50-62.

Neto, A. P., M. L. Galves, O. L. Júnior and D. Tacla, 2008, "Challenges of Urban Transport Problems and City Logistics: Sao Paulo City Center Case", *WIT Transactions on the Built Environment*, 101, 133-142.

Neumann, M., 2007, "Fare Planning for Public Transport", *In Operations Research Proceedings 2006*, 61-66, Springer, Berlin, Heidelberg.

Norusis, M.J., 1993, *SPSS for Windows Advanced Statistics Release 6.0,* SPSS Inc., Chicago.

Nuworsoo, C., A. Golub and E. Deakin, 2009, "Analyzing Equity Impacts of Transit Fare Changes: Case Study of Alameda–Contra Costa Transit, California", *Evaluation and Program Planning*, 32(4), 360-368.

O'sullivan, A., 2007, *Urban* Economics, 225-226, Mcgraw-Hill/Irwin.

Otto, B. and N. Boysen, 2017, "Zone-Based Tariff Design in Public Transportation Networks", *Networks*, 69(4), 349-366.

Pal, N.R. and S.K. Pal, 1989, "Object-Background Segmentation Using New Definitions of Entropy", *IEE Proceedings E: Computers & Digital Techniques*, 136(4), 284-295.

Palma, A. D., M. Kilani and S. Proost, 2014, "Discomfort in Mass Transit and Its Implication for Scheduling and Pricing", *Transportation Research Part B*, 1-18.

Pamučar, D., A. Puška, Ž. Stević and G. Ćirović, 2021, "A New Intelligent MCDM Model for HCW Management: The Integrated BWM–MABAC Model Based on D Numbers", *Expert Systems with Applications*, 175, 114862.

Pamucar, D., M. Yazdani, R. Obradovic, A. Kumar and M. Torres-Jiménez, 2020, "A Novel Fuzzy Hybrid Neutrosophic Decision-Making Approach for The Resilient Supplier Selection Problem", *International Journal of Intelligent Systems*, 35(12), 1934-1986.

Parajuli, P. M. and S. C. Wirasinghe, 2001, "A Line Haul Transit Technology Selection Model", *Transportation Planning and Technology*, 24(4), 271-308.

Parry, I. W. and K. A. Small, 2009, "Should Urban Transit Subsidies Be Reduced?", *American Economic Review*, 99(3), 700-724.

Paulley, N., R. Balcombe, R. Mackett, H. Titheridge, J. Preston, M. Wardman and P. White, 2006, “The Demand for Public Transport: The Effects of Fares, Quality of Service, Income and Car Ownership”, *Transport Policy*, 13(4), 295-306.

Peng, X. and J. Dai, 2018, “Approaches to Single-Valued Neutrosophic MADM Based on MABAC, TOPSIS and New Similarity Measure with Score Function”, *Neural Computing and Applications*, 29(10), 939-954.

Pilgram, C. A. and S. E. West, 2018, “Fading Premiums: The Effect of Light Rail on Residential Property Values in Minneapolis, Minnesota”, *Regional Science and Urban Economics*, 69, 1-10.

Pioneer Institute, 2019, *MBTA Mounthly Measures*, Public Policy Research, https://mbtaanalysis.com, accessed in July 2019.

Pozdena, R. J. and L. Merewitz, 1978, “Estimating Cost Functions for Rail Rapid Transit Properties”, *Transportation Research*, 12(2), 73-78.

Prud'Homme, R., 1995, “The Dangers of Decentralization”, *The World Bank Research Observer*, 10(2), 201-220.

Qin, F., 2014, “Investigating the in-Vehicle Crowding Cost Functions for Public Transit Modes”, *Hindawi Publishing Corporation Mathematical Problems in Engineering*, 1-13.

Rahim, N., L. Abdullah and B. Yusoff, 2020, “A Border Approximation Area Approach Considering Bipolar Neutrosophic Linguistic Variable for Sustainable Energy Selection”, *Sustainability*, 12(10), 3971.

Rappaport, J., 2014, “Monocentric City Redux”, *Research Working Paper*, 14-09, The Federal Reserve Bank of Kansas City.

Region, A., 2004, *Poverty and Urban Mobility in Conakry*, Sub-Saharan Africa Transport Policy Program, SSATP Report No 09/04/CKR.

Rouhani, O.M., 2018, "Beyond Standard Zonal Congestion Pricing: A Detailed Impact Analysis", *Journal of Transportation Engineering, Part A: Systems*, 144(9), 04018052.

