

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF
SCIENCE ENGINEERING AND TECHNOLOGY

**AN INTEGRATED DECISION-MAKING FRAMEWORK FOR ANALYZING
ENVIRONMENTAL SUSTAINABILITY OF ROAD TRANSPORT: CASE OF A
SCHOOL BUS FLEET SERVING TO A COMPLEX URBAN AREA**



M.Sc. THESIS

Sercan AKTİ

Department of Civil Engineering
Transportation Engineering Programme

JUNE 2020

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Transportation Engineering Programme**

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JUNE 2020

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**KARAYOLU ULAŞIMININ ÇEVRESEL SÜRDÜRÜLEBİLİRLİĞİNİN
ANALİZİ İÇİN BÜTÜNLEŞİK BİR KARAR VERME ÇERÇEVESİ:
KARMAŞIK BİR KENTSEL ALANA HİZMET VEREN BİR OKUL OTOBÜSÜ
FİLOSU ÖRNEĞİ**

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Dedicated to my family,



FOREWORD

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ABBREVIATIONS

ABS	: Antilock Brake System
AEBS	: Automatic Emergency Brake System
AHP	: Analytic Hierarchical Process
ANN	: Artificial Neural Network
BEVs	: Battery Electric Vehicles
BRT	: Bus Rapid Transit
CBA	: Cost-Benefit Analysis
CFCs	: Chlorofluorocarbons
CH₄	: Methane
CI	: Consistency Index
CO	: Carbon Monoxide
CO₂	: Carbon Dioxide
COPRAS	: Cooperation Platform for Research and Standards
CR	: Consistency Ratio
DEMATEL	: Decision Making Trial and Evaluation Laboratory
DSD	: Director of Strategy Development
EC	: European Commission
EEA	: European Environment Agency
EIA	: Environmental Impact Assessment
ELECTRE	: ELimination Et Choix Traduisant la REalité
EU	: European Union
EVs	: Electric Vehicles

FCWS	: Forward Collision Warning System
F-GASES	: Fluorinated Gases
GA	: Genetic Algorithm
GDM	: Group Decision Making
GHG	: Greenhouse Gas
GIAI	: Geometrical Analysis for Interactive Aid
GRA	: Grey Relational Analysis
HC	: Hydrocarbons
HEVs	: Hybrid Electric Vehicles
HIA	: Health Impact Assessment
ICEVs	: Internal Combustion Engine Vehicles
IFCI	: Intuitionistic Fuzzy Choquet Integral
IPCC	: Intergovernmental Panel on Climate Change
IRM	: Influential-Relation Map
ITMP	: Istanbul Transport Master Plan
IVIFPRs	: Interval-Valued Intuitionistic Fuzzy Preference Relations
IVIFWA	: Interval-Valued Intuitionistic Fuzzy Weighted Averaging
LCA	: Life Cycle Assessment
LCIA	: Life Cycle Impact Assessment
LDWS	: Lane Departure Warning System
LPG	: Liquefied Petroleum Gas
MABAC	: Multi-Attributive Border Approximation Area Comparison
MADM	: Multi-Attribute Decision-Making
MAIRCA	: Multi-Attributive Ideal-Real Comparative Analysis
MCDM	: Multi-Criteria Decision Making

MGE	: Multilevel Grey Evaluation
MULTIMOORA	: Multi-Objective Optimization by Ratio Analysis plus Full Multiplicative Form
N₂O	: Nitrous Oxide
NO₂	: Nitrogen Dioxide
NO_x	: Nitrogen Oxides
O₃	: Ozone
OECD	: Organization for Economic Cooperation and Development
ORNL	: Oak Ridge National Laboratory
PHEVs	: Plug-In Hybrid Electric Vehicles
PM	: Particulate Matter
PROMETHEE	: Preference Ranking Organization Method for Enrichment Evaluations
PSO	: Particle Swarm Optimization
RI	: Random Index
SCAQMD	: South Coast Air Quality Management District
SEA	: Strategic Environmental Assessment
SMAA	: Stochastic Multi-criteria Acceptability Analysis
SMAWS	: Speed Monitoring And Warning System
SO₂	: Sulfur Dioxide
SO_x	: Sulfur Oxide
SWARA-G	: Step-wise Weight Assessment Ratio Analysis
TEM	: Trans European Motorway
TOPSIS	: Technique for Order Preference by Similarity to Ideal Solution
TSI	: Turkish Statistical Institute
TSP	: Total Suspended Particles

U.S EIA	: United States Energy Information Administration
VIKOR	: Vlekriterijumsko KOmpromisno Rangiranje
VOCs	: Volatile Organic Hydrocarbons
WHO	: World Health Organization



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AN INTEGRATED DECISION-MAKING FRAMEWORK FOR ANALYZING ENVIRONMENTAL SUSTAINABILITY OF ROAD TRANSPORT: CASE OF A SCHOOL BUS FLEET SERVING TO A COMPLEX URBAN AREA

SUMMARY

Decision making may be defined as the process of choosing one alternative among various alternatives. A well-planned decision-making process makes it possible to understand the relationship between the evaluation criteria and to achieve a final decision with a proper approach for decision-makers. A good decision is a logical choice that results from the assessment of possible options using available resources. Making the right decision by employing limited resources in the most effective way has significant importance worldwide. The decision-making process for investments to be made in the transportation sector, which has an important place in the country's economy, should be carried out carefully as transportation investments are costly and mostly they are unlikely to be recycled. Aside from their economic considerations, environmental aspects of these investments should be included in the decision-making process.

In this thesis, the decision-making problem of determining the most suitable vehicle for a bus fleet serving to a complex urban area considering the requirements of an environmentally sustainable transportation system is analyzed. The evaluation criteria to be used in the solution of the problem of renewing the service fleet are determined under different main headings as a result of examining the studies conducted on vehicle selection and consulting the opinions of the vehicle users. Based on their scopes, evaluation criteria are classified as five main headings as follows: i) economic; ii) performance; iii) physical; iv) environmental; and, v) safety measures. Under these five main headings, a total of twenty-four sub-criteria are listed. In addition to these criteria, vehicle alternatives that will be compared and ranked based on the selected criteria are provided. The vehicle alternatives consist of a total of twelve buses belonging to three vehicle classes namely internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs) and electric vehicles (EVs). In order to solve the considered problem, an integrated Multi-Criteria Decision-Making framework including Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Decision Making Trial and Evaluation Laboratory (DEMATEL) and Multi-Objective Optimization by Ratio Analysis plus Full Multiplicative Form (MULTIMOORA) is proposed.

Experts are asked to compare the evaluation criteria using the 1-9 scale developed by Saaty. Employing the AHP method, criteria weights are calculated based on the experts' opinions. AHP method also allows users to eliminate inconsistent pair-wise comparisons of criteria through consistency check.

TOPSIS method is utilized to rank vehicle alternatives considering the calculated criteria weights. In this method, real values of quantitative criteria are used while

different scales are utilized for qualitative criteria. To illustrate, the 1-3 scale, in which 1 represents the worst and 3 represents the best criteria, or 0-1 scale, in which 0 represents “No” or 1 represents “Yes”.

Similar to the AHP method, the DEMATEL method, which is also based on the pairwise comparison, allows users to calculate weights of criteria. As the comparison scale, the 0-4 scale is applied in this method. The present method also allows the graphical representation of the relationship between evaluation criteria through influential-relation maps.

Combining three different approaches, The Ratio System, The Reference Point Approach, and The Full Multiplicative Form, the MULTIMOORA method enables the ranking of alternatives using the calculated criteria weights.

It is shown that the proposed hybrid framework, which consists of pairs of AHP-TOPSIS and DEMATEL-MULTIMOORA approaches, fits the purpose of the considered decision-making problem and provides consistent results in terms of ranking of selected vehicle alternatives.



**KARAYOLU ULAŞIMININ ÇEVRESEL SÜRDÜRÜLEBİLİRLİĞİNİN
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KARMAŞIK BİR KENTSEL ALANA HİZMET VEREN BİR OKUL
OTOBÜSÜ FİLOSU ÖRNEĞİ**

ÖZET

Taşıt kullanımındaki sürekli artış ile birlikte karayolu ulaşımı, diğer ulaşım sistemleri arasında önemli bir konuma gelmiştir. Gelişen karayolu ağının bir sonucu olarak küresel ısınma, doğal arazinin bozulması, enerji tüketimi ve toprağın asitlenmesi gibi olumsuz çevresel etkiler ortaya çıkmaktadır. Bunun yanında karayolu ağları; biyolojik çeşitlilik kaybı, mevcut doğal yaşam alanlarına erişimin engellenmesi ve yaşam alanlarının parçalanması gibi önemli sorunlara da neden olmaktadır. Karayolu ulaşımı tüm dünyada günlük olarak milyonlarca hayatı etkilediğinden bu sistemlerle ilgili karar verme aşamasında ihtiyaçlara en uygun seçeneğin belirlenmesi oldukça önemli bir rol oynamaktadır.

Günümüzde taşıt üreticileri, hem farklı özelliklerde taşıt üretmeye hem de değişen kullanıcı taleplerine göre mevcut tasarımları iyileştirmeye çalışmaktadır. Bu amaca hizmet etmek üzere çok sayıda marka ve model seçeneği sunulmaktadır. Bu seçenekler kendi aralarında boyut ve renk gibi fiziksel donanım özellikleri ile performans ve yakıt tipi gibi mekanik özellikler açısından farklılık göstermektedir. Hedeflenen kullanım için en uygun taşıtı seçmek, çevresel kaygıları olan alıcılar için zorlu bir görev haline gelmektedir.

Karar verme, önceden belirlenmiş bir amaca yönelik olarak çeşitli seçenekler arasından bir veya birden fazla seçeneğin belirlenme süreci olarak tanımlanabilmektedir. Karar verme sürecinde ise mevcut kaynakların kullanılarak olası seçeneklerin değerlendirilmesi ile mantıklı bir seçim yapılması hedeflenmektedir. İyi planlanmış bir karar verme süreci, değerlendirme ölçütleri arasındaki ilişkiyi anlamayı ve karar vericiler için en uygun yaklaşımı kullanarak nihai karar vermeyi mümkün kılmaktadır. Sınırlı kaynakları en etkin şekilde kullanarak doğru kararı vermek büyük önem taşımaktadır. Ülke ekonomisinde önemli bir yere sahip olan ulaştırma yatırımları çok pahalı olduğundan ve genellikle geri dönüştürülmeleri mümkün olmadığından, bu yatırımlar için karar verme süreci dikkatle gerçekleştirilmelidir. Ekonomik etkenlere ek olarak bu yatırımların çevresel yönleri de karar verme sürecine dahil edilmelidir.

Çok Ölçütlü Karar Verme (ÇÖKV) çözümlemesi, ele alınan karar verme problemine yönelik olarak belirlenen ölçütlerin bir arada değerlendirilerek seçeneklere değer atanması ve bu seçeneklere ait tercih edilme sırasının belirlenmesi sürecini ifade etmektedir. ÇÖKV çözümlemesi ile karar vericinin amacına yönelik olarak birden fazla seçenek arasından en uygun bir veya birden fazla seçeneğin tercih edilmesi mümkündür. Yıllar içerisinde geliştirilen farklı modeller ile hem nicel hem de nitel ölçütlerin karşılaştırılmasına olanak sağlayan ÇÖKV çözümlemesi, eğitim, sağlık, işletme ve mühendislik gibi birçok farklı sektörde karar verme sürecinde yaygın

olarak tercih edilmektedir. ÇÖKV çözümlemesinin bu kadar yaygın olarak tercih edilmesindeki en önemli etken, kolay uygulanabilir yöntemlerden oluşan güçlü bir mantık yapısına sahip olmasıdır.

ÇÖKV yöntemleri, birçok gerçek dünya probleminin çözümünde önemli bir rol oynamasına rağmen bu yöntemlerden elde edilen sonuçlar her zaman nihai sonuç olarak değerlendirilmeyebilir. Değerlendirme ölçütlerinin ağırlıklarının hesaplanması bireysel kararlara ve uzmanların kişisel görüşlerine bağlı olduğundan, çözümün doğruluğu özellikle nitel ölçütlerin değerlendirilmesinde önemli ölçüde farklılık gösterebilmektedir. Bu olumsuz durumu ortadan kaldırmak için Analitik Hiyerarşi Süreci (Analytic Hierarchy Process-AHP) yönteminde bireysel tercihlerin tutarlılık oranını hesaplayan ve bu oranı bir sabit ile karşılaştıran tutarlılık çözümlemesi uygulanmaktadır. Farklı ÇÖKV yöntemlerini kullanarak ve bu yöntemlerle elde edilen sonuçları karşılaştırarak karar verme problemleri için daha doğru ve sağlam çözümler elde etmek mümkündür.

Bu tez kapsamında, karmaşık bir kentsel alana hizmet veren bir okul otobüsü filosu için çevresel açıdan sürdürülebilir bir ulaşım sisteminin gereklilikleri göz önünde bulundurularak, en uygun taşıtın belirlenmesi problemi analiz edilmiştir. Servis filosunun yenilenmesi probleminin çözümünde kullanılacak değerlendirme ölçütleri, taşıt seçimi üzerine yapılan çalışmaların incelenmesi ve taşıt kullanıcılarının görüşlerinin alınması sonucunda farklı ana başlıklar altında belirlenmiştir. Değerlendirme ölçütleri kapsamına göre: i) ekonomik; ii) performans; iii) fiziksel; iv) çevresel; ve, v) güvenlik ölçütleri olmak üzere beş ana başlıkta sınıflandırılmıştır. Bu beş ana başlık altında toplam yirmi dört alt ölçüt listelenmiştir. Değerlendirme ölçütlerine ek olarak seçilen ölçütlere göre karşılaştırılacak ve sıralanacak taşıt seçenekleri de sunulmaktadır. Taşıt seçenekleri; içten yanmalı motorlu taşıtlar (ICEV'ler), hibrit elektrikli taşıtlar (HEV'ler) ve elektrikli taşıtlar (EV'ler) olmak üzere üç taşıt sınıfına ait toplam on iki farklı tip otobüsten oluşmaktadır. Göz önünde bulundurulan sorunu çözmek üzere Analitik Hiyerarşi Süreci (Analytic Hierarchy Process-AHP), Ideal Çözüme Benzerliğe Göre Tercihlerin Sıralanması Tekniği (Technique for Order Preference by Similarity to Ideal Solution-TOPSIS), Karar Verme Deneme ve Değerlendirme Laboratuvarı (Decision Making Trial and Evaluation Laboratory-DEMATEL) ve Oran Çözümlemesi ile Çok Amaçlı En İyileme ve Tam Çarpımsal Durum (Multi-Objective Optimization by Ratio Analysis plus Full Multiplicative Form-MULTIMOORA) yöntemlerinden oluşan bütünlük bir ÇÖKV çerçevesi önerilmektedir.

Karar verme sürecinde, önerilen modellerin tamamında ortak olan aşamalar şu şekilde sıralanabilmektedir: i) karar verme probleminin tanımlanması; ii) probleme ait modelin oluşturulması; iii) ölçüt ağırlıklarının belirlenmesi amacıyla ikili karşılaştırma matrislerinin oluşturulması; iv) seçeneklerin değerlendirme aşamasında doğrudan kullanılabilmesi amacıyla normalizasyon işleminin gerçekleştirilmesi; v) önerilen modeller ile çözüme ulaşılması; vi) elde edilen sonuçların karşılaştırılması; ve, vii) nihai kararın belirlenmesi.

AHP yönteminde, uzmanlardan, değerlendirme ölçütlerini Saaty (1994) tarafından geliştirilen 1-9 ölçeğini kullanarak karşılaştırmaları istenmiştir. Bu yöntemde, ölçüt ağırlıkları uzmanların kişisel görüşlerine göre hesaplanmaktadır. AHP yöntemi tutarlılık çözümlemesi ile kullanıcılara, ölçütlere ait ikili karşılaştırmalardan tutarsız olanların değerlendirmeden çıkarılması imkanını tanımaktadır.

Hesaplanan ölçüt ağırlıkları dikkate alınarak taşıt seçeneklerinin tercih edilebilirlik sıralamasını belirlemek amacıyla TOPSIS yöntemi kullanılmıştır. Bu yöntemde, nicel ölçütlerin gerçek değerleri kullanılırken nitel ölçütler için ise farklı ölçekler kullanılmaktadır. Örneğin; en kötü ölçütün 1 en iyi ölçütün 3 ile temsil edildiği 1-3 karşılaştırma ölçeği veya “Hayır” ve “Evet” anlamına gelen 0-1 karşılaştırma ölçeği kullanılabilir.

AHP yönteminde olduğu gibi ikili karşılaştırmaya dayanan DEMATEL yöntemi, kullanıcıların ölçüt ağırlıklarını hesaplamasına izin vermektedir. Karşılaştırma ölçeği olarak bu yöntemde 0-4 ölçeği kullanılmaktadır. Mevcut yöntem ayrıca, Etki-İlişki Haritası yoluyla değerlendirme ölçütleri arasındaki ilişkinin grafiksel olarak gösterilmesine de olanak tanımaktadır.

Oran Sistemi (The Ratio System), Referans Noktası Yaklaşımı (The Reference Point Approach) ve Tam Çarpımsal Durum (The Full Multiplicative Form) olmak üzere üç farklı yaklaşımdan oluşan MULTIMOORA yöntemi, hesaplanan ölçüt ağırlıklarını kullanarak seçeneklere ait tercih edilebilirlik sıralamasının belirlenmesi amacıyla kullanılmaktadır.

Önerilen bütünleşik çerçeve ile seçeneklerin tercih edilebilirlik sıralaması belirlendikten sonra duyarlılık çözümlemesi uygulanmıştır. Duyarlılık çözümlemesi ile AHP ve DEMATEL yöntemleri kullanılarak hesaplanan değerlendirme ölçütlerine ait ağırlık değerlerinin değişiminin, seçeneklerin tercih edilebilirlik sıralaması üzerindeki etkilerinin belirlenmesi hedeflenmiştir.

Tez kapsamında önerilen ve AHP-TOPSIS ve DEMATEL-MULTIMOORA yaklaşım çiftlerinden oluşan bütünleşik karar verme çerçevesinin, dikkate alınan karar verme probleminin amacına uygun olduğu ve belirlenen taşıt seçeneklerinin sıralanması açısından tutarlı sonuçlar verdiği belirlenmiştir. Önerilen bütünleşik çözüm çerçevesi ile elde edilen çözüm tabloları, İstanbul Ulaşım Ana Planı'nda ve İstanbul için önerilen tamamlanmış veya inşaatı devam eden orta ve uzun vadeli projelerde belirlenen sürdürülebilirlik hedefleri ile tutarlı sonuçlar vermektedir.



1. INTRODUCTION

In the following, firstly motivation of the study including a general overview on the transportation sector and problems that exist as a result of transportation are summarized. In the second sub-section, the research objectives of the study are provided. Then, the scope of the thesis is given in the third sub-section, in which the focus and purpose of the study are summarized briefly as well. Finally, the structure of the thesis is provided through the organization of topics.

1.1 Motivation of Research

The transportation system that the economy depends on and the environment is in interaction with is very crucial, and is a priority area of sustainable development intervention. Since it exists in all stages of the production chain, transportation takes a significant part in the economy at all geographical scales (Rodrigue et al., 2013). People can get access to education, goods, job opportunities, etc. thanks to transport. A contribution to the economic enhancement of countries can be accepted as another positive effect of transport systems. Although it possesses several benefits, transportation has also many negative aspects (Boesch et al., 2008). Transport can be regarded as the fastest growing industry in terms of environmental pollution. Studies conducted to analyze the Carbon Dioxide (CO₂) levels reveals that the atmospheric CO₂ concentration, which was previously around 280 parts per million (ppm), reached to around 379 ppm in 2005 and, assuming that no precautions are taken, the level of CO₂ emissions has been anticipated to reach to around 550 ppm by 2050 (Hickman, 2010). Results of increasing CO₂ concentrations are investigated by the (IPCC) and, according to the related report with an increase of 2°C or 3°C in the surface temperature caused by increasing CO₂ concentrations, it is almost likely that there will be: frequently hot days and nights, and less cold days and nights; and, extreme rainfall events, warm periods, and heatwaves (IPCC, 2007). It is also likely to face drought-affected areas, severe tropical cyclone activities, and exceptionally elevated sea levels (IPCC, 2007). It is a well-known fact that transportation,

especially road transportation, is the main reason for Greenhouse Gas (GHG) emissions (Anenberg et al., 2019). In Europe, nearly 100,000 premature deaths are seen each year due to air pollution and road transport emissions make large contributions to this burden (WHO, n.d). Since mainly traditional vehicles that burn fossil fuels are preferred for transportation, hazardous gas emissions, consisting of hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x), have significant environmental and human health consequences. In Figure 1, the share of fuel types that are used by the transportation sector is demonstrated (EIA, 2018). According to the year 2018 figures by the Turkish Statistical Institute, the numbers of i) gasoline vehicles are 3,089,626 (24.9% of total vehicles); ii) diesel vehicles are 4,568,665 (36.8%); iii) Liquefied Petroleum Gas (LPG) vehicles are 4,695,717 (37.9%); iv) electric or hybrid vehicles are 5,367 (nearly 0.01%); and, v) unknown fuel type registered vehicles are 38,815 (0.3%) (TSI, 2019a). The percentage values show the rate of vehicle types compared the total number of vehicles.

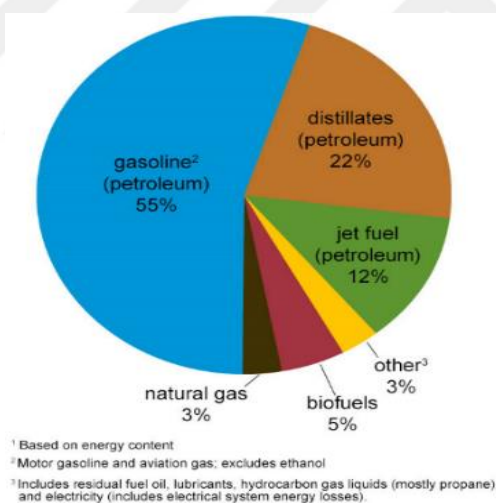


Figure 1.1 : U.S. transportation energy sources/fuels (EIA, 2018).

European Environment Agency (EEA) figured out that 25% of GHG emission is due to transport in 2017, and road transport accounts for a share of 72.1% of all EU-28 countries' domestic transport (Figure 1.2 and 1.3) (EC, 2017). GHG emissions caused by different sectors and the corresponding share of the transport sector are given in Figure 1.4 and Figure 1.5, respectively (TSI, 2019b).

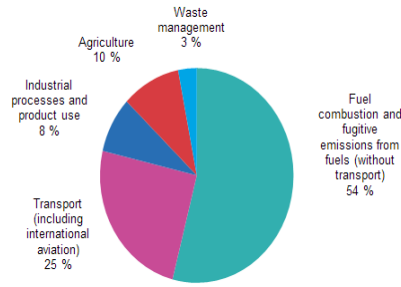


Figure 1.2 : Greenhouse gas emissions by source sector, in EU-28, in 2017 (EC, 2017).

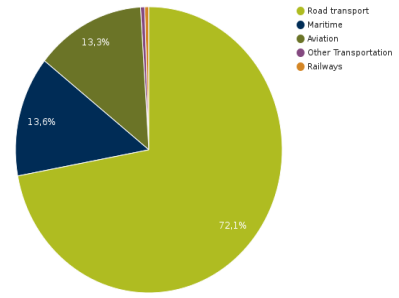


Figure 1.3 : Contribution of transportation sector to greenhouse gas emissions in 2017 - EU (EC, 2017).

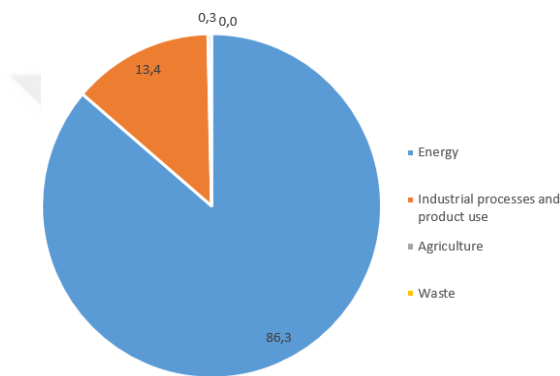


Figure 1.4 : CO₂ emissions by sectors in 2017 in Turkey (TSI, 2019b).

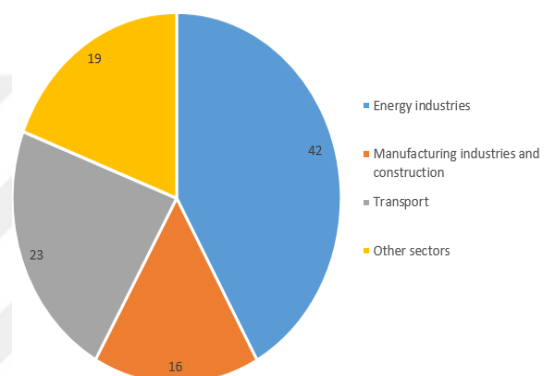


Figure 1.5 : CO₂ emissions of fuel combustion sub-sector under the energy sector in 2017 in Turkey (TSI, 2019b).

According to the 2016 Turkey Greenhouse Gas Emissions Inventory (Republic of Turkey Director of Strategy Development (DSD), 2018), 16.5% of the total of 496.07 Million Tons of CO₂ equivalent emissions stem from the transportation sector. Figure 1.6 indicates the distribution of CO₂ equivalent emissions based on the mode of transport in Turkey.

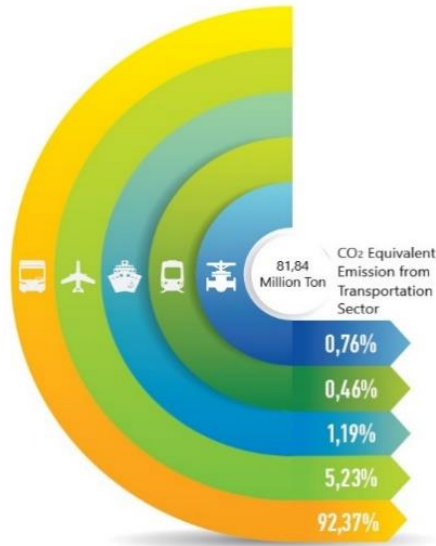


Figure 1.6 : CO₂ equivalent emissions from transportation sector in Turkey in 2016 (DSD, 2018).

In the report prepared by the IPCC (2014), it is stated that the highest decadal increase in human history of anthropogenic GHG was updated between 2000 and 2010 with average annual GHG emissions of 1.0 gigatonne CO₂-equivalent (CO₂e). The biggest pollution source is from fossil fuel combustion and industrial procedures, with a share of approximately 78% (IPCC, 2014). Changes in GHG emissions and GHG per capita values in Turkey are given in Figure 1.7 (Republic of Turkey Ministry of Environment and Urbanization, 2018) and Figure 1.8, respectively.

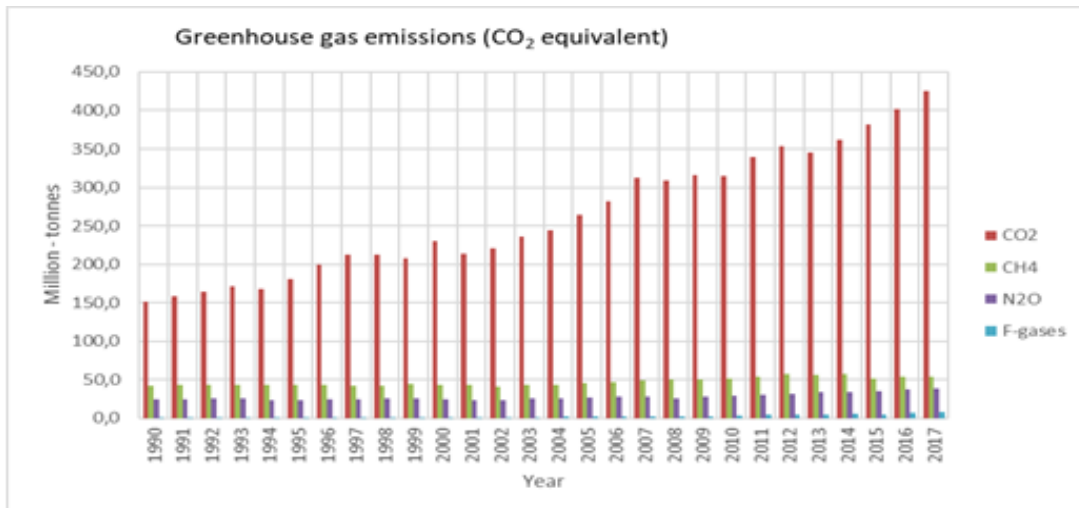


Figure 1.7 : Greenhouse gas emission change between 1990 and 2017 in Turkey (Republic of Turkey Ministry of Environment and Urbanization, 2018).

In the figure, Fluorinated gases (F-gases), which are used in many applications of different industries, are man-made gases. Being a strong GHG emission, F-gases are 23,000 times more effective than CO₂ in terms of global warming (European Commission, n.d).

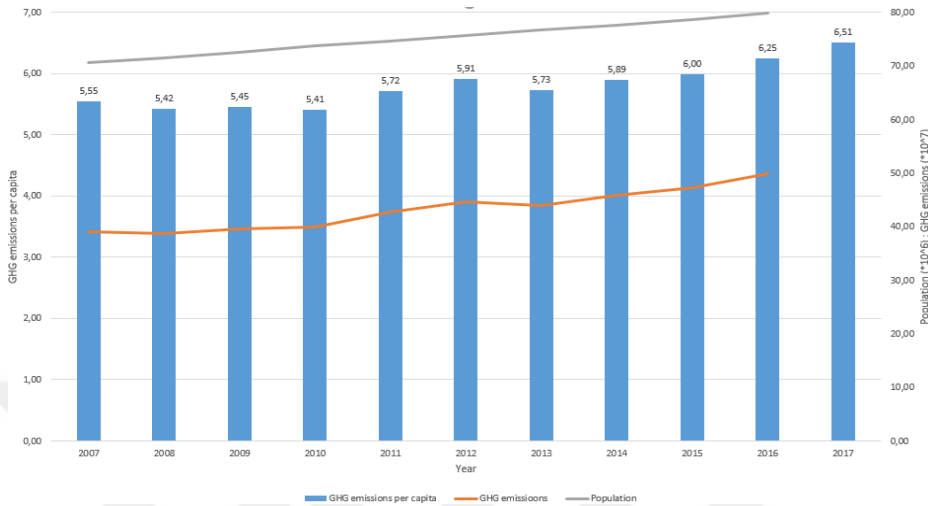


Figure 1.8 : Greenhouse gas emission per capita between 2007 and 2017 in Turkey (Republic of Turkey Ministry of Environment and Urbanization, 2018).

1.2 Research Objective

Allowing people to move between their origins and destinations, the transportation sector takes a significant part in the economy, however, it is also one of the biggest causes of energy consumption and the consequent pollution (Greene, 1992; Mayeres et al., 1996). With increasing environmental awareness and concern, the transportation sector has experienced many differences. A number of both private and governmental institutions have proposed regulations and directives with aims of improving the transportation sector environment-friendly, encouraging an environmentally sustainable transport system, and increasing the competitiveness of transportation networks (Chester and Horvath, 2007).

Today, there are many consequences of communities' travel behaviors since the network constructed for road transport covers a wide area in urban areas. One of these consequences can be given as building a liveable urban environment. Thus, the purpose of the thesis has been determined as to propose an integrated decision-making framework in order to assess the environmental sustainability of the transportation system, particularly road transportation. A sustainable transportation system is closely linked to social life, environment and natural life, and various

economic factors. Thus, it is essential to establish an evaluation framework that allows all of the mentioned factors to be taken into consideration during the evaluation phase.

Transportation's environmental effects should not be calculated based on a single phase in the infrastructure or vehicle life cycle. In order to determine environmental impacts reliably and to understand the impacts of the transport modes, a methodology should be developed. Precise quantification may provide a better understanding of the emissions and resource inputs related to transportation modes.

1.3 Scope of Thesis

This thesis has its focus on evaluating the sustainability level of an urban transport mode in terms of environmental aspects and proposing an integrated decision-making framework, through a case of school bus fleet operation in a complex urban area, that can be used to aid in improving the environmental sustainability of urban transportation systems involving road vehicles. The introduction and the classification of the components of a transportation system are provided on purpose to develop an extensive environmentally sustainable decision-making framework. Within the scope of the thesis, firstly, a review on the current studies on transportation-related problems including environmental pollution, specifically air pollution, etc. is presented highlighting the performance measures of transportation systems and the decision-making methods employed to related transportation problems. As the main objective of the thesis is to propose a framework that can be employed in decision-making, the relevant definitions, and the methods are presented. By using the knowledge and individual judgments obtained from both the studies reviewed and the questionnaires made with several experts from several related disciplines, the problem of how the transportation system can be improved especially from an environmental point of view has been tried to be addressed.

1.4 Organization of Thesis

The organization of the thesis is as follows: Section I constructs the introduction of the thesis. The general information, problems related to the transportation sector, research objectives, and the scope of the study are provided in this section. Section II

presents a review on related literature. In this part, definitions of terms related to sustainability and sustainable transportation, frameworks used for the analysis of environmental issues, and methods utilized in the solution of transport-related environmental problems are given. In Section III, the general description of the decision-making problem dealt with, the methodological approach and the hybrid framework proposed to solve the problem are provided. In Section IV, the case study is introduced. General information including regional and global characteristics of the selected case study area and related data, scenarios determined for the decision-making problem, selected evaluation criteria and alternatives, and a discussion on the performance of the proposed integrated decision-making framework are provided. Using the findings from the study, the conclusions are drawn in Section V: solution of the decision-making problem considering the proposed framework; and, further research directions are discussed.



2. LITERATURE REVIEW

In the following, firstly sustainable transportation-related performance measures and their definitions are presented considering the fundamental concepts provided through studies conducted by environmental agencies, institutions, etc. As the second part of the literature review study, transport-related decision-making frameworks are summarized. Finally, the methods used to evaluate environmental issues and transport-related decision making are explained.

2.1 Definitions and Performance Measures on Environmental Sustainability of Transportation

This sub-section includes definitions of environmentally sustainable transportation-related performance measures.

2.1.1 Definitions

The transport sector-based health and environmental problems have become globally environmental concerns today and, countries have started to take necessary precautions against these problems. Besides air pollution, the global warming, the other sources of environmental pollution, and high oil prices are the main motivation for transport and vehicle industry stakeholders to search for environmentally friend/sustainable transport alternatives.

Sustainability highlights the integrated nature of human actions and hence, the necessity for coordinated planning between various industries, organizations, and jurisdictions. There exist different objectives in transport planning that promote sustainability aims: (i) diversity of transport system; (ii) integration of the system; (iii) affordability; (iv) efficiency of resources (energy and land); (v) efficient pricing and prioritization; (vi) accessibility of land use; (vii) operational efficiency; and, (viii) comprehensive and inclusive planning (Litman, 2007). There are many definitions of sustainable transportation systems in the literature:

According to the European Union (EU)'s definition (EU, 2001), the sustainable transportation system: i) enables the elementary access demands of communities and individuals to be provided in a safe manner and such that it is compatible with environmental and people health, and with equality within and between generations; ii) is economical and effectively operated, provides alternatives for transport modes, and promotes a lively economy; and, iii) restricts both waste and emissions based on the planet absorption capacity, reduces the consumption of non-renewable sources, restricts the consumption of renewable sources based on the sustainability level and allows reusing and recycling of components of renewable sources, and reduces both land use and noise generation.

The European Union's Sustainable Development Strategy (EC, 2003), defines the transport sustainability as the capability of satisfying community's requirements such as moving freely, gaining access, interacting, trading and building relationships without giving up from other vital human and ecological values today and in the future generation.

According to the World Health Organization (WHO)'s definition (WHO, 2004), sustainable transportation is the main objective to perform simultaneously not only the transportation of humans (people) and products (goods) but also a contribution to succeeding economic, environmental, and social sustainability.

A method of evaluation to analyze the relationship between policies, services, and initiatives in terms of their performances about their intended objectives can be defined as the performance evaluation. In a performance evaluation process, the definition for the performance measures can be given as characteristic tangible measures used in the assessment of progress in terms of the goals and priorities set.

2.1.2 Performance measures

While transportation contributes significantly to the economy, it is also a large and growing risk factor for the environment and human health (Dobranskyte-Niskota et al., 2009). According to EC (EC, 2006; EC, 2009), meeting the social, economic, and environmental requirements of a society is the fundamental aim of sustainable transport in the EU. Other objectives of the transport sustainability are providing solutions for negative externalities having influences on the economy, society, and environment (EC, 2009). In the processes of both decision-making and policy-

making, indicators that have been developed to measure and used in evaluating transport activities take a vital part. Considering environmental, social, and economic purposes, these indicators can be implemented at many different levels including the planning process, alternatives and stimulatory measures, travel behaviors, physical influences, impacts on both human and environment, economic impacts, and performance objectives (Dobranskyte-Niskota et al., 2007). Based on the Vancouver principles, criteria used to describe sustainable transport can be listed as follows: accessibility, equality, safety, health, individual responsibility, prevention of pollution, integrated planning, use of both land and resource, public participation, and education (OECD, 1996).

Transportation systems have close interactions with several important measures such as environmental, economic, and social in terms of sustainability. The representation of sustainable transport systems' interaction with these measures is given in Figure 2.1.

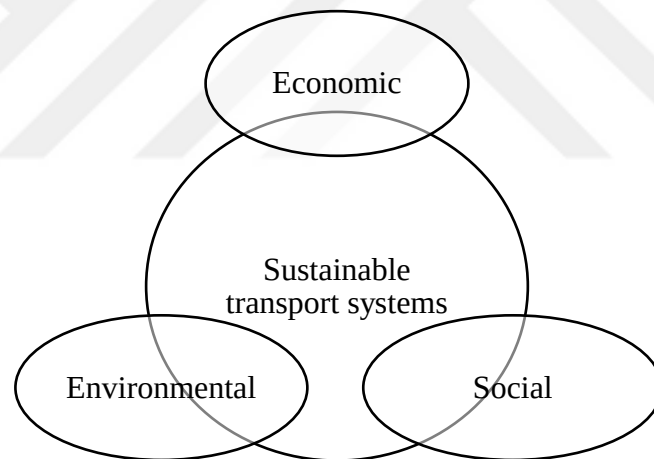


Figure 2.1 : Interaction of sustainable transport systems with related measures (Senning and Sundberg, 2013).

The indicators used to measure the performance of sustainable transport systems are shown in Table 2.1.

Table 2.1 : Performance measures of sustainable transportation.

Economic	Social	Environmental
Transportation expenditures	Social equity	Air quality
Infrastructure expenditures	Accessibility	Exhaust emissions
Vehicle operation costs including fuel costs and taxing	Affordability	Climate change
External costs of transportation	Livability	Greenhouse gas effect
The usage rate of transportation modes including road, air, rail and maritime in passenger and freight transport	Safety	Water quality
Energy efficiency	Health	Noise
Fuel consumption	Number of people, injured or died, in traffic accidents	Land quality
Pricing of transportation modes	Transportation diversity	Waste management
Transport options	System integration	Hazardous components
Employment	Human exposure to harmful pollutants	Resource utilization
Productivity		Biodiversity
		Habitat conservation

Taking financial, social, and environmental requirements into account, sustainable transport focuses on providing secure, and efficient mobility and access for the future. Three pillars of sustainability consist of economic effectiveness, protection of the environment, and social equity, which is the main discussion (Ramani et al., 2009). According to Jeon and Amekudzi (2005), characteristics of system efficiency and system impacts on social quality of life, financial development, and environmental integrity should be combined. System performance of a multimodal transportation system, some of which are transit systems and regional highways, is considered by some vital components of the transportation system for sustainability (Jeon et al., 2012):

Environmental elements: conservation of resources including land and fossil fuels, avoidance of noise and air pollution, and GHG impact,

Economic elements: financial effectiveness and affordability, improvement of the regional economy with increased accessibility, and

Social elements: social equity, the well-being of the community, safety, security, and accessibility to the services.

Transport of both goods and people from one point to another contributes to society in many ways. However, transport is also an important contributor to air pollution, in addition to energy production and industrial processing. Air pollution is defined by the European Environment Agency (EEA) as the presence of contaminants in the atmosphere at a level that is detrimental to human health, cultural inheritance, and environment (EEA, 2016). It causes several environmental problems at different levels: deterioration of air quality at urban and street scale as well as (GHG) emissions on a global scale (Greene and Wegener, 1997). In the literature, there exist studies conducted about the effects and influence area of emissions. Transport based environmental effects differ with respect to their spatial expansion, varying from global to local. Oak Ridge National Laboratory (ORNL) and the United States Environmental Protection Agency (US EPA) analyzed pollution emissions caused by different motor vehicles and, summarized the effects of emissions as given in Table 2.2 (Sirikijpanichkul et al., 2006).

Table 2.2 : Air pollutant emissions (Sirikijpanichkul et al., 2006).