Roy, J., D. Pamučar and S. Kar, 2020, "Evaluation and Selection of Third Party Logistics Provider under Sustainability Perspectives: An Interval Valued Fuzzy-Rough Approach", *Annals of Operations Research*, 293(2), 669-714.

Rubensson, I., Y. Susilo and O. Cats, 2020, "Is Flat Fare Fair? Equity Impact of Fare Scheme Change", *Transport Policy*, 91, 48-58.

Saaty, T. L. and J. M. Alexander, 1981, *Thinking with Models: Mathematical Models in the Physical, Biological, and Social Sciences*, RWS Publications.

Sadayuki, T., 2018, "Measuring the Spatial Effect of Multiple Sites: An Application to Housing Rent and Public Transportation in Tokyo, Japan", *Regional Science and Urban Economics*, 70, 155-173.

Şahin, O. and I. Gökaşar, 2020, "Evaluation of the Travel Behaviours and Attitudes of the Passengers Towards The BRT Line in Istanbul", *Journal of Transportation Systems*,16-27.

Şahin, R. and F. Altun, 2020, "Decision Making with MABAC Method under Probabilistic Single-Valued Neutrosophic Hesitant Fuzzy Environment", *Journal of Ambient Intelligence and Humanized Computing*, 11(10), 4195-4212.

Salarzadeh Jenatabadi, H., P. Babashamsi and N. I. M. Yusoff, 2016, "The Combination of a Fuzzy Analytical Hierarchy Process and the Taguchi Method to Evaluate the Malaysian Users' Willingness to Pay for Public Transportation", *Symmetry*, 8(9), 90.

Samanta, S. and M. K. Jha, 2011, "Modeling a Rail Transit Alignment Considering Different Objectives", *Transportation Research Part A: Policy and Practice*, 45(1), 31-45.

Santos, T., M. A. Silva, V. A. Fernandes and G. Marsden, 2020, "Resilience and Vulnerability of Public Transportation Fare Systems: The Case of the City of Rio De Janeiro, Brazil", *Sustainability*, 12(2), 1-22.

Savage, I., 1997, "Scale Economies in United States Rail Transit Systems", *Transportation Research Part A: Policy and Practice*, 31(6), 459-473.

Schade, J. and B. Schlag, 2003, "Acceptability of Urban Transport Pricing Strategies", *Transportation Research Part F: Traffic Psychology and Behaviour*, 6(1), 45-61.

Schlag, B. and J. Schade, 2000, "Public Acceptability of Traffic Demand Management in Europe", *Traffic Engineering+ Control*, 41(8), 314-318.

Schlossberg, M. and N. Brown, 2004, "Comparing Transit-Oriented Development Sites by Walkability Indicators", *Transportation Research Record*, 1887(1), 34-42.

Schöbel, A., 1995, "Fair Zone Design in Public Transportation Networks", *In Operations Research Proceedings*, 1994, 191-196, Springer, Berlin, Heidelberg.

Shannon, C.E., 1948, "A Mathematical Theory of Communications", *The Bell System Technical Journal*, 27(3), 379-423.

Sharaby, N. and Y. Shiftan, 2012, "The Impact of Fare Integration on Travel Behavior and Transit Ridership", *Transport Policy*, 21, 63-70.

Shen, K.W., X.K. Wang, D. Qiao and J.Q. Wang, 2020, "Extended Z-MABAC Method Based on Regret Theory and Directed Distance for Regional Circular Economy Development Program Selection with Z-Information", *the Institute of Electrical and Electronics Engineers Transactions on Fuzzy Systems*, 28(8), 1851-1863.

Shi, H., H. C. Liu, P. Li and X. G. Xu, 2017, "An Integrated Decision Making Approach for Assessing Healthcare Waste Treatment Technologies from a Multiple Stakeholder", *Waste Management*, 59, 508-517.

Smarandache, F., 1998, *Neutrosophy: Neutrosophic Probability, Set, and Logic: Analytic Synthesis & Synthetic Analysis*, American Research Press.

Smarandache, F., 2003, *A Unifying Field in Logics Neutrosophic Logic. Neutrosophy, Neutrosophic Set, Neutrosophic Probability*, 3rd Ed., Xiquan, Phoenix, American Research Press.