Emissions	Definition	Sources	Harmful Impacts	Scale
Carbon dioxide (CO ₂)	A byproduct of combustion	Engines and fuel production	Climate change	Global
Carbon monoxide (CO)	A toxic gas that impairs the ability of the blood to carry oxygen	Engine	Climate change and human health	Very local
Chlorofluorocarbons (CFCs)	A durable chemical which damages the ozone layer and atmosphere	Earlier air conditioners and aerosol	Ozone depletion	Global
Fine particulates (PM ₁₀ ; PM _{2.5})	Inhalable particles made of fuel and carbon particles	Diesel engines and other sources	Aesthetics and human health	Local and regional
Hydrocarbons (HC)	Ozone caused by uncombusted gasoline	Fuel production and engines	Ozone precursor and human health	Regional
Lead	Elements in older fuel supplements	Battery and fuel ingredients	Circulatory, nervous and reproductive system	
Methane (CH ₄)	A gas with important characteristics of greenhouse gases	Fuel production and engines	Climate change	Local
Nitrogen oxides (NO _x)	Different compounds, some of which are harmful and all which lead to ozone	Engine	Ozone precursor, human health and ecological effects	Global
Ozone (O ₃)	The main problem of urban air pollution due to NO _x and VOCs combined in the sun	VOCs and NO _x	Aesthetics, plants and human health	Local and regional
Road dust	Particles of dust generated by vehicle movement	Vehicle operation	Aesthetics and human health	Regional
Sulfur Oxide (SO _x)	Irritating to the lung and causing acid rain	Diesel engines	Acid rain and human health risks	Local
Volatile organic hydrocarbons (VOCs)	Various organic compounds which form aerosols	Fuel production and engines	Ozone precursor and human health	Local and regional
Toxics (e.g. benzene)	Harmful and carcinogenic VOCs *	Fuel production and engines	Risks related to human health	Very local

* South Coast Air Quality Management District (SCAQMD) (2002) US EPA (1999a) and Oak Ridge National Laboratory (ORNL) (2000)

With the increasing traffic volume and vehicle passenger ratio in the 1990s, transportation emissions have raised in both developed and developing countries. Environmental effects including air, water and land pollution, energy effects, accessibility, economic improvement, transportation costs, and safety are some of the transport externalities. However, the most significant externality is the health impacts of transport-related air pollution (Sirikijpanichkul et al., 2006). The risk of severe health problems including cardiovascular and respiratory illnesses, cancer, higher rates of death have increased based on the higher air pollution density in urban areas (Sirikijpanichkul et al., 2006). Particulate matter (PM_{2.5} and PM₁₀), Nitrogen Oxides (NO_x), ground-level of Ozone (O₃), and Carbon Monoxide (CO) are transport-related air pollutants causing air pollution-related diseases, deaths (WHO, n.d.). The impacts of these pollutants and other exhaust emissions, and elements that result from road transport have been the subject of studies conducted by various researchers, institutes, organizations for years. Based on the literature review, the transport sector-related pollutants and their health impacts are given in Table 2.3.

Table 2.3 : Health impacts of air pollutants and population risk (Sirikijpanichkul et al., 2006; Nowak et al., 2014; Ghorani-Azam et al., 2016; EEA, 2016).

Pollutant	Quantified Health Effects	Unquantified Health Effects	Other Possible Effects	Population at Risk
Sulfur Dioxide (SO ₂)	Pulmonary function changes and respiratory problems		Respiratory indications in non-asthmatics and hospital admissions	Older people and people with respiratory problems
Nitrogen Oxides (NO _x)	Respiratory diseases	Increase in airway responsiveness	The decrease in pulmonary function, lung inflammation, and immunological changes	People with respiratory problems (i.e children with asthma)
Particulate Matter (PM) / Total Suspended Particles (TSP) / Sulfates	Chronic and acute bronchitis, lower and upper respiratory diseases, chest problems, hospital admissions, and breathing symptoms	Pulmonary function changes	Chronic respiratory problems, except for chronic bronchitis, and lung inflammation	People with respiratory and cardiovascular problems
Lead	Hypertension, non-fatal strokes, non-fatal coronary heart disease, loss of intelligence quotient (IQ) in lifetime earnings	Delinquent and antisocial behavior in children, neurobehavioral function, other cardiovascular illnesses, reproductive impacts, fetal effects due to maternal exposure		
Ozone (O ₃)	Respiratory symptoms, asthma attacks, pulmonary function changes, hay fever, and chronic sinusitis	Lung inflammation, increased airway responsiveness to stimuli, and centroacinar fibrosis	Chronic respiratory illnesses, immunologic changes, and extrapulmonary impacts (structural or functional changes of the organs)	Older people and people with respiratory illnesses
Carbon Monoxide (CO)	Congestive cardiac failure, shortened angina startup period	Behavioral impacts and other hospital admissions	Other cardiovascular and developmental effects	People with ischemic heart conditions

There exist studies that give quantitative information about both the short-term and long-term effects of O₃ and PM emissions on human health. Bell et al. (2004) and

Jerrett et al. (2009) studied the effects of ozone (O_3) in the case of short-term and long-term exposure conditions. They concluded that while O_3 is giving rise to respiratory morbidity and mortality in the short-term, it leads to premature respiratory mortality in the long-term. Pope and Dockery (2006) and Burnett et al. (2014) analyzed the influences of Particulate Matter ($PM_{2.5}$) in the case of short-term and long-term exposure conditions. They figured out that while $PM_{2.5}$ is causing increased respiratory and cardiovascular-related daily mortality rates in the short-term, it gives rise to detrimental chronic health problems such as cardiopulmonary illnesses and lung cancer in the long-term. In the study conducted by Cohen et al. (2017), it is stated that O_3 causes 254,000, and anthropogenic $PM_{2.5}$ causes 4.2 million premature deaths per year according to the estimates in The Global Burden of Disease Study carried out in 2015. In another study carried out by Silva et al. (2013), it is concluded that anthropogenic $PM_{2.5}$ caused 2.1 million deaths due to lung cancer (7%) and cardiopulmonary diseases (93%), and anthropogenic ozone leads to 470,000 premature respiratory deaths in 2000. Brandt et al. (2013) analyzed the effects of air pollution caused by O_3 , SO_2 , CO , and $PM_{2.5}$ in Europe and it is figured out that 570,000 premature deaths were seen in 2011 due to emission-based air pollution.

In the literature, studies, which compare the GHG emissions in terms of their effectiveness, exist as well. In a study conducted by Rhode (1988), it is concluded that besides CO_2 , there are also other ingredients causing GHG emissions. The GHG emissions and their global warming potentials are given in Table 2.4.

Table 2.4 : Greenhouse gases and their global warming potentials (Rodhe, 1990).

Greenhouse gas	Relative effectiveness	Decay time (years)	Relative effectiveness in 100 years
CO_2	1	120-500	1
CH_4	70	7-14.5	15-30
N_2O	210	120	320
O_3	1800	0.01	3
CFCs	4000	50	4000

Various researches analyze the consequences of emission of harmful gases. According to the European Commission (2005), current concentrations of air pollutions have led to serious health problems in the European Union: 370,000 people died prematurely, hospital admissions and medication need increasing, and

millions of working days are lost. Moreover, World Health Organization (WHO, 2014) emphasized that the largest environmental health danger in the world is the air pollution, and in 2012, outdoor and indoor emissions based air pollution exposure caused the death of around 7 million people prematurely.

The air pollution can be seen in different forms: Levinson et al (1998) carried out a study about air pollution and concluded that air pollution types are divided into four, as their causes and effects are given in Table 2.5.

Table 2.5 : Characteristics, causes, and impacts of air pollutants (Levinson, 1998).

Air pollution	Characteristics	Causes	Effects
Photochemical Smog	It occurs at low levels in the atmosphere and at ground level, and at peak levels in the summertime	Tailpipe emissions by automobiles, O ₃ by the reaction of VOCs, NO _x , and water in the presence of sunlight	Damages on health, material, and vegetation
Acidic Deposition (Acid Rain)	It occurs most prevalently in Eastern North America and Europe in the troposphere layer	Sulfuric and Nitric Acid are formed due to reaction of SO ₂ , and NO ₂ with H ₂ O	Damages on health, material, and vegetation
Stratospheric Ozone Depletion	The ozone layer becomes thinner by CFCs	CFCs	More intense ultraviolet radiation to the earth
Global Warming (Greenhouse Effect)	warming the global atmosphere occurs as a result of the back reflection of the gases that absorb the heat emitted by the world in the troposphere layer	Man-made contaminants including CO ₂ , CH ₄ , O ₃ , N ₂ O, and CFCs	Melting of polar ice-caps and a consequent rise in the sea level based on the increase in the average planetary temperature

There are also other studies that analyze the effects of GHG emissions on economies of countries and, give statistical information. According to Organization for Economic Cooperation and Development (OECD) estimates, the cost of outdoor pollution was USD 1.57 trillion in 2010 in member countries, where the US had a share of USD 500 billion, and Europe had a share of USD 660 billion (OECD, 2014).

In the directives (EPA, 2019) on air quality prepared by the European Commission (2008/50/EC Directive on Ambient Air Quality and Cleaner Air for Europe and 2004/107/EC Directive on heavy metals and polycyclic aromatic hydrocarbons in

ambient air), the thresholds that should not be exceeded within a certain period of time are determined. If these thresholds are exceeded, the need to develop and implement air quality management plans is emphasized by the authorities. With these plans, it is desired to reduce the density of air pollutants below the limits. WHO guidelines and EU standards are given in Table 2.6.

Table 2.6 : Threshold values determined by European Union standards and World Health Organization guidelines for air pollutant concentrations (EPA, 2019).

European Union Air Quality Directive				World Health Organization	
Pollutant name	Average time	Target and legal concentrations	Comment	Concentrations	Comment
PM _{2.5}	Hourly			25 µg/m ³	99th percentile (3days/year)
PM _{2.5}	Annual	Limit value, 25 µg/m ³		10 µg/m ³	
PM ₁₀	Hourly	Limit value, 50 µg/m ³	Not to be exceeded on more than 35 days per year	50 µg/m ³	99th percentile (3days/year)
PM ₁₀	Annual	Limit value, 40 µg/m ³		20 µg/m ³	
O ₃ µg/m ³	Maximum daily 8-hour mean	Target value, 120 µg/m ³	Not to be exceeded on more than 25 days per year	100 µg/m ³	
NO ₂ µg/m ³	Hourly	Limit value, 200 µg/m ³	Not to be exceeded on more than 18 times a calendar year	200 µg/m ³	
NO ₂ µg/m ³	Annual	Limit value, 40 µg/m ³		40 µg/m ³	

Except climate change and air pollution, the transportation sector has also many negative impacts on other environmental areas such as land, water, waster, etc. The release of toxic chemicals, e.g. gasoline or oil from road vehicles, can also contribute to soil and water degradation, in addition to the greenhouse effect caused by harmful gases. In the study conducted by OECD (2014), impacts of road transportation are given for different areas as follows:

Lands: construction of facilities such as roads, terrain modification caused by construction of roads, and material procurement for road construction,

Water: underground water veins' division by tunnels, waters regions' development and water system changes resulted from road construction, contamination of both surface and groundwater,

Waste: disposal of facilities and vehicles, disposal batteries, particularly for hybrid and electric vehicles,

Noise, vibration: noise and vibration caused by automobiles in cities and along significant routes,

Ecological effects: fragmentation of habitats, accidents, disruption resulted from pollutants, contamination due to anti-freeze agents, light pollution caused by streetlights, and

Landscape: natural and traditional landscape disruption, new landscape resources creation such as bridges.

2.2 Frameworks/Tools to Integrate Environmental Issues into Transport Related Decision Making

In this section, the frameworks used to evaluate the decision-making process in the transportation sector, and the ways to integrate environmental concerns into these processes are analyzed. All the frameworks, which are given in detail in the following, generally include some common processing steps. In the solution of transport-related decision-making problems considering environmental aspects, the definition of the problem and the determination of evaluation criteria constitutes one of the initial and the most important steps. A significant difference between such tools is that while most of them are not able to consider qualitative criteria in the solution process, Multi-Criteria Decision Making methods are capable of considering not only quantitative but also qualitative criteria in the solution step, which makes them one of the most preferred methods in decision-making processes of projects, such as transportation projects. The selection of alternatives to be compared and comparison of these alternatives according to the selected criteria constitutes another common feature of these tools.

2.2.1 Strategic environmental assessment

Strategic Environmental Assessment (SEA) can be seen as a new tool for integrating environmental concerns into the decision-making process. Fischer (2003) defined the SEA as a decision-making tool to be used both for the generation of suitable environmental considerations and for the explanation of industrial policies and sustainable spatial. Through it evaluates the effects at an early stage in the decision-making process, SEA can be effective in making choices required in the conventional and project-related Environmental Impact Assessment (EIA). The other benefits of SEA can be listed as follows (Hilden et al., 2004; Dalal-Clayton and Sadler, 2004): i) SEA enables to evaluate the aggregate effects of projects; ii) SEA improves the effectiveness of environmental evaluation; and, iii) SEA decreases both the number and complexity of environmental impact assessment of projects.

Therivel (2010) gives the definition of SEA as a systematic, formalized, and comprehensive approach with the purpose of assessing the environmental effects of Policies, Plans, and Programs (PPP) and their alternatives. According to OECD (2006), SEA is “a collection of theoretical and participatory methods” to incorporate environmental factors into PPPs and to determine their potential relations to economic and social considerations.

In the study conducted by Josimovic et al. (2016), SEA is used in the evaluation of noise pollution as a result of the expansion works of Tivat Airport. By integrating goals, measures, and criteria in the evaluation of airport noise effects on the population, SEA is considered as a multi-criteria assessment in Josimovic et al. (2016). Fischer (2006) introduced a generic SEA approach to evaluate transport planning components including policies, network and corridor plans, and programmes. Fischer (2006) also aimed to prepare a basis to develop specific guidance for transport planning using SEA.

An illustration of the main potential contributions to a sample SEA approach is given in Figure 2.2 (Siqueira-Gay and Sanchez, 2019).

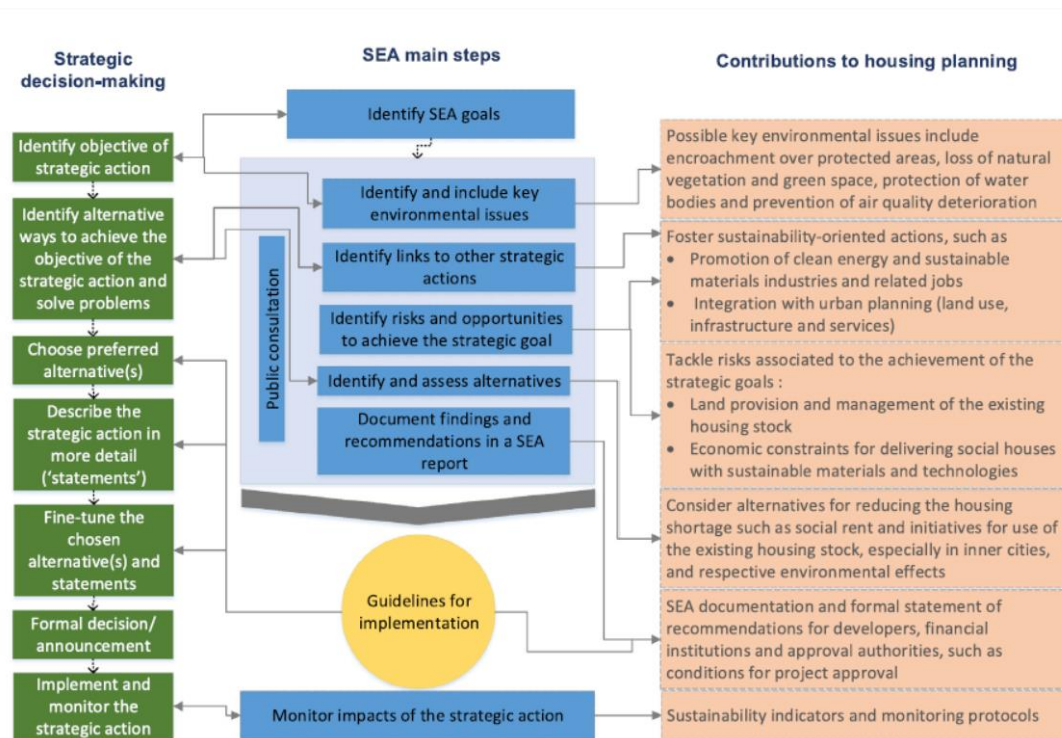


Figure 2.2 : An example of employing SEA approach to housing plans involving environmental and social issues (Siqueira-Gay and Sanchez, 2019).

2.2.2 Environmental impact assessment

Environmental Impact Assessment (EIA) can be defined as a regional and point-source based assessment of environmental impacts considering the time-related factors, the particular regional geographic situation, and the current contextual stress on the environment.

In order to address the drawback of conventional cost-benefit analysis, in which the maximum total net benefit is used as the criterion to determine the best solution, the EIA approach was developed, and, EIA will promote policy decisions on transport infrastructures having a significant effect on the environment, culture, and territories (Colorni et al., 1999).

The purpose of EIA is to provide a decision-making process, which takes actions with a significant effect on the environment into accounts, considering the environmental parts of the decision. It is concluded from (EU, 1997) that EU Directive 85/337, which is updated as Directive 97/11, provides legal support for EIA. In (EU, 1997), required information, which should be included by an EIA is given as in the following: i) project description, which includes information about project site, design, and size; ii) precautions to prevent, decrease, and enhance the

crucial negative effects; iii) data needed for the measurement and evaluation of the major potential environmental influences of the project; and, iv) summary of the developers' key alternatives and explanation of their final decisions considering the environmental impacts.

An illustration of a classic EIA approach adopted from (Tukker, 2000) is given in Figure 2.3.

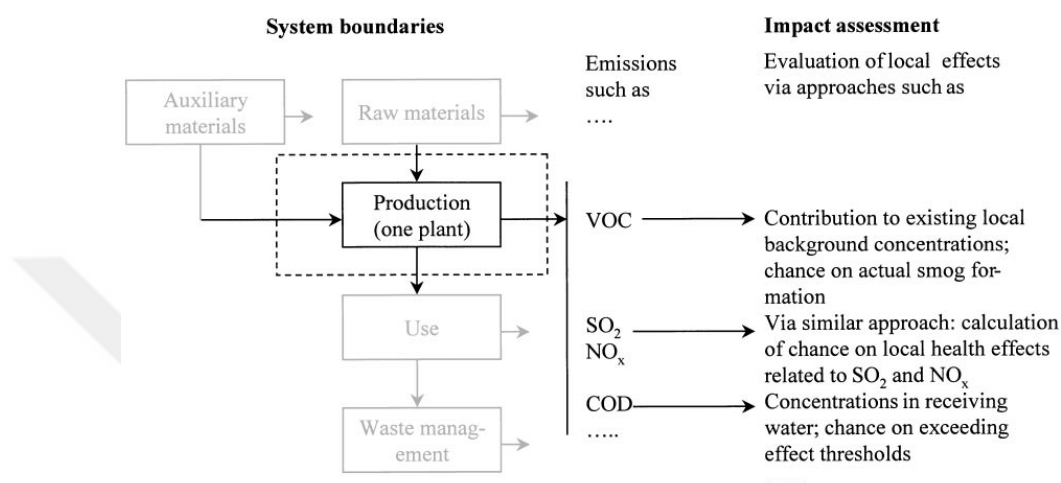


Figure 2.3 : A classic environmental assessment in EIA approach (Tukker, 2000).

2.2.3 Health impact assessment

According to WHO (n.d.), Health Impact Assessment (HIA) combining processes, techniques, and resources together and utilizing both qualitative and quantitative models, analyze the likely impacts of a strategy, project, or programme.

HIA, which considers health impacts on people, has been evolved in a different way from other impact assessment techniques such as EIA and SEA (Harris-Roxas, et al., 2012). Three separate but connected fields of public health activities including wider determining factors of health and equality in health, and environmental health constitute the origin of HIA (Harris-Roxas and Harris, 2011). In the study carried out by Likhvar et al. (2015), a framework of climate-air quality-health modeling for the assessment of impacts of Ozone and PM_{2.5} on health is utilized. Geographical scales including Ile-de-France, Europe, and World, and two different emission scenarios consisting of maximum feasible reductions (MFR) and current legislation emissions (CLE) are considered in (Likhvar et al., 2015). In the proposed HIA modeling framework given in Figure 2.4 (Likhvar et al., 2015), a concentration-response

function is utilized to compute the changes occurring in health outcomes based on the variation of air pollutant concentrations.

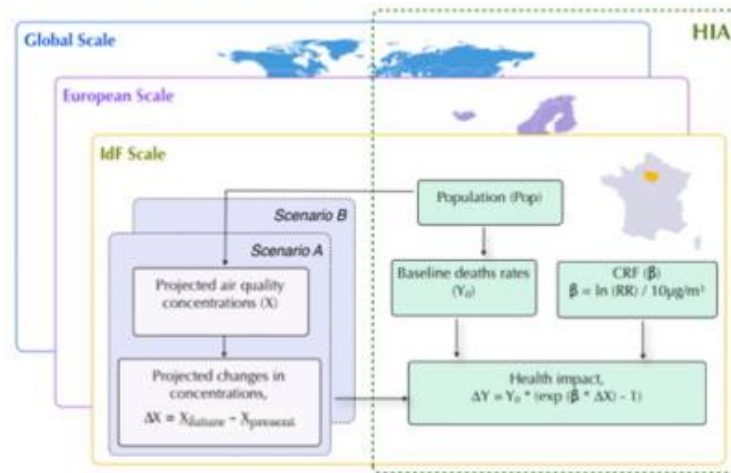


Figure 2.4 : A framework for climate-air quality-health modeling (Likhvar et al., 2015).

2.2.4 Cost-benefit analysis

Cost-Benefit Analysis (CBA), which is often employed in public decision-making, such as about infrastructure investments, provides the comparison of costs and benefits of a number of projects based on projections of possible future scenarios (Asplund and Eliasson, 2016). In (Sjöstrand et al., 2018), the definition of CBA is given as the systematic technique that predicts and compares both positive and negative influences of intervention options and policies according to a reference option. In the study conducted by Sælensminde (2004), the cost-benefit analysis of cycling and walking networks for three different cities in Norway is introduced. The health benefits resulting from increased mobility due to the use of non-motor vehicles and the benefits obtained by reducing the insecurity are considered in the cost-benefit analysis. Besides health benefits, external costs, e.g. noise and air pollution, are considered. In (Eliasson, 2008), CBA is utilized for the evaluation of the congestion charging system in Stockholm using the significant data sources including travel time and measurements of traffic flow, Eliasson (2008) calculated the effects on both traffic safety and emissions.

2.2.5 Multi-criteria decision making

The evaluation of possible alternatives and strategies has become more complicated over the past several decades (Ciegis et al., 2009). In the evaluation of the complex problems, Multi-Criteria Decision Making (MCDM), which is a sub-area of operations research, has two significant characteristics: i) it takes criteria weights into consideration; and, ii) it allows stakeholders' judgments to be incorporated into the ranking phase (Doukas and Nikas, 2019). MCDM evaluates the decision alternatives based on a multiple criteria set (Ishizaka and Siraj, 2017). Giving an opportunity of considering qualitative terms beside quantitative terms, MCDM methods are used commonly. According to Chatterje et al. (2009), MCDM can be split into five parts: i) to generate alternatives; ii) to build criteria; iii) to determine weights/priorities of criteria; iv) to evaluate alternatives; and, v) to rank alternatives. Each of the selected criteria represents the objective of a particular decision framework and, the application of the normalization of evaluation criteria is required for a suitable measurement (Jahan et al., 2011).

Nowadays, MCDM methods are becoming increasingly popular. The widening spectrum of multi-criteria problems includes school ranking, business decision-making, and public procurement. These MCDM methods are also employed to solve transportation engineering-related problems, as the related literature shows.

In (Vreeker et al., 2002), three different methods, i.e., Regime Analysis, the Saaty's Analytic Hierarchical Process (AHP) Model and the Flag Model, all of which are multi-criteria analysis methods, were jointly utilized to solve the problem of analyzing the alternative plans of airport expansion work in the Netherlands. Using the AHP method, the structure of the decision problem including objective, main-criteria, sub-criteria, and alternatives, respectively, was constructed. The impact matrix consisting of weights and mixed data, which enable to rank the alternatives, was evaluated with Regime Analysis. Finally, with the Flag, determined alternatives are controlled in terms of their acceptability considering sustainability concepts. Due to some challenges such as the collection of data from field and conflicts between various criteria, Chen et al. (2014) aimed to utilize an integrated MCDM framework, involving a Multilevel Grey Evaluation (MGE) method and a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method, to analyze the performance of passenger transportation. Firstly, the weights of the evaluation

criteria were calculated by the entropy method. Evaluation of complex systems including several quantitative indicators was performed with the MGE method, and selected alternatives for the decision-making problems are ranked according to the TOPSIS method. In (Liu et al., 2017), with the purpose to analyze the elements influencing the diffusion of electric vehicles in China, a framework based on three phases was introduced. The solution to the problem was performed in three steps. In the first step, a literature review was conducted to determine the influencing factors in addition to expert opinions. In the second step, direct relations of the selected criteria were analyzed with the 2-tuple linguistic method. To evaluate the influential criteria, pair-wise comparisons of criteria were performed by different stakeholders. The automotive manufacturers, government, and research institutions were selected as stakeholders to fill the matrices including the pair-wise comparison of criteria. In the last step, the Decision Making Trial and Evaluation Laboratory (DEMATEL) method was employed for the determination of the critical criteria among selected ones in the first step. The direct-influence diagram was drawn using this method, where the critical factors could be visualized on. With the goal of determining the best location for electric vehicle charging stations (EVCSs), two different MCDM methods were proposed by Liu et al. (2019). A grey DEMATEL and uncertain linguistic multi-objective optimization by ratio analysis plus full multiplicative form (UL-MULTIMOORA) methods were integrated for the solution of the decision-making problem (Liu et al., 2019). While the priorities of the criteria were determined with the grey DEMATEL method, evaluation, and selection of the alternative locations for charging stations were performed using the UL-MULTIMOORA method. Three main criteria including environment, economy, and society, and nine sub-criteria were selected. As alternatives, four different locations were determined. Although CBA is often the preferred method in the decision-making process for transportation projects, it is not suitable to take non-economic criteria including air pollution, noise, accidents into consideration in the evaluation (Tudela et al., 2006). MCDM has been developed as an alternative to address overcome this deficiency of CBA. In (Tudela et al., 2006), improvement in a part of the highway system in the Chiguayante district was evaluated using both the CBA and AHP methods with the purpose of comparing the results obtained from the CBA and AHP method. To improve the road section, two different alternatives; expanding the Manuel Rodriguez and O'Higgins streets (A1), and prolongation and expanding

the Manuel Rodriguez street (A2) were suggested. Two main criteria consisting of economic benefits-costs and environmental benefits-costs were considered in the solution. Moreover, eleven sub-criteria were determined in total. The results obtained from CBA and AHP, when only the economic criteria were considered, were found as the same. Moreover, if the non-economic criteria were included in the AHP method, the final ranking of the alternatives was found as different from each other. Feyzioglu et al. (2008) conducted a study to evaluate alternative bus systems considering their contributions in terms of sustainable urban transportation. To solve the decision-making problem, the Choquet integral method, one of the Multi-Attribute Decision-Making (MADM) methods, was used. Also, other MCDM methods were used and the results obtained from these methods were compared. Four main criteria were determined; technical issues, economic issues, environmental issues, and social issues. For the priority calculation, the Delphi study was utilized. As alternatives to be evaluated and ranked, four different groups of vehicles were determined; diesel engine, hybrid electrical, electric, and alternative fuel engine vehicles. Besides the Choquet method, the TOPSIS method was utilized for the assessment and ranking of the alternatives. In Meethom and Kengpol (2009), in order to help both logistic service provider and the small-medium enterprises (SMEs) in determining the route between the origin and the destination based on not only quantitative data such as budget and time but also qualitative data, three models including AHP, Multimodal Transport Cost-Model, and Zero-One Goal Programming models were utilized. The multimodal transport cost-model was used in the determination of time and cost of each selected route, AHP was used to calculate the weights of criteria, and Z0GP was used in the determination of the optimum value of transportation routing time, cost and other qualitative criteria. Gercek et al. (2004) analyzed a number of rail transit projects proposed for the Istanbul transportation system. Gercek et al. (2004) employed the AHP method as an MCDM support system to assess the project alternatives considering determined criteria that consist of substitutional, commercial, and social functions. Zografos et al. (1997) utilized the AHP method for the determination of the most preferred alternative for a major urban arterial street to be constructed in Miami, Florida. The study was carried out in two parts: evaluation of corridor alternatives for the street and selection of the best one were performed in the first part, and, secondly, assessment of the alternatives including sections/alignments and determination of the

most suitable alternative for the determined corridor in the first part. The problem of selecting the best location for a military airport was dealt with by Sennaroglu and Varlik Celebi (2018). Taking the different evaluation criteria including security, infrastructure, climate, transportation, social and environmental impacts into account, three MCDM methods, AHP, Vlekkriterijumsko KOmpromisno Rangiranje (VIKOR), and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) were utilized to solve the problem. The priorities of evaluation criteria were determined using the AHP method and ranking of alternatives was performed with the integration of VIKOR and PROMETHEE methods. Other MCDM methods, e.g. the Cooperation Platform for Research and Standards (COPRAS), MultiAtributive Ideal-Real Comparative Analysis (MAIRCA), and Multi-Attributive Border Approximation Area Comparison (MABAC), were also employed to control the results of the first three methods. The following problem of “what can be done both to develop the Bus Rapid Transit (BRT) performance and to increase the users’ satisfaction?” was addressed by Mavi et al. (2018). The authors considered four different options which consist of the increase of the speed of BRT buses, the addition of buses to the BRT line, the capacity increase of buses, and the reduction in delay time. In the solution of the decision-making problem, Grey Step-wise Weight Assessment Ratio Analysis (SWARA-G) method was used to calculate the criteria weights; and, Grey Complex Proportional Assessment of alternatives (COPRAS-G) method was used for the ranking of the alternatives (Mavi et al., 2018). In the study carried out by Fancello, Carta, and Fadda (2019), road intersections were evaluated considering road safety. Taking both the geometric criteria and traffic volume into account, the decision-making problem of determination of the most significant road section in urban networks were solved using TOPSIS, VIKOR, and Concordance Analysis methods. The study (Donais et al., 2019) was conducted with the aim of the introduction of an MCDA. Since sustainable transportation necessities, such as protection of the environment and health, were not included while planning transportation projects, a combination of the decision-making process with sustainability was purposed in (Donais et al., 2019). Evaluation and ranking of Quebec City’s street segments, having a possibility for becoming Complete Street, was performed by suggested MCDA approach, MACBET. Oztaysi et al. (2017) aimed to determine the most suitable alternative fuel technology type, among alternatives; biodiesel, compressed natural gas (CNG),

liquefied natural gas (LPG), ethanol, electric and hydrogen for a utility company in the USA. To solve the problem, interval-valued intuitionistic fuzzy (IVIF)-TOPSIS method and IVIF-preference relations (IVIFPRs), which are originated from MCDM, were proposed. In the solution, firstly hierarchy of the decision problem was formed. Then, using an IVIF-weighted averaging (IVIFWA) method was used to calculate the priorities of evaluation criteria, and finally, alternatives were ranked with IVIF-TOPSIS method based on calculated priorities. The study conducted by Castro-Nuno and Arevalo-Ouijada (2018) included the evaluation of urban road safety performance using the PROMETHEE method, which is known as one of the best proper MCDM methods for decision-making problems including evaluation and ranking of alternatives (Al-Shemmeri et al. (1997). Seven selection criteria, including road safety, economic conditions, tourism activity, demographic structure, healthcare system, sustainability and urban transport, and mobility and road network, were determined based on the literature review for ranking of determined alternatives in 50 Spanish provinces. Using the PROMETHEE Geometrical Analysis for Interactive Aid (GIAI) method, preferences of the evaluation criteria are calculated and the alternatives were ranked. In the solution to the problem, the software, Visual PROMETHEE Academic is utilized (Castro-Nuno and Arevalo-Ouijada, 2018).

2.2.6 Life cycle assessment

Life Cycle Assessment (LCA) gives weight to the evaluation of possible effects on a production system as a whole independently from time and location. It can be accepted as a tool developed for the evaluation of the effects of processes related to goods such as use, production, and waste management. The LCA is required in: i) decisions needed in the product and process development; ii) decisions in the purchasing process; iii) construction of any information; iv) eco-labeling; v) environmental product declarations; and, vi) decisions about adjustments (Consoli et al., 1993).

Three steps for the assessment framework in LCA can be listed as (Consoli et al., 1993; Udo de Haes, H.A., 1996):

Definition of the aim and scope: the goal of the study, its context, and the technique of quality standards for the results are specified in this process.

Inventory: a system comprising all applicable process chains for the use, production, and management of the product function is specified in this process.

Effect evaluation: classification, characterization, and valuation procedures are performed in this process.

A number of evaluation methods exist in LCA to demonstrate the environmental effects of product systems, products, or services throughout the life cycle. Firstly, the systematic determination of the material flows is performed in the phase of production, phase of use, and a product's end-of-life (Life Cycle Inventory (LCI)). Secondly, significant emissions, which are observed in various environmental compartments such as air, soil, and water are assigned to environmental effect groups (Life Cycle Impact Assessment (LCIA)) to help the prediction of the potential for cumulative environmental impact (May, 2018).

An illustration of a classic LCA approach is given in Figure 2.5 (Tukker, 2000).

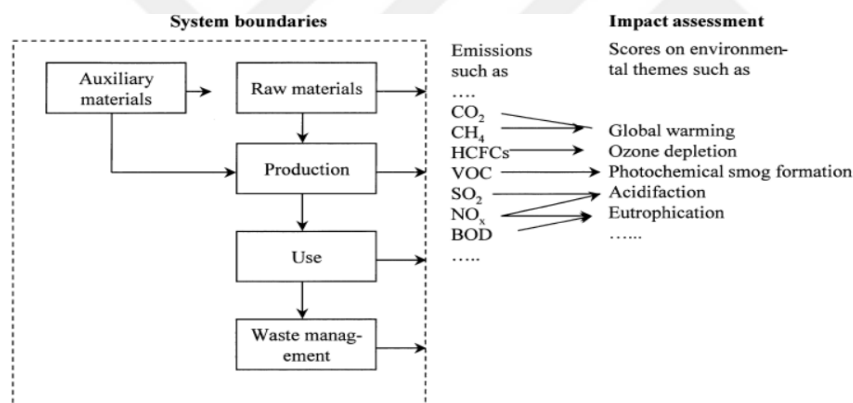


Figure 2.5 : A classic environmental assessment in LCA approach (Tukker, 2000).

2.3 Methods Employed

MCDM methods can be divided into three, i.e., deterministic methods, stochastic methods, and hybrid methods, all of which are summarized in the following subsections with their applications in different study areas.

2.3.1 Deterministic methods

In deterministic MCDM methods, weights showing the importance of the objectives are obtained with the questions asked to the experts and by using analytical methods. In deterministic MCDM methods, which enable determination of criteria,

explanation of alternatives performances based on criteria with exact values, and representation of relative importance of criteria with also exact numbers, there is no uncertainty (Kolios et al., 2016). With the deterministic MCDM techniques using numerical methods, decision-makers can make a selection between alternatives in an alternative set. The most widely known MCDM method including weighted sum methods such as the AHP and weighted product methods, e.g. TOPSIS and ELimination Et Choix Traduisant la REalité (ELECTRE), can be given as examples of deterministic MCDM methods (Triantaphyllou, 2000).

2.3.2 Stochastic methods

Stochastic Multicriteria Acceptability Analysis (SMAA) is an efficient decision support model that has been developed to be employed in the decision-making process where weights and criteria values are not available (Ternonen and Lahdelma, 2007). SMAA, which can be used for the main three problems of MCDM including selection, ranking, or sorting, is a family of recently developed methods for MCDM problems with incomplete or uncertain data (Ternonen and Figueira, 2008a). These methods determine the order of alternatives and the weight vector used in the ordering process by simulating uncertain decision values. These methods are successfully applied to problems with uncertain information as a multi-criteria decision support method (Lahdelma et al., 1998). In literature, there are many studies including SMAA methods used in conjunction with MCDM methods. Tervonen et al. (2008b) carried out a study on the planning of the elevator system, which is constructed in a 20-floor building. In the planning, different evaluation criteria including level of service, economy, and performance of the system, were considered. While these criteria were represented in different ways such as deterministic values, ranking information, and multivariate Gaussian distribution, alternative configurations determined for the elevator system were assessed using the SMAA technique. In another study conducted by Tervonen et al. (2009), the SMAA-TRI approach was proposed to allow ELECTRE TRI, which is successfully applied to real-world problems, to be used with uncertain criteria weights.

2.3.3 Artificial intelligence and heuristic methods

Heuristics methods enable users to obtain near-optimal solutions while solving difficult problems. These methods have a wide range of applications such as

simplification of selections, identifications of good initial solutions, and decomposition of problems into sub-problems (Dyer et al., 1992). There are many heuristic methods including Ant Colony Search Algorithm, Particle Swarm Optimization (PSO), Genetic Algorithm (GA), etc. employed to solve optimization-based engineering problems (El-Sharkawi and Lee, 2008). Today, as each factory has its own service parameters including costs of operation and production, production time, Chan et al. (2005) suggested a method incorporating the GA and AHP method for demand allocations of factories. The operating criteria were arranged using the AHP method while GA was used to assess the job assignment to appropriate production plants. In another study conducted by Qu and Chen (2008), an integrated MCDM framework including Artificial Neural Network (ANN) and Fuzzy AHP methods was proposed in order to determine the best route for multimodal transportation systems. After identification of six main-criteria and fifteen sub-criteria related to multimodal transportation systems, weights of these evaluation criteria, which are input-output nodes of the ANN method, were calculated with the fuzzy AHP method. Using the calculated criteria weights as input, the relationship among evaluation criteria and alternatives performance were studied applying the ANN method.

2.3.4 Hybrid methods

Hybrid methods referred in this study are the methods that enable decision-makers to use two different MCDM methods together for a problem of decision making to obtain more reliable and robust results. Deficiencies of MCDM methods in case they are used as a single method for a decision-making problem can be coped with the application of the integrated methods (Tian et al., 2018). Buyukozkan et al. (2018) proposed an integrated MCDM method to evaluate and determine the most suitable alternative for a sustainable urban transportation system. Group Decision Making (GDM) and Intuitionistic Fuzzy Choquet Integral (IFCI) techniques were aggregated in the (Buyukozkan et al., 2018) to obtain the evaluation criteria weights and to rank determined alternatives. In order to compare the results obtained from the proposed model and evaluate the performance of the model, alternatives were also ranked using another integrated approach including TOPSIS, one of the MCDM methods, and 2-additive Choquet integral. In the study carried out by Awasthi et al. (2018), to analyze the urban mobility projects considering sustainability evaluation, ideal

solution based MCDM methods consisting of fuzzy VIKOR, fuzzy TOPSIS, and fuzzy Grey Relational Analysis (GRA) were employed. Using these three methods, pre-defined alternatives were ranked. For the final decision, veto rule was utilized. Comparing ranking obtained from these three methods, the alternative or alternatives were chosen based on ranked highest by the majority of these models.





3. ANALYSIS FRAMEWORK

In this section, the decision-making problem handled in this study is described in detail firstly. Then, air pollutant emissions, which are selected as sub-criteria in the comparison of alternative vehicles, and air quality parameters, are defined. The MCDM methods selected, together with their mathematical explanations, are presented in the third subsection. Finally, the proposed hybrid MCDM framework employed for the solution of the problem is presented.

3.1 General Overview to Problem

The increase in vehicle usage for daily travel causes roads to become an important part of the transportation system. However, as a consequence of the growing road network, several detrimental effects including global warming, land transformation, energy consumption, and soil acidification, on the environment are encountered (Jiang and Wu, 2019). Furthermore, road networks cause major problems worldwide such as loss of biodiversity, increase human access to the current natural habitats, and habitat fragmentation (Alkemade et al., 2009). Vehicles affect millions of lives on a daily basis all around the world. Thus, the determination of the vehicle that best suits the needs is very significant in decision making. Purchasing a vehicle, which is based on users'/purchasers' preferences, can be accepted as a decision-making problem. In the determination of the most suitable vehicle, considerations can vary based on purchasers' demand. While some people prioritize safety, others may consider the economy including price, fuel consumption, etc. Vehicle manufacturers try both to produce vehicles in different specifications and to improve current designs based on changing user demands. As today, there are a number of brands that produce their own vehicles, all of which have various characteristics including size, performance, quality, and fuel type. Selecting the best vehicle for their intended use may be a challenging decision for purchasers with environmental concerns.

In the present thesis, with the ultimate incentive to assist the decision-making process of renewing the shuttle bus fleet, which serves a university campus and currently

consists of all internal combustion engine vehicles, the problem of choosing the most appropriate vehicle for the intended use is addressed providing the road network of a complex urban environment. Given the characteristics of shuttle operation, road geometry, and passenger flow in addition to the technical specifications of vehicles, the solution to the problem using different groups of hybrid MCDM methods is sought. In the first phase of the proposed hybrid MCDM framework, the AHP and the TOPSIS methods are employed for the solution of the problem. Both the TOPSIS and the AHP method allow making the best selection among alternatives. Utilizing the AHP method, the most appropriate alternative is decided considering the overall priorities of the alternatives. The main expectation in the TOPSIS method is that a selected alternative should be further away from the negative ideal solution and close to the positive ideal solution. In this thesis, the AHP method is employed for the determination of the weights of main and sub-criteria considering quantitative and qualitative data. Then, the TOPSIS method is utilized in an integrated manner for the alternatives' ranking from a total of twelve including the electric, hybrid, and internal combustion engine vehicles according to the criteria weights. In the second phase of the proposed framework, the DEMATEL and MULTIMOORA methods are combined to be used in conjunction. While the priorities of criteria are calculated employing the DEMATEL method, the MULTIMOORA method is used for the ranking of vehicle alternatives. At the final step of the proposed hybrid MCDM framework, the results obtained from two integrated approaches with two purposes: i) to achieve a robust and reliable solution for the decision-making problem; and, ii) to measure the performance of the proposed hybrid framework are compared.