Stojanovski, T., 2013, "Public Transportation Systems for Urban Planners and Designers: The Urban Morphology of Public Transportation Systems", *In Urban Public Transportation Systems*, 2013, 75-89.

Stone, J. R., J. D. Allen, A. Moerz and B. Gardner, 1992, "Transit System Evaluation: Guideway Bus Vs. Light Rail Transit", *Journal of Advanced Transportation*, 26(3), 213-240.

Stradling, S. G., 2002, "Transport User Needs and Marketing Public Transport", *In Proceedings of the Institution of Civil Engineers-Municipal Engineer*, Vol. 151, No. 1, 23-28, Thomas Telford Ltd.

Štraub, D., 2020, "The Effects of Fare-Free Public Transport: A Lesson from Frýdek-Místek (Czechia)", *Sustainability*, 12(21), 1-15.

Sun, R., J. Hu, J. Zhou and X. Chen, 2018, "A Hesitant Fuzzy Linguistic Projection-Based MABAC Method for Patients' Prioritization", *International Journal of Fuzzy Systems*, 20(7), 2144-2160.

Tang, C., A. A. Ceder and Y. E. Ge, 2017, "Integrated Optimization of Bus Line Fare and Operational Strategies Using Elastic Demand", *Journal of Advanced Transportation*, 2017.

Tirachini, A. and C. Antoniou, 2020, "The Economics of Automated Public Transport: Effects on Operator Cost, Travel Time, Fare and Subsidy", *Economics of Transportation*, 21, 1-15.

Tirachini, A., D. A. Hensher and J. M. Rose, 2014, "Multimodal Pricing and Optimal Design of Urban Public Transport: The Interplay Between Traffic Congestion and Bus Crowding", *Transportation Research Part B: Methodological*, 61, 33-54.

Tirachini, A., D. A. Hensher and S. R. Jara-Díaz, 2010, "Comparing Operator and Users Costs of Light Rail, Heavy Rail and Bus Rapid Transit Over a Radial Public Transport Network", *Research in Transportation Economics*, 29(1), 231-242.

Tiwari, R.K. and R. Kumar, 2020, "A Framework for Prioritizing Cloud Services in Neutrosophic Environment", *Journal of King Saud University - Computer and Information Sciences*.

Transportation Research Board, 1994, *Curbing Gridlock Peak-Period Fees to Relieve Traffic Congestion*, Special Report 242, National Academy Press, Washington, DC.

Tsai, F. M., S. Chien and C. H. Wei, 2012, "Joint Optimization of Temporal Headway and Differential Fare for Transit Systems Considering Heterogeneous Demand Elasticity", *Journal of Transportation Engineering*, 139(1), 30-39.

Tsai, F.M., S.I.J. Chien and L.N. Spasovic, 2008, "Optimizing Distance-Based Fares and Headway of an Intercity Transportation System with Elastic Demand and Trip Length Differentiation", *Transportation Research Record: Journal of the Transportation Research Board*, 2089(1), 101-109.

Tsallis, C., 1988, "Possible Generalization of Boltzman-Gibbs Statistics", *Journal of Statistical Physics*, 52, 479-487.

TUIK, 2020, *Adrese Dayalı Nüfus Kayıt Sistemi*, https://biruni.tuik.gov.tr/medas/?kn=95&locale=tr, accessed in January 2021.

Verbich, D. and A. El-Geneidy, 2017, "Public Transit Fare Structure and Social Vulnerability in Montreal, Canada", *Transportation Research Part A: Policy and Practice*, 96, 43-53.

Verma, A. and S. L. Dhingra, 2006, "Developing Integrated Schedules for Urban Rail and Feeder Bus Operation", *Journal of Urban Planning and Development*, 132(3), 138-146.

Verma, A., D. Upadhyay and R. Goel, 2011, "An Integrated Approach for Optimal Rail Transit Corridor Identification and Scheduling Using Geographical Information System", *Journal of King Saud Universityscience*, 23(3), 255-271.

Wachs, M., 1981, "Pricing Urban Transportation a Critique of Current Policy", *Journal of the American Planning Association*, 47(3), 243-251.

Wang, B., Z. Lv, J. Zhao, X. Wang and T. Zhang, 2016, "An Adaptively Disperse Centroids K-Means Algorithm Based on Mapreduce Model", *In 2016 12th International Conference on Computational Intelligence and Security (CIS)*, 142-146.