The particulars of main vehicle types, i.e., electric, hybrid, and internal combustion engine, which are considered for the problem of vehicle selection in shuttle operations with specific reference to the case study conducted are summarized in the following.

Internal Combustion Engine Vehicles (ICEVs): The internal combustion engine is the mechanism in which the force caused by the fuel burning in a limited area -the combustion chamber- pushes the piston. In ICEVs, the unburned fuel entering the system is burned in the engine, and mechanical energy is produced by the resulting chemical energy. Finally, the waste is removed from the system. While on the one hand, ICEVs have some advantages for their users, including high-efficiency motor

power, lower purchase costs, and types of fuel commonly available. On the other hand, since they release harmful exhaust gases, ICEVs have negative effects on the environment including pollution, mainly the air, and global warming.

Hybrid Electric Vehicles (HEVs): HEVs, which have two different power suppliers, i.e. the electric motor and the internal combustion engine, can be regarded as transitional vehicles from conventional vehicles to electric vehicles. Driving at higher speeds is possible with the internal combustion engine and the electric motor provides torque. The energy required by the electric motor is stored in HEV batteries, and the batteries are charged by the electric motor. HEVs are less fossil-fuel-dependent, eco-friendly, and have a regenerative braking system. This braking system helps the vehicle to recover some portion of the energy which is consumed in driving. However, as fossil fuels and electric energy are used by HEVs, they also have negative environmental impacts similar to the ICEVs.

Electric Vehicles (EVs): EVs which use an electric motor to generate the required energy can be divided into two: plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). In BEVs, the energy is supplied by on-board batteries. These batteries are charged at a charging station or by being plugged in. In P-HEVs, rechargeable batteries are utilized similar to the HEVs. Although EVs are accepted as emission-free, pollutants are released in their manufacturing phase. In addition to their market prices, the technical specifications of EVs, mainly the driving ranges and charging times, have become crucial to the consumer preferences of users.

3.2 Definitions of Air Quality Parameters and Evaluation Criteria

In the following, air quality parameters and evaluation criteria to be used in the comparison of vehicle alternatives are defined.

3.2.1 Definitions of air quality parameters and air pollutant emissions

In this sub-section, definitions of both emissions causing air pollution, and the air quality parameters are provided. All the definitions related to air pollutant emissions and air quality parameters are given as the World Health Organization proposes (WHO, 1980).

Greenhouse gas effect: The greenhouse gas effect is the increase in temperature of atmospheric layers in the lower parts because of the solar radiation in both short wavelength and large wavelength.

Ground-level concentration: The ground level concentration is the pollutant density in the air, in which people are in contact (the distance between the ground and 2 m from the ground).

Ozone layer: The ozone layer is the layer in the atmosphere, which is located 10 and 50 km above the earth's surface.

Pollutant: The pollutant is the unwanted materials in solid, liquid, or gas forms. There are two types of pollutants namely the primary pollutant, which is a contaminant/pollutant released from a detectable source into the atmosphere, and secondary pollutants, which is a contaminant/pollutant produced in the atmosphere by chemical reaction.

Pollution: The pollution is the existence of contaminants in a liquid or gaseous environment or unwanted alteration of liquid or gaseous environment composition.

Carbon dioxide (CO₂): CO₂ is a gas without color and odor, which has a formula CO₂. Being a normal component of air and heavier than air with a rate of 50%, CO₂ has several negative influences on human health, buildings, and corrosion at high concentrations.

Carbon monoxide (CO): CO is a gas without color, with an ambiguous odor and high flammability, which has a formula CO. Being very poisonous at concentrations exceeding 100 cm³ /m³, CO has many negative effects on human health.

Hydrocarbon (HC): HC is an organic compound that consists of carbon and hydrogen elements only. While open-chain types of hydrocarbons are not dangerous for human health, closed rings hydrocarbons such as aromatics are very poisonous.

Methane (CH₄): CH₄ is a gas without color and odor, which has a formula CH₄. Being a flammable gas, CH₄ creates an explosive mixture with air.

Nitrogen oxide (NO_x): NO_x represents the mixture of NO and NO₂. The types of NO_x having significant effects in the atmosphere are Nitrous oxide (N₂O), which is a gas without color and takes an important part in the nitrogen cycle, Nitric oxide (NO), which is a toxic gas without color, and Nitrogen dioxide (NO₂), which is also a poisonous gas.

Ozone (O₃): O₃ is a pale blue gas having a characteristic odor, which has a formula O₃. Being a very toxic, highly reactive, and oxidizing agent, ozone is accepted as a very severe pollutant at concentrations exceeding 125 µg/m³.

Particulate Matter (PM): PM is the particles in solid and liquid forms, which are not settled on the surface of the earth under the gravity effect due to their sizes.

Particulate Matter (PM_{2.5}): PM_{2.5} is the particulate matter with a diameter of less than 2.5 micrometers.

Particulate Matter (PM₁₀): PM₁₀ is the particulate matter with a diameter of less than 10 micrometers.

3.2.2 Definitions of evaluation criteria

Purchasing cost: Purchasing cost represents the amount of money that is paid for something, in this thesis it represents the amount of money paid for buses.

Taxing: The taxing is the percentage of money that will be paid to the government after purchasing a product or service.

Maintenance cost: The cost of maintenance is the cost of maintaining a road, structure, vehicle, or machine in good condition by inspecting it regularly and fixing it when necessary.

Fuel cost: The fuel cost means all costs associated with fuel products, including imbalance charges and applicable taxes. In the thesis, fuel cost is considered as the amount of money paid for fuel or electricity required to fill the vehicle's fuel tank or battery.

Secondary market price: The secondary market price represents the price of vehicles previously purchased by someone else and sold.

Vehicle life: Vehicle life refers to the amount of time a vehicle is expected to be functional and fit-for-purpose.

Motor power: The motor or engine power is the maximum power that an engine can put out.

Range: The range refers to the distance that a vehicle can travel with a fuel tank or full battery.

Climbing ability: The climbing ability is a measure of maximum allowable grade a vehicle can climb without losing power or maximum allowable gradient the vehicle can climb.

Torque: The torque is a rotating force produced by an engine's crankshaft.

Energy efficiency: Energy efficiency represents the ratio of the distance traveled by a vehicle and the amount of fuel or energy consumed.

Capacity: The capacity refers to the number of seats and authorized standing places available in a vehicle.

Vehicle weight: The vehicle weight is the maximum allowable operating weight of a vehicle as defined by the producer, consisting of body, chassis, engine fluids, engine, driver, fuel, passengers, cargo, and accessories of the vehicle.

Turning radius: The turning radius is the radius of the smallest circular turn that can be performed by a vehicle.

Antilock brake system (ABS): ABS is the braking system that provides full control of the steering wheel by preventing the wheels from locking in sudden braking in all kinds of loads and road conditions and compulsory conditions at various speeds.

Automatic emergency brake system (AEBS): EBS is a braking system that provides functions such as adjusting the braking force in situations such as wear adjustment, and provides instant brake responses such as applying and releasing the pedal pressure.

Forward collision warning system (FCWS): FCWS is an innovative safety technology that measures the velocity of a vehicle, the velocity of the vehicle ahead, and the distance between the vehicles and warns drivers in the event of an imminent frontal collision.

Lane departure warning system (LDWS): LDWS is an innovative safety technology that warns drivers when they move out of their lanes unintentionally without a turn signal.

Speed monitoring and warning system (SMAWS): SMAWS is a safety system that supplies a safe output signal in order to indicate whether the motor speed is below the defined limit value.

3.3 Methodology

In the following, the methodological backgrounds of the MCDM methods used in the proposed hybrid framework are explained.

3.3.1 Analytic hierarchy process (AHP)

In the following, the fundamentals of the AHP method and the way to calculate the weights of the criteria using the AHP method are presented.

3.3.1.1 Fundamentals of AHP method

The AHP method, which allows management of the multi-criteria elements in both qualitative and quantitative manner, is developed by Saaty in the 1970s (Fathoni et al., 2017). A hierarchical structure that consists of the goal, main criteria, sub-criteria, and alternatives, is constructed in the decision-making process to solve the complex problem of decision (Zak and Kruszyński, 2015). Having two characteristics such that allowing decision-makers to cope with not only quantitative but also qualitative attributes, and allowing decision-makers to observe their decisions through the consistency check, the AHP approach differs from other methods (Roper-Lowe and Sharp, 1990). In Table 3.1, the calculation steps of the AHP method are shown.

Table 3.1 : Calculation steps of AHP method (Saaty, 1990).

Steps		Definition
1	Determine the decision-making problem	Description of the problem and establishment of the purpose
2	Construct the hierarchical structure of the problem	Determination of evaluation criteria and alternatives based on the aim
3	Construct the pair-wise comparison matrix	Comparison of the main and sub-criteria reciprocally according to the goal
4	Calculate the normalization matrix	Calculation of normalization matrix in order to enable direct comparison of a number of diverse criteria in the comparison matrix with each other
5	Calculate the criteria weights	Determination of the criteria priorities showing the importance of one criterion compared to another
6	Calculate the consistency ratio	Performing the consistency check since decision-makers' subjective preferences are used in the filling of the comparison matrices

A hierarchical structure example including a three-level structure is given in Figure 3.1. An additional level, i.e the level of sub-criteria, may exist between the main criteria and alternatives in some circumstances. The benefits of the hierarchy are that it helps to understand: the decision to be made; the criteria to be evaluated; and, the alternatives to be ranked (Mu and Pereyra-Rojas, 2017).

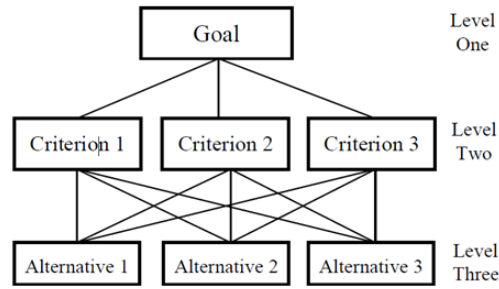


Figure 3.1 : Hierarchical structure for a decision-making problem (Lai et al., 2015).

In the AHP method, both the comparison of the criteria pair-wise with respect to the goal and the comparison of the alternatives pair-wise with respect to the main or sub-criteria are performed (Zak and Kruszyński, 2015). In case that there exists a main criterion with sub-criteria, the comparison of alternatives with respect to the considered main criterion is not required, only the comparison of alternatives with respect to the sub-criteria is performed. Figure 3.2 shows the pair-wise comparison scale proposed by Saaty (1994), which is used in the construction of the comparison matrices. As the decision-makers' subjective preferences are used to construct the comparison matrices, consistency of judgments should be checked in order to eliminate any inconsistency in the decision-making process. Saaty (1994) developed Random Consistency Index values (Figure 3.3) to be used in the calculation of the consistency.

Verbal judgment	Numeric value
Extremely important	9
	8
Very Strongly more important	7
	6
Strongly more important	5
	4
Moderately more important	3
	2
Equally important	1

Figure 3.2 : Pair-wise comparison scale proposed by Saaty (Saaty, 1994).

<i>Dimension</i>	<i>RI</i>
1	0
2	0
3	0.5799
4	0.8921
5	1.1159
6	1.2358
7	1.3322
8	1.3952
9	1.4537
10	1.4882

Figure 3.3 : Random consistency index proposed by Saaty (Saaty, 1994).

3.3.1.2 Calculation of criteria weights with AHP method

In the following, the six steps considered in order to calculate the criteria weights by the AHP method are provided.

Determination of the decision-making problem: The purpose is to determine the most suitable vehicle in the process of renewing the fleet of shuttle bus services operated through a complex urban area.

Construction of the hierarchical structure of the problem: Figure 3.4 shows the constructed hierarchical structure including four-level: the goal, main criteria, sub-criteria, and alternatives, respectively.

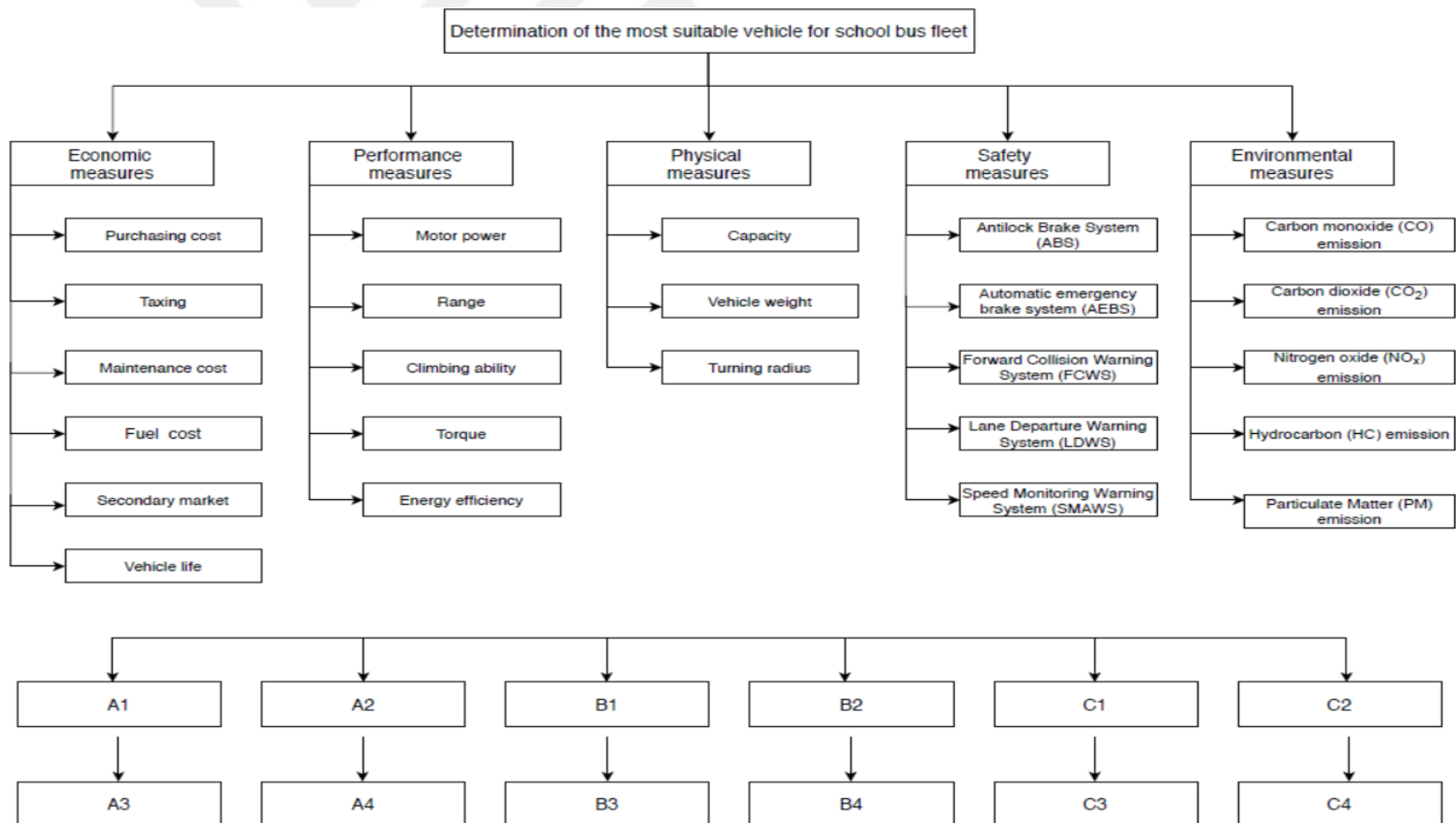


Figure 3.4 : Hierarchical structure of decision-making problem.

Construction of the pair-wise comparison matrices: The pair-wise comparison matrices are filled utilizing Saaty's 1-9 scale (Mu and Pereyra-Rojas, 2017). The matrices that consist of the comparison of main criteria according to the goal, and the sub-criteria according to the main criteria are given in Section 4. The comparison matrices are constructed by 25 experts in total including academic experts from the disciplines of Transportation Engineering, Environmental Engineering, Meteorological Engineering, Industrial and Management Engineering, Mechanical Engineering, Construction Management, and engineers and administrators working at the General Directorate of Highways, and Automotive Industry.

Calculation of the normalization matrix: Since many diverse criteria exist in the comparison matrices, a normalization process is required for the direct comparison of these criteria. In order to calculate the normalized values, each cell in the comparison matrix is divided by the total of the values in the column (Mu and Pereyra-Rojas, 2017):

$$n_{ij} = \frac{x_{ij}}{\sum_{i,j \in M} x_{ij}} , \quad i, j \in M \quad (3.1)$$

where, n_{ij} is the normalized value, x_{ij} represents the comparison of criterion i with respect to criterion j , $\sum_{i,j \in M} x_{ij}$ represents the column sum, and M is the criteria set.

Calculation of the criteria weights (priorities): In order to calculate the priorities of the criteria, the average of each row in the normalization matrix is taken (Mu and Pereyra-Rojas, 2017). The weights refer to the importance of each criterion with respect to another.

Calculation of consistency ratio: Since experts' subjective preferences are used to construct the comparison matrices, consistency of these matrices should be calculated to control the validity of the matrices (Temiz and Calis, 2017). In the first step, calculation of the Consistency Index (CI) is performed using Equation (3.2), secondly, calculation of the Consistency Ratio (CR) is performed based on the Random Index Matrix proposed by Saaty with Equation (3.3).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3.2)$$

where, λ_{max} is the maximum eigenvalue, and n represents the matrix size. The highest eigenvalue is chosen from the Eigen matrix. The highest eigenvalue is obtained by vectorial multiplication of the priority matrix with the original pair-wise comparison matrix.

$$CR = \frac{CI}{RI} \quad (3.3)$$

Finally, in case that the CR value is calculated less than 0.10, then judgments in the comparison matrices are deemed consistent and acceptable. In case that the CR value exceeds 0.10, preferences should be controlled (Mu and Pereyra-Rojas, 2017). The results obtained performing consistency check of the comparison matrices are presented in Section 4. In Figure 3.5, the flowchart of the AHP method is given.

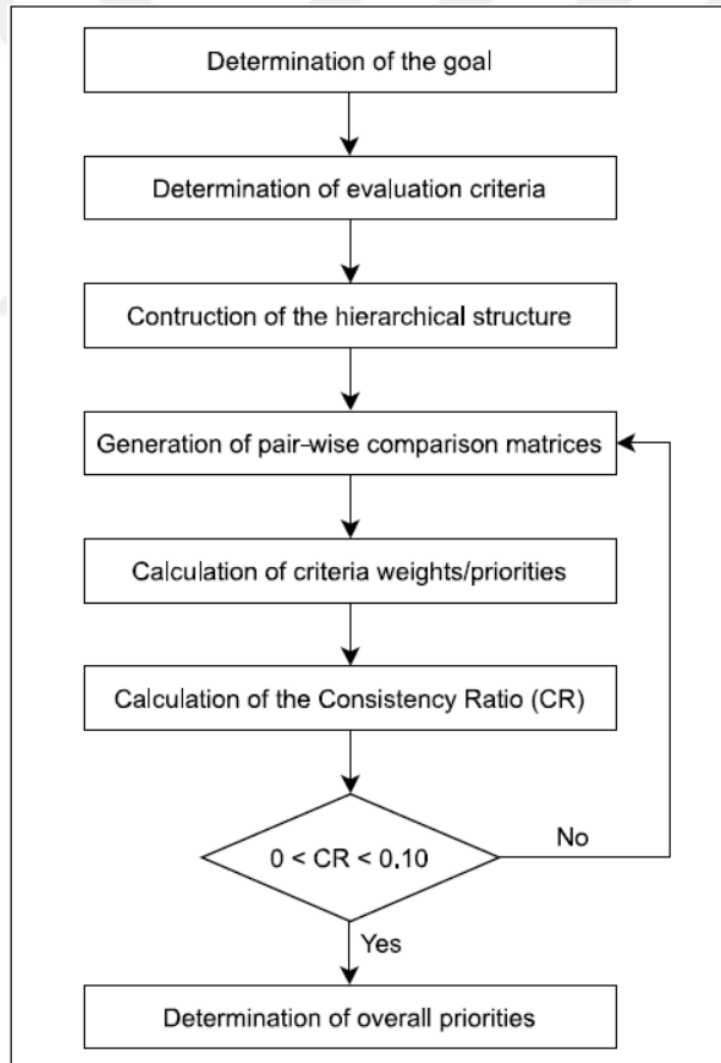


Figure 3.5 : AHP flowchart.

3.3.2 Technique for order preference by similarity to ideal solution (TOPSIS)

In the following the fundamentals of the TOPSIS method and the way to rank the alternatives using the TOPSIS method are presented.

3.3.2.1 Fundamentals of TOPSIS method

TOPSIS method, proposed by Hwang and Yoon in 1981, is utilized for the determination of the most suitable alternative having the furthest distance to a negative ideal solution and the shortest distance to a positive ideal solution, between several alternatives (Buyukozkan et al., 2018). Here, the aim of the positive ideal solution is the maximization of the beneficial criteria and minimization of the cost criteria and, while the purpose of the negative ideal solution is to minimize the beneficial criteria and to maximize the cost criteria (Yang et al., 2012).

The calculation steps considered in the TOPSIS method are explained in Table 3.2 (Chen et al., 2014).

Table 3.2 : Calculation steps of TOPSIS method (Hwang and Yoon, 1981).

Steps		Definition
1	Determine the decision-making problem	Description of the problem and establishment of the purpose
2	Construct the decision matrix	Construction of decision matrices with either the real values of the criteria or using a 1-3 scale
3	Calculate the normalization matrix	Calculation of normalization matrix in order to enable direct comparison of a number of diverse criteria in the comparison matrix with each other
4	Calculate the weighted normalization matrix	Involving of criteria weights calculated previously and calculation of weighted normalized values
5	Determine the positive and negative ideal solution	Calculation of the distance from the positive and negative ideal solutions
6	Calculate separation measures for alternatives and rank	Determination of the values utilized in the relative closeness to the ideal solution and ranking of the alternatives

3.3.2.2 Ranking of alternatives with TOPSIS method

In the following, the six steps utilized in the ranking of the alternatives in the TOPSIS method are explained.

Determination of the decision-making problem: The purpose to determine the best vehicle in the process of renewing the fleet of shuttle bus services operated through a complex urban area.

Construction of decision matrix: Either real values of evaluation criteria or a 1-3 scale are used in the construction of the decision matrices. In the 1-3 scale, the worst alternative is referred by 1, and the best alternative is referred by 3. Table 3.3 includes the decision matrix constructed for the considered problem.

Calculation of the normalization matrix: Since several diverse criteria exist in the comparison matrices, a normalization process is needed for the direct comparison of these criteria. In order to calculate the normalized values, each cell in the comparison matrix is divided by the square root of the squared sum of the values in each column (Gardziejczyk and Zabicki, 2014):

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i \in A} (x_{ij})^2}} , \quad i \in A , j \in M \quad (3.4)$$

where, n_{ij} is the normalized value, x_{ij} represents the outcome of alternative i according to criterion j , $\sqrt{\sum_{i \in A} (x_{ij})^2}$ is the square root of the squared sum of the values in each column, and A and M are the alternatives and criteria sets.

Calculation of the weighted normalization matrix: In order to rank the alternatives, the criteria weight values are included (Chen et al., 2014). Each cell in the normalized matrices is multiplied by the calculated weight of the considered criterion:

$$v_{ij} = w_{ij} * n_{ij} , \quad i \in A , j \in M \quad (3.5)$$

where, v_{ij} is the weighted normalization value, w_{ij} represents the weight of each criterion, n_{ij} is the normalized value, and A and M are the alternatives and criteria sets.

Table 3.3 : Decision matrix for decision-making problem constructed for TOPSIS method.

Alternatives	Vehicle type	ECONOMIC MEASURES						PERFORMANCE MEASURES						PHYSICAL MEASURES			ENVIRONMENTAL MEASURES						SAFETY MEASURES				
		Purchasing Price (TL)	Taxing	Maintenance cost (1-3)	Fuel cost (TL)	Secondary market (TL)	Vehicle life (1-3)	Motor power (kW)	Range (km)	Climbing ability (%)	Torque (Nm)	Energy efficiency (l/100 km or kWh/100km)	Capacity (passenger)	Vehicle weight (kg)	Turning radius (m)	CO emission (g/km)	CO2 emission (g/km)	NOx emission (g/km)	HC emission (g/km)	PM emission (g/km)	Anti-lock brake system (ABS)	Automatic emergency brake system (AEB)	Forward collision warning system (FCWS)	Lane departure warning system (LDWS)	Speed monitoring and warning system (SMAWS)		
Direction		min ↓	min ↓	min ↓	min ↓	max ↑	max ↑	max ↑	max ↑	max ↑	max ↑	min ↓	max ↑	min ↓	min ↓	min ↓	min ↓	min ↓	min ↓	min ↓	max ↑	max ↑	max ↑	max ↑	max ↑		
weights		0.029	0.041	0.029	0.028	0.038	0.033	0.037	0.043	0.045	0.043	0.036	0.062	0.085	0.073	0.037	0.040	0.036	0.039	0.037	0.033	0.033	0.036	0.042	0.048		
A1	ICE V	463,386.00	3,114.00	1	982.50	230,000.00	3	141.68	830.00	40.90	510.00	18.00	29	9,100.00	6.45	0.500	147.00	0.080	0.170	0.005	1	1	0	0	1		
A2	ICE V	524,701.00	3,114.00	1	655.00	285,000.00	3	112.00	555.00	42.00	493.00	18.00	27	8,500.00	5.80	0.500	147.00	0.080	0.170	0.005	1	1	0	1	0		
A3	ICE V	660,906.00	3,114.00	1	1,244.50	124,000.00	3	129.00	1055.00	35.00	682.00	18.00	31	8,800.00	6.60	0.500	147.00	0.080	0.170	0.005	1	1	0	1	0		
A4	ICE V	349,197.40	3,114.00	1	786.00	172,000.00	3	107.00	667.00	40.00	362.00	18.00	27	7,500.00	6.30	0.500	147.00	0.250	0.300	0.025	1	0	0	0	0		
B1	EV	1,051,744.80	649.25	3	110.00	556,802.22	2	125.00	210.00	25.00	290.00	17.00	25	5,000.00	6.80	0.000	0.000	0.000	0.000	0.000	1	0	0	0	1		
B2	EV	1,672,351.70	649.25	3	210.00	560,000.00	2	90.00	220.48	17.00	550.00	35.00	22	13,500.00	9.45	0.000	0.000	0.000	0.000	0.000	1	0	0	0	0		
B3	EV	3,256,627.00	778.50	3	162.00	1,104,826.00	2	127.00	176.00	15.00	300.00	10.80	29	19,051.00	10.97	0.000	0.000	0.000	0.000	0.000	1	0	0	0	0		
B4	EV	707,950.92	778.50	3	165.00	178,195.26	2	145.00	215.00	17.00	350.00	13.00	26	18,000.00	16.60	0.000	0.000	0.000	0.000	0.000	1	0	0	0	0		
C1	HE V	1,590,921.35	5,003.00	2	1,330.00	485,105.63	1	120.00	660.00	10.00	832.00	30.00	37	19,000.00	21.40	0.500	147.00	0.080	0.170	0.005	1	1	0	0	0		
C2	HE V	1,915,591.05	5,003.00	2	1,718.00	386,833.36	1	120.00	615.00	18.00	800.00	4.80	32	16,200.00	10.83	0.500	147.00	0.080	0.170	0.005	1	1	0	0	0		
C3	HE V	1,971,836.75	5,003.00	2	1,580.00	590,295.05	1	130.00	400.00	18.00	860.00	42.56	22	9,300.00	8.53	0.500	147.00	0.250	0.300	0.025	1	1	0	0	0		
C4	HE V	1,774,350.00	5,003.00	2	1,540.00	944,033.04	1	220.00	800.00	10.00	1200.00	48.00	36	19,000.00	21.24	0.500	147.00	0.080	0.170	0.005	1	1	0	0	0		

Determination of the positive and negative ideal solution: In the evaluation of the beneficial criteria -criteria to be maximized- the positive ideal solution is the highest value, while the negative ideal solution is the smallest value. For the cost criteria -criteria to be minimized-, it is the opposite. The solution tables of the method are presented in Section 4.

Calculation of separation measures for alternatives: In this step, the values utilized in specifying the relative closeness to the ideal solution are calculated using Equation (3.6), Equation (3.7), and Equation (3.8) (Chen et al., 2014).

$$S_i^* = \sqrt{\sum_{j \in M} (v_{ij} - A^*)^2} \quad , \quad i \in A, j \in M \quad (3.6)$$

$$S_i^- = \sqrt{\sum_{j \in M} (v_{ij} - A^-)^2} \quad , \quad i \in A, j \in M \quad (3.7)$$

$$C_i = \frac{S_i^-}{(S_i^-) + (S_i^*)} \quad , \quad i \in A, j \in M \quad (3.8)$$

where, S_i^* is the separation measure from the positive ideal solution of each alternative, S_i^- is the separation measure from the negative ideal solution of each alternative, A^* is the positive ideal solution, A^- is the negative ideal solution, C_i is the relative closeness, A and M are the alternatives and criteria sets.

C_i values are considered in the ranking process of the alternatives such that the alternative with the highest C_i value is accepted as the most appropriate alternative for the considered decision-making problem. The final order of the alternatives obtained by the integrated structure involving AHP and TOPSIS methods is presented in Section 4.

Figure 3.6 shows the flowchart of the TOPSIS method.

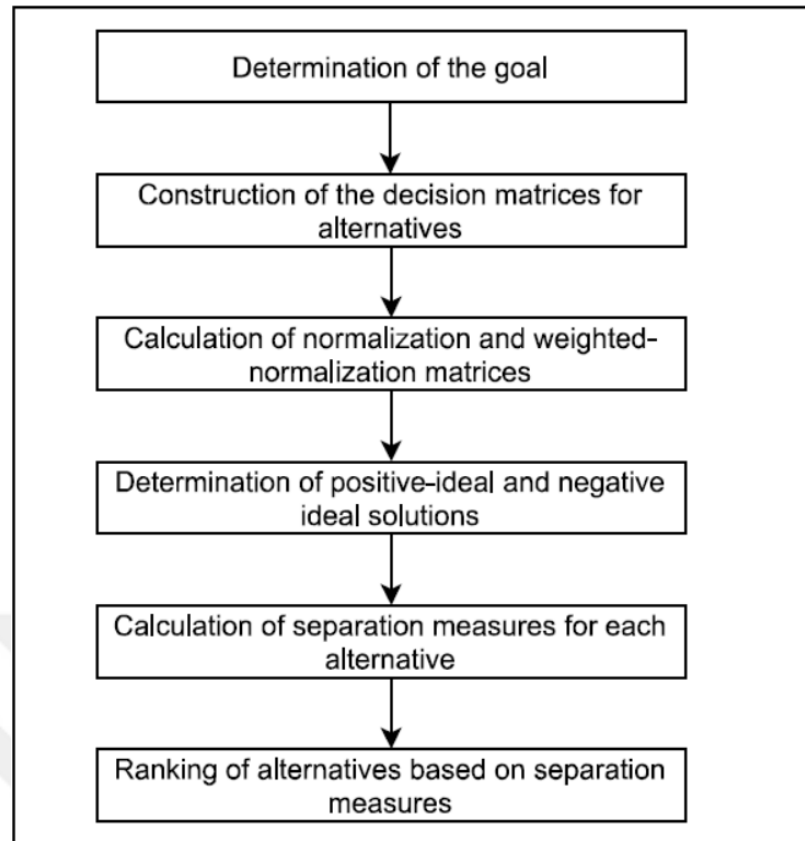


Figure 3.6 : TOPSIS flowchart.

3.3.3 Decision-making trial and evaluation laboratory (DEMATEL)

In the following the fundamentals of the DEMATEL method and the way to calculate the criteria weights using the DEMATEL method are presented.

3.3.3.1 Fundamentals of DEMATEL method

With the aim of visualizing the complex causal relationship with the help of matrices and diagraphs, Geneva Research Centre of the Battelle Memorial Institute developed the DEMATEL technique in 1972 (Gabus and Fontela, 1972). Being a structural modeling technique, DEMATEL analyzes the causes and effects of relationships between the elements of a system (Acuna-Carvajal et al., 2019). For the evaluation of the relation between attributes, a network relation design is constructed with the application of the DEMATEL method (Alinezhad and Khalili, 2019).

In the model, for the pairwise comparison of criteria, a 0-4 comparison scale is used, where 0, 1, 2, 3, and 4 represent respectively “no influence”, “low influence”, “medium influence”, “high influence”, and “extremely high influence” (Acuna-

Carvajal et al., 2019). The calculation steps of the DEMATEL method are given in Table 3.4.

Table 3.4 : Calculation steps of DEMATEL method (Gabus and Fontela, 1972).

	Steps	Definition
1	Determine the decision-making problem	Description of the problem and establishment of the purpose
2	Construct the direct-influence matrix	Construction of the direct-influence matrices using a 0-4 scale
3	Calculate the normalized direct-influence matrix	Calculation of normalization matrix in order to enable direct comparison of many diverse criteria in the comparison matrix with each other
4	Construct the total- influence matrix	Construction of the total-influence matrices representing direct and indirect effects of evaluation criteria
5	Draw the influential relation map (IRM)	Drawing of IRM, where “Prominence” is the strength of impacts given and received of the factor, “Relation” is the net effect that the factor contributes to the system
6	Calculate of the importance weights for criteria	Determination of the weights of criteria showing the importance of one criterion compared to another

3.3.3.2 Calculation of criteria weights using DEMATEL method

The calculation steps listed in the following are used to calculate the weights of the evaluation criteria while employing the DEMATEL method.

Construction of the direct-influence matrix: In the first step of a decision-making problem, determined n- evaluation criteria are compared pair-wise employing an N-scale comparison scale, that creates the average matrix (Venkatesh et al., 2017).

Calculation of the normalized direct-influence matrix: In order to enable the direct comparison of different evaluation criteria, the initial matrix is required to be normalized such that each value in the obtained matrices will take values between 0-1. In order to calculate the normalized values, after calculation of the sum of each column and row, the highest sum value is determined. After this step, each cell in the initial matrix is divided by the value obtained from Equation (3.9) (Venkatesh et al., 2017):

$$X_{ij}^* = \frac{X_{ij}}{\min[\max(\sum_{j=1}^n X_{ij}), \max(\sum_{i=1}^n X_{ij})]} , \quad i, j \in (1, 2, \dots, n) \quad (3.9)$$

where, X_{ij} is the influence of criterion i on criterion j , X_{ij}^* is the normalized value, and n is the criteria number.

Construction of the total-influence matrix: The total influence matrix, which allows the understanding of the relationship among the evaluation criteria, is obtained using Equation (3.10) (Venkatesh et al., 2017):

$$T = X * (I - X) \quad (3.10)$$

where, T is the total-influence matrix, X is the initial direct-influence matrix, and I is the identity matrix.

Drawing of the influential relation map: The sum of each row (D_i) and column (R_i) are calculated using Equation (3.11) and Equation (3.12) (Venkatesh et al., 2017):

$$D_i = [d_i]_{nx1} [\sum_{j=1}^n t_{ij}]_{nx1} \quad , \quad i, j \in (1, 2, \dots, n) \quad (3.11)$$

$$R_i = [r_j]_{1xn} [\sum_{i=1}^n t_{ij}]_{1xn} \quad , \quad i, j \in (1, 2, \dots, n) \quad (3.12)$$

where, d_i is the sum of i th row in the matrix T , r_j is the sum of the j th column in the matrix T , and t_{ij} is the value of each of the cells in the matrix T .

Calculation of the importance weights for criteria: The weights of criteria are determined considering the prominence and relation using Equation (3.13) (Venkatesh et al., 2017):

$$w_i = \frac{\sqrt{(D_i + R_i)^2 + (D_i - R_i)^2}}{\sum_{i=1}^n \sqrt{(D_i + R_i)^2 + (D_i - R_i)^2}} \quad , \quad i, j \in (1, 2, \dots, n) \quad (3.13)$$

where, w_i is the weight of i th criterion. $D_i + R_i$ is called the “prominence” and, $D_i - R_i$ is called the “relation”. If $D_i - R_i > 0$, the criterion is referred to cause criterion affecting all other criteria, and, if $D_i - R_i < 0$, the criterion is referred to effect criterion affected by all the other criteria (Wu, 2008).

The flowchart for the DEMATEL method is shown in Figure 3.7.

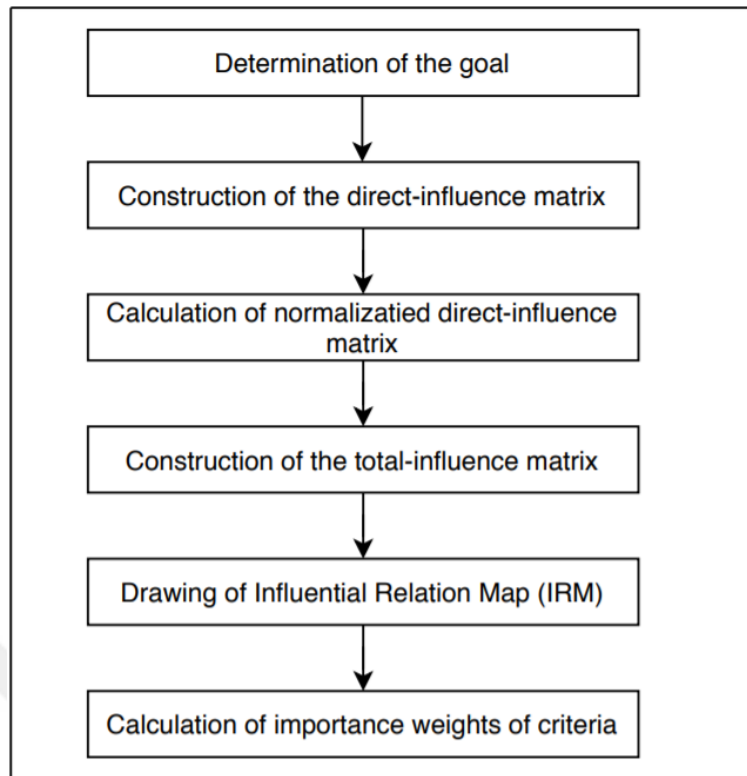


Figure 3.7 : DEMATEL flowchart.

3.3.4 Multiple objective optimization on basis of ratio analysis plus full multiplicative form (MULTIMOORA)

In the following the fundamentals of the MULTIMOORA method and the way to rank the selected alternatives using the MULTIMOORA method are presented.

3.3.4.1 Fundamentals of MULTIMOORA method

MULTIMOORA method, which is proposed by Brauers and Zavadskas in 2010, emerged as an extended version of the multi-objective optimization on the basis of ratio analysis (MOORA) method. It can be accepted as one of the most effective and simple attribute decision-making (MADM) methods. As the MULTIMOORA method adopts a variety of approaches that are the Ratio System, the Reference Point Approach, and the Full Multiplicative Form it provides an efficient solution for users (Dahooie et al., 2019). The calculation steps to be followed when employing the MULTIMOORA method are given in Table 3.5.

Table 3.5 : Calculation steps of MULTIMOORA method (Brauers and Zavadskas, 2009; Zavadskas et al., 2010).

	The Ratio System Steps	The Reference Point Approach Steps	The Full Multiplicative Form Steps
1	Determine the decision-making problem	Determine the decision-making problem	Determine the decision-making problem
2	Construct the decision matrix of the problem	Construct the decision matrix of the problem	Construct the decision matrix of the problem
3	Calculate the normalized and weighted normalized matrix	Calculate the normalized and weighted normalized matrix	Calculate the normalized and weighted normalized matrix
4	Determine the overall importance of beneficial and non-beneficial criteria	Determine the reference point based on the maximum and minimum values	Multiply weighted normalization values for beneficial and non-beneficial criteria
5	Rank alternatives	Rank alternatives	Rank alternatives

3.3.4.2 Ranking of alternatives with MULTIMOORA method

The three approaches while employing the MULTIMOORA method are employed for the alternative ranking in the solution of the problem.

The Ratio System: In the Ratio System, firstly the normalized and weighted normalized values are calculated for the evaluation criteria using respectively the Equation (3.14) and Equation (3.15) (Dahooie et al., 2019):

$$X_{ij}^* = \frac{X_{ij}}{\sqrt{\sum_{i=1}^m X_{ij}^2}} \quad , \quad X_{ij}^* \in [0,1], \quad i \in (1,2, \dots, m), \quad j \in (1,2, \dots, n) \quad (3.14)$$

where, X_{ij} is the response of alternative i on criterion j , X_{ij}^* is the normalized response of alternative i on criterion j , m is the alternatives number, and n is the criteria number.

After the construction of the normalized matrix, the weighted normalization matrix is obtained by multiplication of the calculated criteria weights with the normalized values (Dahooie et al., 2019):

$$v_{ij} = w_{ij} * n_{ij} \quad j \in (1,2, \dots, n) \quad (3.15)$$

where, v_{ij} is the weighted normalized value, and w_{ij} is the weight of the criterion j .

For the beneficial criteria, the weighted normalized values are summed, while for the non-beneficial criteria, they are subtracted in the assessment of the evaluation criteria considering the Equation (3.16) (Dahooie et al., 2019):

$$y_i = \sum_{j=1}^g v_{ij} - \sum_{j=g+1}^n v_{ij} \quad (3.16)$$

where, y_i is the overall importance of alternative i, $\sum_{j=1}^g v_{ij}$ is the overall importance of alternative i based on the benefit criteria (to be maximized), $\sum_{j=g+1}^n v_{ij}$ is the overall importance of alternative i based on the cost criteria (to be minimized), g and n are the total numbers of benefit criteria and cost criteria, respectively.