Wang, H., Z. Jiang, H. Zhang, Y. Wang, Y. Yang and Y. Li, 2019, "An Integrated MCDM Approach Considering Demands-Matching for Reverse Logistics", *Journal of Cleaner Production*, 208, 199-210.

Wang, P., J. Wang, G. Wei, C. Wei and Y. Wei, 2019, "The Multi-Attributive Border Approximation Area Comparison (MABAC) for Multiple Attribute Group Decision Making under 2-Tuple Linguistic Neutrosophic Environment", *Informatica*, 30(4), 799-818.

Wang, Q. and L. Deng, 2019, "Integrated Optimization Method of Operational Subsidy with Fare for Urban Rail Transit", *Computers & Industrial Engineering*, 127, 1153-1163.

Wang, Q., L. Deng and G. Xu, 2020, "Operational Subsidy Optimization in Urban Rail Transit under the Break-Even Mode: Considering Two Fare Regimes", *Computers & Industrial Engineering*, 149, 1-15.

Wang, Z. J., F. Chen, B. Wang and J. L. Huang, 2018, "Passengers' Response to Transit Fare Change: An Ex Post Appraisal Using Smart Card Data", *Transportation*, 45(5), 1559-1578.

Wang, Z. J., X. H. Li and F. Chen, 2015, "Impact Evaluation of a Mass Transit Fare Change on Demand and Revenue Utilizing Smart Card Data", *Transportation Research Part A: Policy and Practice*, 77, 213-224.

Wardrip, K., 2011, *Public Transit's Impact on Housing Costs: A Review of the Literature*.

Wei, G., Y. He, F. Lei, J. Wu and C. Wei, 2020, "MABAC Method for Multiple Attribute Group Decision Making with Probabilistic Uncertain Linguistic Information", *Journal of Intelligent & Fuzzy Systems*, 39(3), 3315-3327.

Wenxing, L. I. and Y. I. N. Shuai, 2012, "Analysis on Cost of Urban Rail Transit", *Journal of Transportation Systems Engineering and Information Technology*, 12(2), 9-14.

Wirasinghe, S. C. and P. N. Seneviratne, 1986, "Rail Line Length in an Urban Transportation Corridor", *Transportation Science*, 20(4), 237-245.

Woo, C. K., Y. Liu, K. H. Cao and J. Zarnikau, 2020, "Can Hong Kong Price-Manage Its Public Transportation's Ridership?", *Case Studies on Transport Policy*, 8(4), 1191-1200.

Xueyu, Z. and Y. Jiaqi, 2013, "Research on the Bi-Level Programming Model for Ticket Fare Pricing of Urban Rail Transit Based on Particle Swarm Optimization Algorithm", *Procedia-Social and Behavioral Sciences*, 96, 633-642.

Yamada, T., 1985, "The Probable Effects of Introducing a Sectional Fare System into New York City Subway", *International Journal of Transport Economics/Rivista Internazionale Di Economia Dei Trasporti*, 315-331.

Yamane, T., 1967, *Statistics: An Introductory Analysis*, No. HA29 Y2 1967.

Yang, L., R. Saigal and H. Zhou, 2012, "Distance-Based Dynamic Pricing Strategy for Managed Toll Lanes", *Transportation Research Record*, 2283(1), 90-99.

Yang, Z. and M. Tang, 2018, "Does the Increase of Public Transit Fares Deteriorate Air Quality in Beijing?", *Transportation Research Part D: Transport and Environment*, 63, 49-57.

Yook, D. and K. Heaslip, 2014, "Determining Appropriate Fare Levels for Distance-Based Fare Structure: Considering Users' Behaviors in a Time-Expanded Network", *Transportation Research Record*, 2415(1), 127-135.

Yuan, Z. and M.R. Hesamzadeh, 2016, "Implementing Zonal Pricing in Distribution Network: The Concept of Pricing Equivalence", *2016 the Institute of Electrical and Electronics Engineers Power and Energy Society General Meeting (PESGM)*, 1-5.

Yusoff, Z. M., N. A. Adnan and F. Othman, 2014, *Income and Limits of Low-Income Earner in the City: Quantifying the Transportation Affordability*, Centre of Studies Surveying Science and Geomatics FSPU, Universiti Teknologi MARA, Shah Alam, Malaysia.

Zhang, C., H. Xia and Y. Song, 2017, "Rail Transportation Lead Urban Form Change: A Case Study of Beijing", *Urban Rail Transit*, 3(1), 15-22.

Zhang, J., X. Yan, M. An and L. Sun, 2017, "The Impact of Beijing Subway's New Fare Policy on Riders' Attitude, Travel Pattern and Demand", *Sustainability*, 9(5), 1-21.

Zhang, J., Y. Wang and W. Zhao, 2018, "An Improved Probabilistic Relaxation Method for Matching Multi-Scale Road Networks", *International Journal of Digital Earth*, 11(6), 635-655.

Zhang, K., D. Liu, L. Yu and B. Xie, 2021, "Rail Transit Corridor Design Modeling based on TOD Project Development", *The International Journal of Electrical Engineering & Education*, 1-20.

Zhang, L., 2020, "The Model of the Relationship Between Urban Rail Transit and Residential Location", *Scientific Programming*, 2020, 1-15.

Zhang, S., G. Wei, F.E. Alsaadi, T. Hayat, C. Wei and Z. Zhang, 2020, "MABAC Method for Multiple Attribute Group Decision Making under Picture 2-Tuple Linguistic Environment", *Soft Computing*, 24(8), 5819-5829.

Zhang, S., S. Jia, C. Ma and Y. Wang, 2018, "Impacts of Public Transportation Fare Reduction Policy on Urban Public Transport Sharing Rate Based on Big Data Analysis", *In 2018 the Institute of Electrical and Electronics Engineers 3rd International Conference on Cloud Computing and Big Data Analysis (ICCCBDA)*, 280-284.

Zhao, L., S. I. Chien, L. N. Spasovic and X. Liu, 2018, "Modeling and Optimizing Urban Bus Transit Considering Headway Variation for Cost and Service Reliability Analysis", *Transportation Planning and Technology*, 41(7), 706-723.

Zhao, P. and Y. Zhang, 2016, "Subway Ticket Pricing and Travel Behavior: The Impacts of an Increase of Subway Fare on Residents' Travel Trips in Beijing", *In Bridging the East and West*, 272-281.

Zhao, P. and Y. Zhang, 2019, "The Effects of Metro Fare Increase on Transport Equity: New Evidence from Beijing", *Transport Policy*, 74, 73-83.

Zhou, F. and Z. Zheng, Whitehead, J., Perrons, R. K., Washington, S., & Page, L., 2020, "Examining the Impact of Car-Sharing on Private Vehicle Ownership", *Transportation Research Part A: Policy and Practice*, 138, 322-341.

Zhou, J., W. H. Lam and B. G. Heydecker, 2005, "The Generalized Nash Equilibrium Model for Oligopolistic Transit Market with Elastic Demand", *Transportation Research Part B: Methodological*, 39(6), 519-544.

Zhu, Y., B. Mao, Y. Bai and S. Chen, 2017, "A Bi-Level Model for Single-Line Rail Timetable Design with Consideration of Demand and Capacity", *Transportation Research Part C: Emerging Technologies*, 85, 211-233.

APPENDIX A: TICKET TARIFFS AND MAXIMUM DISTANCES BASED ON STATIONS

Table A.1. Ticket tariffs and maximum distances based on stations.

Station	Maximum Distance (Km)	Full Fare (TL)	Student (TL)	Teacher (TL)	Staff (Credit)
Aliağa	135.54	10.60	6.07	7.73	4
Biçerova	130.33	10.23	5.86	7.47	4
Hatundere	122.03	9.65	5.53	7.05	4
Menemen	109.96	8.81	5.05	6.45	4
Egekent-2	103.92	8.38	4.81	6.15	3
Ulukent	102.87	8.31	4.76	6.09	3
Egekent	97.87	7.96	4.56	5.84	3
Ata Sanayi	96.86	7.89	4.52	5.79	3
Çiğli	95.84	7.82	4.48	5.74	3
Mavişehir	93.84	7.68	4.40	5.64	3
Şemikler	92.84	7.61	4.36	5.59	3
Demirköprü	91.84	7.54	4.32	5.54	3
Nergiz	89.76	7.39	4.24	5.44	3
Karşıyaka	88.76	7.32	4.20	5.39	3
Alaybey	88.16	7.28	4.18	5.36	3
Naldöken	87.13	7.21	4.14	5.31	3
Turan	85.11	7.07	4.05	5.21	3
Bayraklı	84.05	6.99	4.01	5.15	3
Salhane	82.01	6.85	3.93	5.05	3
Halkapınar	79.99	6.71	3.85	4.95	3
Alsancak	76.99	6.50	3.73	4.80	3
Hilal	75.47	6.39	3.67	4.72	3
Kemer	75.01	6.36	3.65	4.70	3
Şirinyer	70.99	6.08	3.49	4.50	3
Koşu	69.99	6.01	3.45	4.45	3
İnkılap	67.96	5.87	3.37	4.35	3

Table A.2. Ticket tariffs and maximum distances based on stations (cont).