In the final decision, the alternative having the highest y_i value is considered as the best.

The Reference Point Approach: For the beneficial criteria, the Reference Point Approach considers the maximum normalized value as the reference point. Moreover, for the non-beneficial criteria, the minimum normalized value is considered as the reference point. The alternatives are ranked according to the deviation from the reference point using Equation (3.17) and E Equation (3.18) (Li, 2014):

$$d_i^{max} = \max_j (w_j * |X_j^* - X_{ij}^*|) \quad (3.17)$$

where, d_i^{max} is the maximum distance of alternative i to the reference point, and X_j^* is the reference point for the criterion j.

$$X_j^* = \begin{cases} \max_j X_{ij}^* & j \in \Omega_{max} \\ \min_j X_{ij}^* & j \in \Omega_{min} \end{cases} \quad (3.18)$$

where, Ω_{max} and Ω_{min} are the benefit criteria and cost criteria sets, respectively.

In the final decision, the alternative having the lowest d_i^{max} value is considered as the best (Hafezalkotob and Hafezalkotob, 2015).

The Full Multiplicative Form: In Equation (3.19), employed in the Full Multiplicative Form, the numerator represents the product of the weighted normalization values of beneficial criteria while the denominator represents the

product of the weighted normalization values of non-beneficial criteria (Hafezalkotob et al., 2016).

$$U_i = \frac{\prod_{j \in \Omega_{max}} r_{ij}^{w_j}}{\prod_{j \in \Omega_{min}} r_{ij}^{w_j}} \quad (3.19)$$

where, U_i represent scores of alternatives, Ω_{max} and Ω_{min} are the benefit criteria and cost criteria sets, respectively, $\prod_{j \in \Omega_{max}} r_{ij}^{w_j}$ is the multiplication of the weighted normalization values of beneficial criteria, and $\prod_{j \in \Omega_{min}} r_{ij}^{w_j}$ is the multiplication of the weighted normalization values of cost criteria.

In the ranking process, the alternative having the highest U_i value is considered as the best.

The results achieved by the three methods are compared. The best alternative is determined such that the alternative which mostly appears in the first positions on all ranking tables is considered as the most suitable one.

In Figure 3.8, the flowchart for the MULTIMOORA method is given.

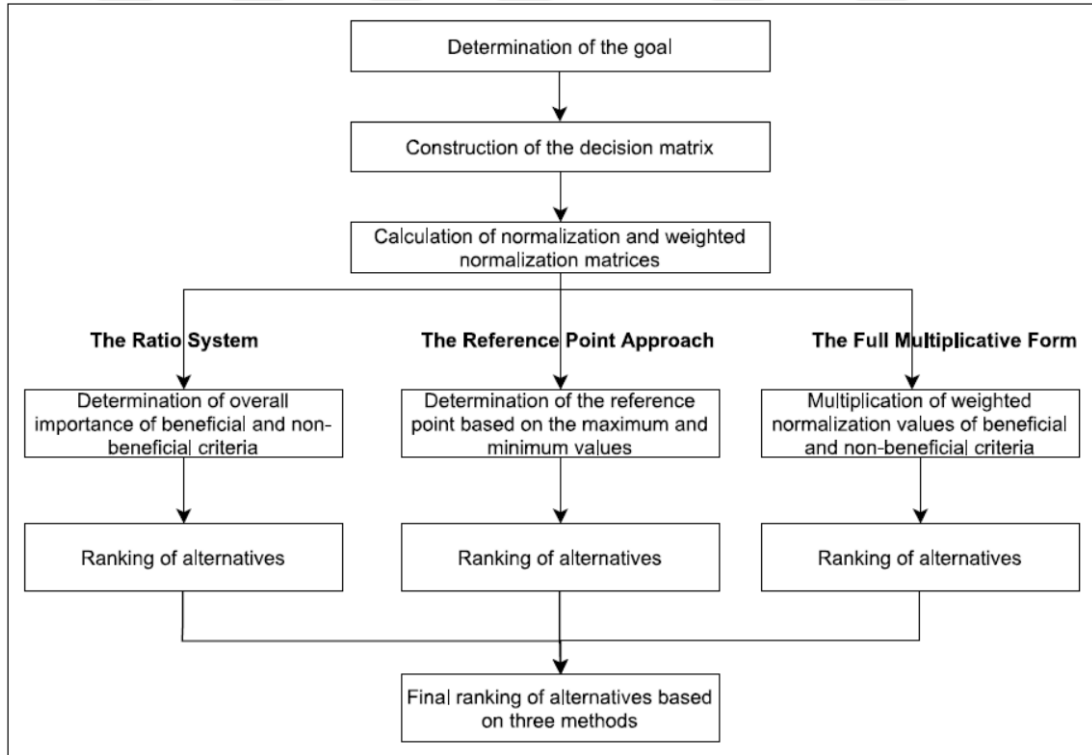


Figure 3.8 : MULTIMOORA flowchart.

3.4 Integrated Decision Making Framework

In the solution of the vehicle selection problem, four different MCDM methods, i.e., AHP, TOPSIS, DEMATEL, and MULTIMOORA, are employed. Although the AHP method is capable of performing both the calculation of criteria weights and ranking of alternatives, the other three methods are employed to improve the reliability and robustness of the solution. In the study, AHP and DEMATEL methods are used to calculate weights of evaluation criteria while TOPSIS and MULTIMOORA methods are used to perform the ranking of alternatives. The integration of methods is obtained using two methodological combinations, which are the AHP-TOPSIS combination and the DEMATEL-MULTIMOORA combination, to solve the decision-making problem of determining the most suitable vehicle. In the end, results obtained from two integrated model structures are compared and, the final decision is determined. The flowchart of the proposed integrated framework involving the hybridization of MCDM methods is given in Figure 3.9.

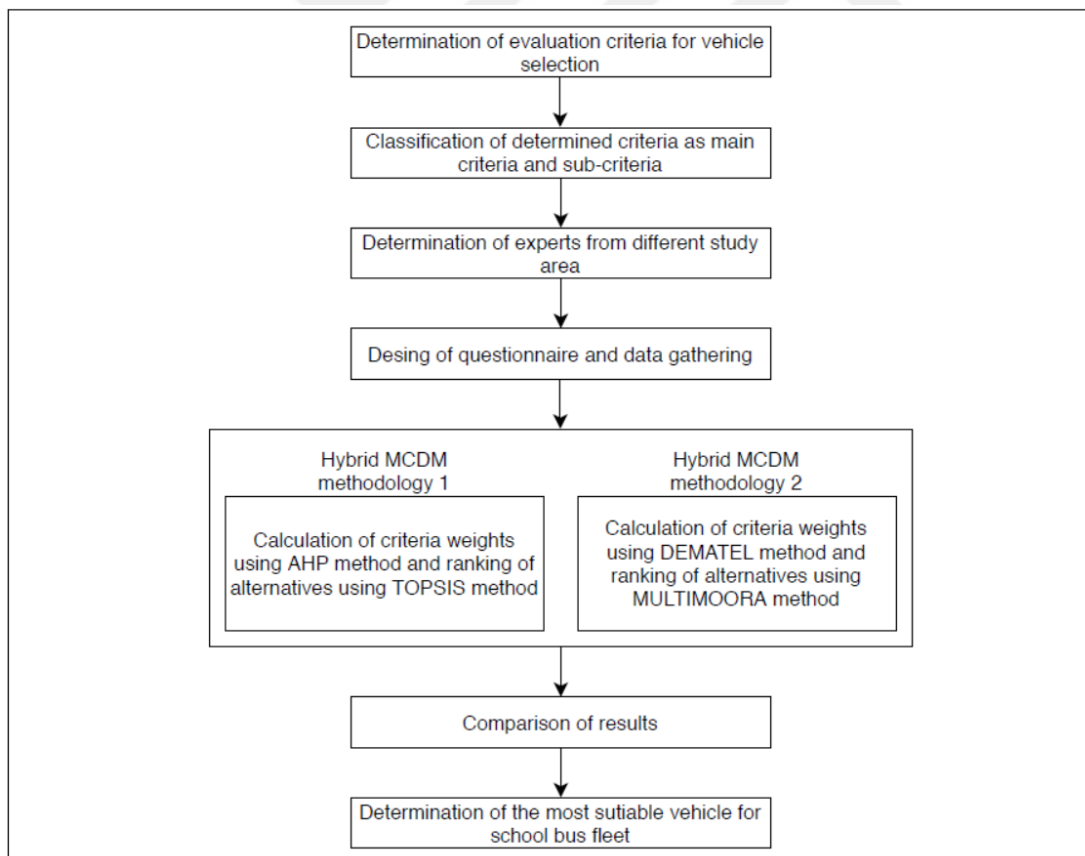


Figure 3.9 : Flowchart of proposed integrated framework involving hybrid MCDM methods.

4. CASE STUDY

In the following, firstly, general information about Istanbul considering the transport-related plans, the zonal and transport network characteristics of the city that are retrieved from the Istanbul Transportation Master Plan (ITMP, 2011) are presented. In the second part of this section, the case study area is explained with specific emphasis on the routes of the bus fleet investigated. Finally, the solution of the decision-making problem and the solution tables obtained by the proposed hybrid framework are summarized.

4.1 City of Istanbul, Turkey

Istanbul is located as the most important connection between Southern Europe and Asia. Due to its location between the Black Sea and the Marmara Sea, it is an important gateway to both the Aegean Sea and the Mediterranean Sea. Figure 4.1 shows the road network in and around Istanbul. In parallel with economic growth, Istanbul's population is rapidly increasing, while its metropolitan area is growing rapidly. The population, which was around 6 million in 1985, has exceeded 15 million by the end of 2019 (TSI, 2020). The number of registered vehicles in the city also increased continuously and has exceeded 12 million by the end of 2019 (TSI, 2019c). With the intense urbanization, population growth, and economic growth in Istanbul, the use of motor vehicles has increased rapidly, the congestion problem has reached emerging levels and, serious negative effects such as accidents and exhaust emission problems have been being encountered. In Istanbul, where daily trips are very high, most of these trips are made by road and a large share of the vehicles constituting the traffic is private vehicles (ITMP, 2011).

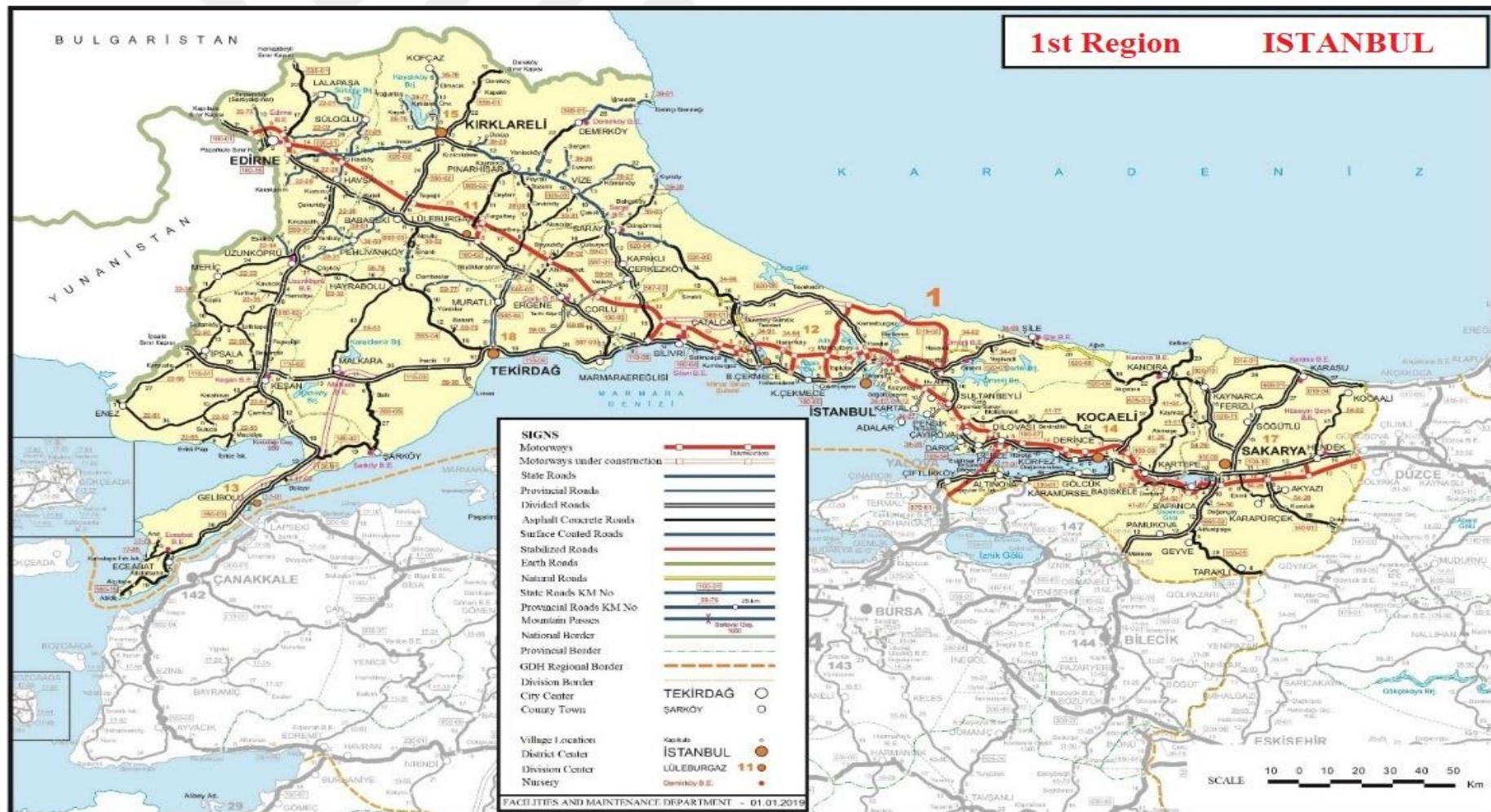


Figure 4.1 : Road network in Istanbul (General Directorate of Highway, 2019).

4.1.1 Transport master plans of Istanbul

Since the bus fleet to be analyzed within the scope of this thesis is operated in Istanbul, road network characteristics and land use characteristics are obtained from Istanbul Transportation Master Plan.

In May 2006, Istanbul Metropolitan Municipality started to work on the Istanbul Metropolitan Area Integrated Urban Transportation Master Plan called ITMP, and technical cooperation was provided with Japan International Cooperation Agency (JICA). However, before the completion of the IUAP study, the 1/100.000 scaled Istanbul Provincial Environmental Plan was revised in 2009, which necessitated the revision of the Istanbul Transportation Master Plan. In line with these developments, the revision of the Istanbul Transportation Master Plan started in June 2009. The study area covers the entire Istanbul Metropolitan area (the administrative boundary of Istanbul) and the Gebze district of Kocaeli, which has a close relationship with the Istanbul Metropolitan Municipality.

Purpose of the master plan: Based on the land use and population, to meet the transportation demands of the inhabitants by establishing a sustainable transportation system with the following specifications are purposed for Istanbul in 2023: i) economical and cost-effective; ii) contribute to the planned development of the city; iii) minimizes the ecological harm to the environment; iv) puts emphasis on the principle of social equality in social terms; v) compatible with the historical and cultural identity of the city; and, accessible, comfortable, safe, reliable.

The general objective of the ITMP is to create a more livable urban environment as a result of increasing mobility and accessibility in the city by reducing motor vehicle traffic, improving public transport infrastructure, and shifting traffic demand from private vehicles to public transportation vehicles. The relationship between the targets from the upper-scale Istanbul Provincial Environmental Plan and the targets of the sub-scale Istanbul Metropolitan Area Integrated Urban Transportation Plan is shown in Table 4.1.

Table 4.1 : Objectives of Istanbul Provincial Environmental Plan and Istanbul Transportation Master Plan (ITMP, 2011).

Objectives of Istanbul Provincial Environmental Plan	Objectives of the Transportation Master Plan
Establishment of public transport weighted transportation network integrated with transport types	Increase of urban accessibility and provision of integration between transport types
Determination of the key travel-producing focal points in relation to transport strategies	Acquisition of a sustainable transportation system with effective use of the transportation system
Provision of economic and rapid transportation of people primarily instead of vehicles in Istanbul	Development of the railway network for a fast and comfortable public transportation system
Determination of new focal points to balance the population-employment distribution across Istanbul and both-sides	Construction of the fast network infrastructure that supports the planned urban development
Planning of railway transportation systems parallel to linear development in East-West direction	Establishment fast railway and highway connections for integration between transport centers (logistics, organized industrial zones, bus stations, central areas, airports...)
Reduction the traffic of rubber-tired vehicles and creation of pedestrian transportation axes in the historical structures of the city, primarily in Historical Peninsula	Conservation of historical and cultural assets in the Historical Peninsula by developing alternatives to minimize exhaust emissions

Besides general objectives, the master plan has also other sub-objectives. Firstly, it is aimed to establish the coordinated main network structure necessary for a sustainable transportation system intended to an integrated public transportation system between the highway-railway-seaway to meet the transportation needs of the city at a civilized scale. Determination of the effects of major transportation projects on the transportation system of the city at a strategic level to meet the transportation demands in the target year of 2023 and performing feasibility assessments for these projects are other important objectives. The last objective of the master plan is to establish a network structure to support the development of new residential areas envisaged in land use plans.

In order to achieve a sustainable transportation system, several policies are determined by authorities. These policies can be listed as follows: i) holding the private vehicle usage at a low level with the improvement of public transportation infrastructure; ii) enhancing the highway network that can respond to increased vehicle traffic in the short term; iii) constructing public transportation infrastructure facilities that will support the planned urban development in the long term; and, iv) improving traffic demand management and to ensure more efficient use of existing roads.

In addition to policies, many strategies are also set to arrange transport systems and other related areas. Preparation of the master plan of the city based on the land-use decisions in the provincial border of Istanbul, plan and projection of the transportation systems (railway systems, highway systems, car parks, transfer centers) within the scope of this plan, construction of the transport decisions based on the strategies mentioned above are told as primary considerations. Also, with the developed master plan, it is aimed to improve the public transportation by: i) using modern public transportation systems and technologies; ii) extending railway systems by taking care of priorities to construct an optimum network structure; iii) enhancing seaway transport; and, iv) developing the techniques and models for the financing of public transportation investments, especially for railway systems. With the purposes of performing the transport demand management, providing the application, and keeping private vehicle usage at a low level, several strategies are determined. The first consideration is to give priority to the integration of private vehicle usage with public transportation. Activating and improving traffic management and control, developing a system informing drivers and passengers, extending traffic education, and setting a price for the congestion in the highway infrastructure are also considered as beneficial actions in terms of transportation system management.

4.1.2 Other long and mid-term plans affecting Istanbul

Istanbul hosts many mega projects, some of which have been completed and some are still under construction (Ministry of Transport and Infrastructure, 2019). Istanbul Airport, which contributes to Turkey in becoming the most important transit center along both north-south and east-west axis, is predicted to serve 90 million passengers per year with its first phase. When the project is completed, it is expected to serve 150-200 million passengers per year. With the North Marmara Motorway, most of which has been completed but some are still under construction, the expected benefits are listed as the decrease in transit traffic load of Istanbul, access control of vehicles without entering the city traffic, time-saving with a high standard, uninterrupted, safe and comfortable road, reduction in the traffic density in Istanbul by providing integration with other transportation modes, elimination of air pollution and environmental problems caused by heavy traffic. With the Yavuz Sultan Selim Bridge, which is opened to service, it is aimed to both relax the traffic and eliminate

environmental problems such as air and pollution by removing heavy vehicles and transit traffic from the city. With the Eurasia Tunnel, it is aimed to provide a more balanced urban transport service by reducing the heavy traffic load on the east-west axis in Istanbul, especially at peak hours. Metro services take an active part in passenger transportation and undertake a large part of daily passenger transportation in Istanbul. In Istanbul, which currently has a 233.05 km long rail system line, new rail system lines with a total length of 221.70 km are under construction (Metro Istanbul, 2019).

4.1.3 Zonal characteristics

Natural and Geographical Structure: The urban structure of Istanbul is shaped by a rolling topography. This situation affects and determines the current urbanization and land use structure, transportation systems, and the general structure of the city. Areas with an elevation above 100 or 150 meters are generally classified as forest areas. Forest areas and water basins are vital for the ecological environment of Istanbul. According to Figure 4.2, the east side is more mountainous than the west side and the west side has more agricultural lands.