Station	Maximum Distance (Km)	Full Fare (TL)	Student (TL)	Teacher (TL)	Staff (Credit)
Semt Garajı	68.62	5.91	3.39	4.38	3
Esbaş	70.64	6.05	3.48	4.48	3
Gaziemir	71.66	6.13	3.52	4.53	3
Sarnıç	73.70	6.27	3.60	4.64	3
Havalimanı	76.75	6.48	3.72	4.79	3
Cumaovası	79.78	6.69	3.84	4.94	3
Develi	86.71	7.18	4.12	5.29	3
Tekeli	89.69	7.39	4.24	5.43	3
Pancar	94.96	7.76	4.45	5.70	3
Kuşçuburun	101.77	8.23	4.72	6.04	3
Torbalı	107.24	8.62	4.94	6.31	4
Tepeköy	110.04	8.81	5.05	6.45	4
Sağlık	117.54	9.34	5.35	6.83	4
Belevi	124.84	9.85	5.64	7.19	4
Selçuk	135.54	10.60	6.07	7.73	4

APPENDIX B: DETAILED MATRICES USED IN CHAPTER 5

Table B.1. The T2NN initial decision matrices.

Alternative	**Expert**	**Criterion**		
		C_1	···	C_{13}
A_1: Flat fare	D_1	<(0.50, 0.45, 0.50), (0.40, 0.35, 0.50), (0.35, 0.30, 0.45)>	···	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>
	D_2	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>	···	<(0.40, 0.30, 0.35), (0.50, 0.45, 0.60), (0.45, 0.40, 0.60)>
	D_3	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>	···	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>
	D_4	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>	···	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>
	D_5	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>	···	<(0.40, 0.30, 0.35), (0.50, 0.45, 0.60), (0.45, 0.40, 0.60)>
A_2: Distance-based fare	D_1	<(0.50, 0.45, 0.50), (0.40, 0.35, 0.50), (0.35, 0.30, 0.45)>	···	<(0.40, 0.30, 0.35), (0.50, 0.45, 0.60), (0.45, 0.40, 0.60)>
	D_2	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>	···	<(0.95, 0.90, 0.95), (0.10, 0.10, 0.05), (0.05, 0.05, 0.05)>
	D_3	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>	···	<(0.95, 0.90, 0.95), (0.10, 0.10, 0.05), (0.05, 0.05, 0.05)>
	D_4	<(0.40, 0.30, 0.35), (0.50, 0.45, 0.60), (0.45, 0.40, 0.60)>	···	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
	D_5	<(0.40, 0.30, 0.35), (0.50, 0.45, 0.60), (0.45, 0.40, 0.60)>	···	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
A_3: Zonal pricing	D_1	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>	···	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
	D_2	<(0.50, 0.45, 0.50), (0.40, 0.35, 0.50), (0.35, 0.30, 0.45)>	···	<(0.50, 0.45, 0.50), (0.40, 0.35, 0.50), (0.35, 0.30, 0.45)>
	D_3	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>	···	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
	D_4	<(0.40, 0.30, 0.35), (0.50, 0.45, 0.60), (0.45, 0.40, 0.60)>	···	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
	D_5	<(0.50, 0.45, 0.50), (0.40, 0.35, 0.50), (0.35, 0.30, 0.45)>	···	<(0.50, 0.45, 0.50), (0.40, 0.35, 0.50), (0.35, 0.30, 0.45)>
A_4: Rent-based fare	D_1	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>	···	<(0.95, 0.90, 0.95), (0.10, 0.10, 0.05), (0.05, 0.05, 0.05)>
	D_2	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>	···	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
	D_3	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>	···	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
	D_4	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>	···	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
	D_5	<(0.40, 0.30, 0.35), (0.50, 0.45, 0.60), (0.45, 0.40, 0.60)>	···	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>

Table B.2. The T2NN aggregated decision matrix.

Criterion	**Alternative**		
	A_1: Flat fare	···	A_4: Rent-based fare
C_1	<(0.604, 0.513, 0.566), (0.213, 0.179, 0.278), (0.121, 0.238, 0.186)>	···	<(0.318, 0.296, 0.158), (0.542, 0.689, 0.769), (0.474, 0.673, 0.654)>
C_2	<(0.454, 0.407, 0.405), (0.435, 0.432, 0.572), (0.394, 0.386, 0.511)>	···	<(0.399, 0.305, 0.328), (0.460, 0.432, 0.567), (0.356, 0.435, 0.501)>
C_3	<(0.351, 0.308, 0.213), (0.521, 0.613, 0.717), (0.471, 0.584, 0.636)>	···	<(0.686, 0.625, 0.685), (0.217, 0.221, 0.257), (0.126, 0.222, 0.193)>
C_4	<(0.686, 0.717, 0.769), (0.157, 0.191, 0.250), (0.100, 0.162, 0.191)>	···	<(0.375, 0.346, 0.251), (0.495, 0.589, 0.695), (0.446, 0.559, 0.598)>
C_5	<(0.350, 0.350, 0.100), (0.500, 0.750, 0.800), (0.500, 0.750, 0.650)>	···	<(0.825, 0.756, 0.831), (0.174, 0.172, 0.156), (0.105, 0.129, 0.138)>
C_6	<(0.421, 0.376, 0.331), (0.461, 0.499, 0.627), (0.428, 0.458, 0.558)>	···	<(0.473, 0.390, 0.382), (0.351, 0.338, 0.461), (0.242, 0.395, 0.343)>
C_7	<(0.773, 0.783, 0.839), (0.141, 0.180, 0.195), (0.090, 0.126, 0.161)>	···	<(0.725, 0.647, 0.724), (0.231, 0.217, 0.243), (0.153, 0.187, 0.208)>
C_8	<(0.734, 0.726, 0.790), (0.185, 0.216, 0.237), (0.126, 0.158, 0.207)>	···	<(0.412, 0.355, 0.381), (0.478, 0.456, 0.596), (0.400, 0.409, 0.544)>
C_9	<(0.397, 0.339, 0.360), (0.492, 0.475, 0.613), (0.409, 0.429, 0.560)>	···	<(0.774, 0.718, 0.786), (0.154, 0.152, 0.174), (0.086, 0.145, 0.130)>
C_{10}	<(0.636, 0.574, 0.531), (0.348, 0.476, 0.428), (0.297, 0.407, 0.364)>	···	<(0.832, 0.771, 0.830), (0.190, 0.213, 0.172), (0.127, 0.144, 0.156)>
C_{11}	<(0.584, 0.510, 0.565), (0.238, 0.213, 0.314), (0.148, 0.252, 0.229)>	···	<(0.419, 0.395, 0.301), (0.454, 0.540, 0.653), (0.429, 0.505, 0.555)>
C_{12}	<(0.523, 0.519, 0.527), (0.340, 0.376, 0.483), (0.289, 0.325, 0.412)>	···	<(0.531, 0.501, 0.507), (0.305, 0.328, 0.431), (0.233, 0.328, 0.344)>
C_{13}	<(0.337, 0.292, 0.218), (0.535, 0.612, 0.718), (0.465, 0.582, 0.640)>	···	<(0.759, 0.745, 0.805), (0.149, 0.169, 0.195), (0.090, 0.140, 0.152)>

Table B.3. The score decision matrix, extreme values, and criteria types.

Alternative	**Criterion**												
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
A_1	0.714	0.510	0.370	0.790	0.308	0.460	0.832	0.790	0.463	0.593	0.693	0.597	0.366
A_2	0.423	0.550	0.643	0.487	0.663	0.715	0.610	0.757	0.686	0.566	0.669	0.657	0.820
A_3	0.477	0.693	0.719	0.522	0.695	0.728	0.686	0.589	0.664	0.904	0.291	0.371	0.711
A_4	0.325	0.477	0.745	0.399	0.833	0.565	0.758	0.479	0.822	0.820	0.444	0.618	0.821
Minimum	0.325	0.477	0.370	0.399	0.308	0.460	0.610	0.479	0.463	0.566	0.291	0.371	0.366
Maximum	0.714	0.693	0.745	0.790	0.833	0.728	0.832	0.790	0.822	0.904	0.693	0.657	0.821
Type	Min	Min	Min	Min	Max	Min	Max	Min	Max	Min	Max	Max	Max