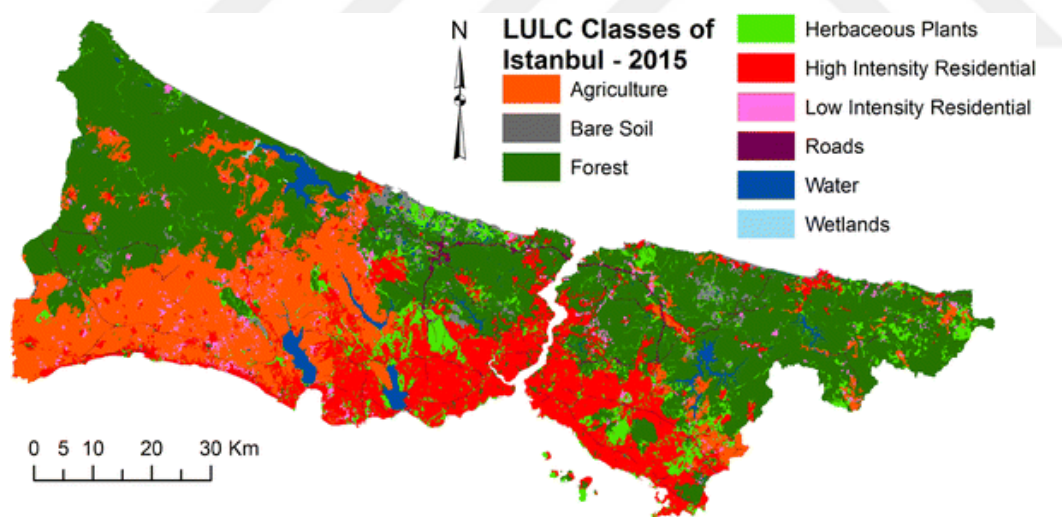


Figure 4.2 : Land use map of Istanbul (ITMP, 2011).

Urban Structure of Istanbul: Land use in Istanbul is generally characterized as “mixed land use”. It houses residential, commercial, office, and other land use together. On the other hand, this mixed-use structure is seen on the scale of a street and even a building, revealing the city's fragmented land use.

4.1.4 Characteristics of the transport network

The road network in Istanbul shows a linear structure due to the development of urbanization in the east-west direction. The TEM (Trans European Motorway) and the D100 Highway extending on the east-west axis constitute the two main corridors of Istanbul. In addition, there are ring roads surrounding the “Historical City Center” and the Central Business District region. Radial roads include roads such as TEM motorway, east and west extensions of D-100 Highway, Old Edirne Road, “Piyale Paşa Boulevard, Büyükdere Street, Şile Road. TEM motorway and D-100 Highway are designed as highways/express roads having high traffic capacities with 2x3 and 2x4 lanes and are connected to other roads with grade-separated interchanges.

In Istanbul, the roads are divided into three classes: motorway, main roads, and other roads. D-100 Highway has been constructed as a highway due to its road structure, lane width, and access control features. However, with the addition of the “Bus Rapid Transit” line, D100 has lost its motorway characteristic since it has lost the “access control” characteristic, which constitutes an important privilege of the motorway.

The highest rate in the morning peak hour interval (07:00-10:00) was found to be 60%-75% based on the measurements performed at entrance (inside) and exit (outside) points of Istanbul.

4.1.5 Characteristics of transport network flows

According to the household survey conducted in 2006, the number of daily trips in 2006 was approximately 20.9 million. Excluding pedestrian journeys, the number of vehicle journeys was 10.3 million. Travel objectives were classified as home-work, home-school, home-other, and other. Based on the survey results, it was concluded that home-other trips have the highest rate with 37.2%, home-work trips with 32.3%, home-school trips with 21.4%, and other trips with 9.1%. Motorized and non-motorized daily travel distributions were calculated based on travel types. Accordingly, approximately 15% of the journeys were automobile and taxi trips, 32% were shuttle and bus, 2% were railway, 1% was by sea and 49% was on foot.

In the master plan, mobility is defined as the number of trips per person per day. There are two types of mobility rates: The first mobility rate is the gross rate applicable to all people independent from the journey. The second rate is the net rate,

which is calculated by considering the passengers. In Table 4.2, the individual mobility rates of households with and without automobiles are shown.

Table 4.2 : Mobility rates of households in terms of vehicle ownership and purpose.

Purpose	Total	Households without automobiles	Households with automobiles
Home - Work	0.55	0.53	0.59
Home - School	0.43	0.42	0.44
Home - Other	0.63	0.62	0.65
Other	0.13	0.10	0.18
Total	1.74	1.68	1.86

Trip generation and attraction refer to trips drawn from other traffic analysis areas to one traffic analysis area and produced in this area. Based on the household survey conducted within the scope of the master plan, total trip generations, and attractions of different districts of Istanbul are given in Figure 4.3.

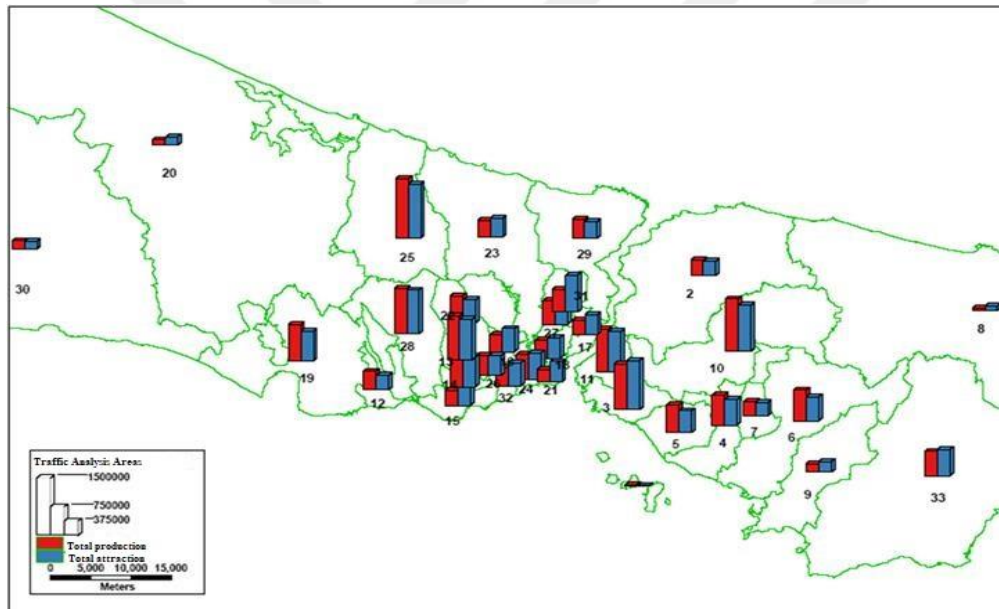


Figure 4.3 : Rates of production and attraction of total trips (ITMP, 2011).

Figure 4.4, shows the distribution of trips between districts according to all transportation types and purposes. The thickness of the lines is directly proportional to the traffic volume values. The figure does not show trips below 10,000. When the travel distribution lines are examined, it is seen that the movements are limited to the Bosphorous and are mostly completed within each side. The trips are concentrated in Kadıköy, Üsküdar and Ümraniye districts on the Asian side; and concentrates around Şişli, Gaziosmanpaşa, Küçükçekmece, Büyükçekmece, Bakırköy, Fatih, Güngören and Bağcılar districts on the European side.

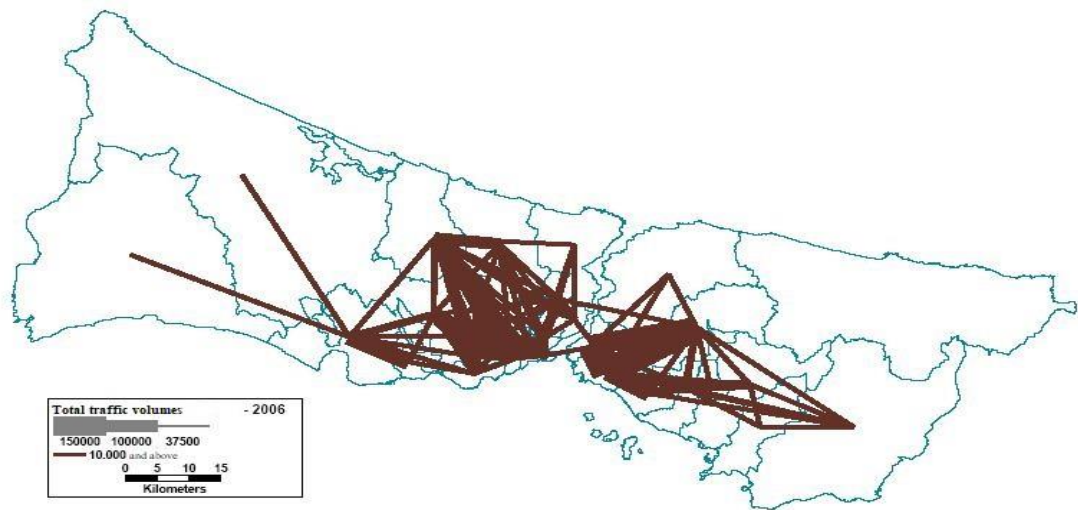


Figure 4.4 : Trip distribution with all purposes (10,000 and above) (ITMP, 2011).

4.2 Case Area and Data Description

This sub-section presents general information about the area selected for the case study. The provided information consists of location and importance of the case area, general characteristics of vehicles serving to the case areas, routes of these serving vehicles, and flow characteristics along the routes to our interest.

4.2.1 Case study area

The bus fleet serves to Istanbul Technical University Ayazaga Campus, which is the main campus of the university and located in Maslak, Istanbul, Turkey. Housing 8 faculties (Faculty of Computer and Informatics, Faculty of Electrical-Electronics, Faculty of Science and Letters, Faculty of Naval Architecture and Ocean Engineering, Faculty of Civil Engineering, Faculty of Chemical and Metallurgical Engineering, Faculty of Mines, Faculty of Aeronautics and Astronautics), 4 institutes (Graduate School of Science, Engineering and Technology, Energy Institute, Eurasia Institute of Earth Sciences and Informatics Institute), Rectorate Building, Management Offices, the Ayazaga Campus has 1,600,000 m² of land area. Academic and administrative staff working in offices and faculties use service vehicles to reach their homes from the campus or vice versa.

Figures from 4.5 to 4.10 show the peak hour flows of different locations that belong to bus routes (Figure 4.11) between January 2018 and October 2019. In the figures, the monthly change of traffic flows at the and morning and evening peak hours of the

selected routes. For the morning peak, the interval of 07:00 and 10:00 hours is selected while for the evening peak, the interval of 16:30 and 19:00 hours is selected.

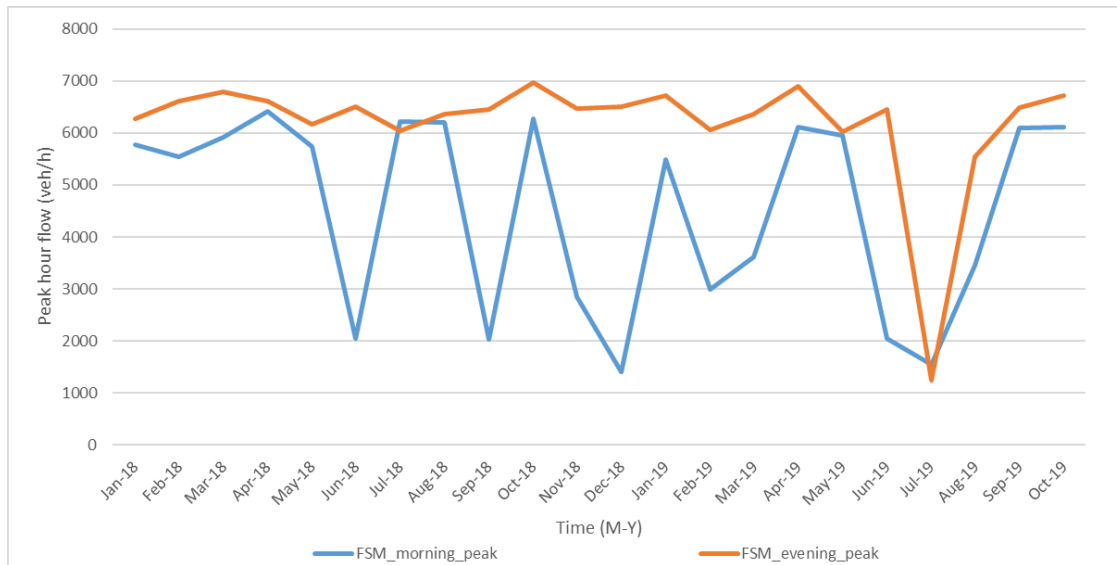


Figure 4.5 : Peak hour flow of Fatih Sultan Mehmet Bridge between January 2018 and October 2019.

Connecting the European and Asian sides of Istanbul, Fatih Sultan Mehmet Bridge is one of the most important sections along the bus route. The route consists of 4 traffic lanes in each direction. It can be concluded from the figure that flow rates at morning peak hours vary significantly between 6000 veh/hr and 2000 veh/h. However, flow rates ranging from 6000 veh/h to 7000 veh/h at evening peak hours are more stabilized compared to morning peak values.

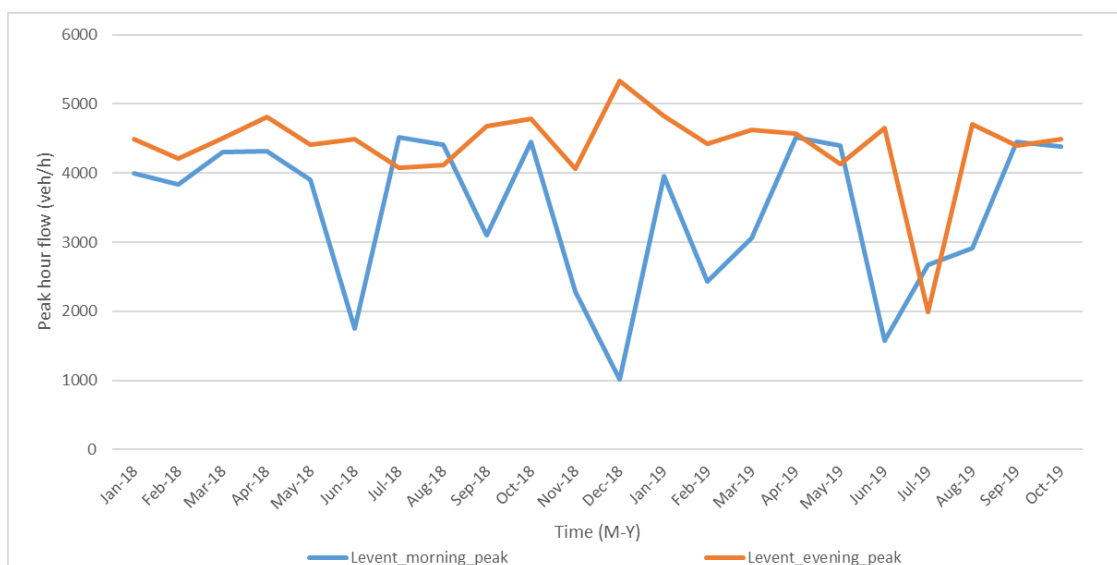


Figure 4.6 : Peak hour flow of Levent between January 2018 and October 2019.

Surrounded by Büyükdere Street, Çeliktepe and Gültepe in the west, Etiler, and Akatlar in the east, Levazım neighborhoods in the south and Maslak districts in the north, Levent district is among the regions with high traffic density. The route consists of 4 traffic lanes in each direction. It can be concluded from the figure that flow rates at morning peak hours vary significantly between 4500 veh/hr and 1000 veh/h. However, flow rates ranging from 4000 veh/h to 5000 veh/h at evening peak hours are more stabilized compared to morning peak values.

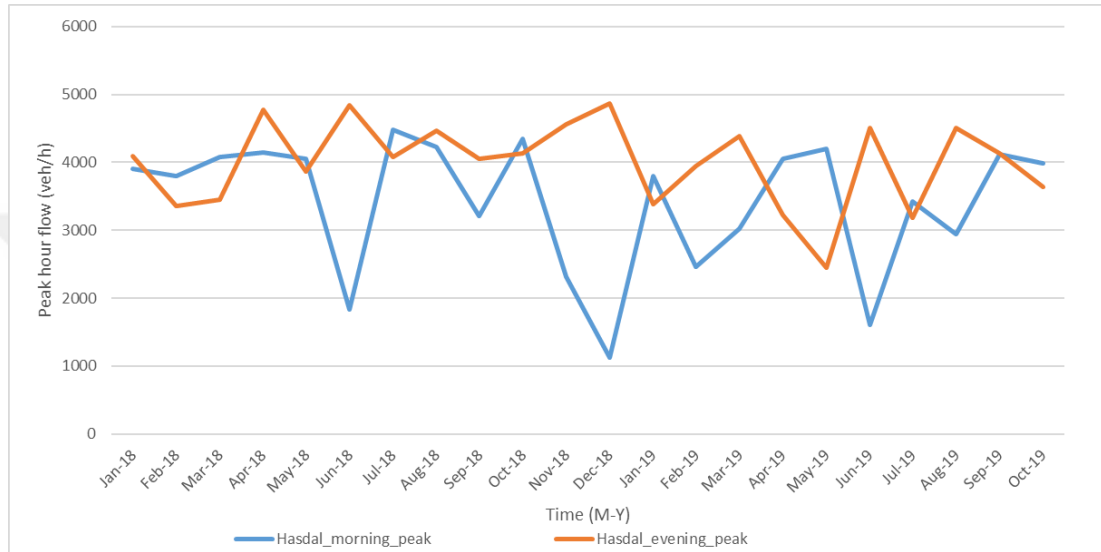


Figure 4.7 : Peak hour flow of Hasdal between January 2018 and October 2019.

Hasdal Intersection located on TEM has an important place in terms of transportation due to its location. The route consists of 3 traffic lanes in each direction. It can be concluded from the figure that flow rates at morning peak hours vary significantly between 4500 veh/hr and 1000 veh/h. However, flow rates ranging from 5000 veh/h to 2500 veh/h at evening peak hours are more stabilized compared to morning peak values.

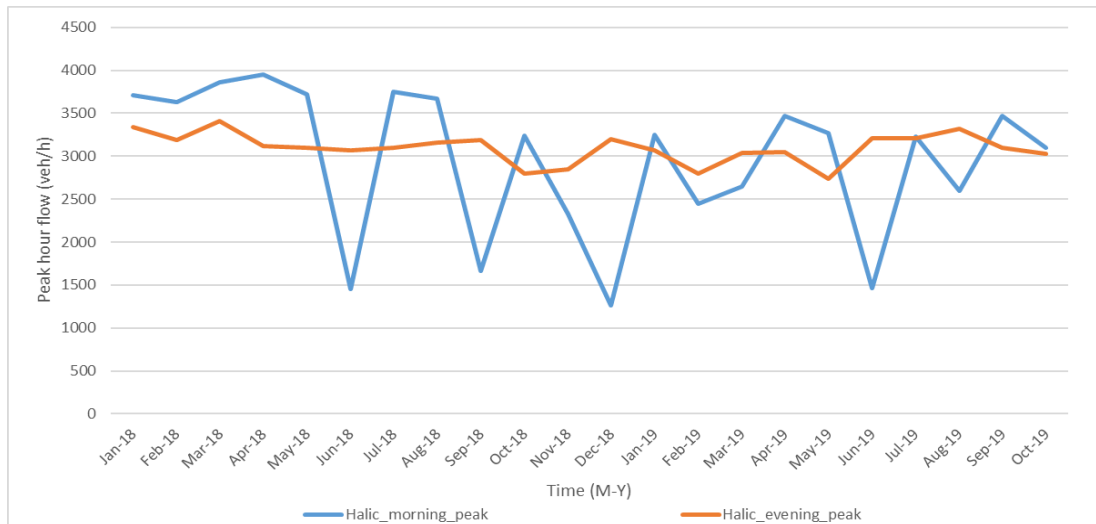


Figure 4.8 : Peak hour flow of Golden Horn between January 2018 and October 2019.

The Golden Horn Bridge, constructed between Ayvansaray and Halıcıoğlu districts, provides a crossing of the Bosphorus Bridge ring roads from the Golden Horn. The route consists of 2 traffic lanes in the direction of Ayvansaray district and 3 traffic lanes in the direction of Halıcıoğlu district. It can be concluded from the figure that flow rates at morning peak hours vary significantly between 4000 veh/hr and 1500 veh/h. However, flow rates ranging from 3000 veh/h to 3500 veh/h at evening peak hours are more stabilized compared to morning peak values.



Figure 4.9 : Peak hour flow of TUYAP between January 2018 and October 2019.

Büyükcçekmece district, located on the transit route of TEM and D-100 highways, is surrounded by Beylikdüzü and Esenyurt in the east, Silivri in the west, Çatalca and

Arnavutköy districts in the north, and the Marmara Sea in the south. This region is the last destination of the service fleet on the European side. The route consists of 3 traffic lanes in the direction of Avcılar district and 4 traffic lanes in the direction of Silivri district. It can be concluded from the figure that flow rates at morning peak hours vary significantly between 3000 veh/hr and 1000 veh/h. However, flow rates ranging from 3000 veh/h to 4000 veh/h at evening peak hours are more stabilized compared to morning peak values.

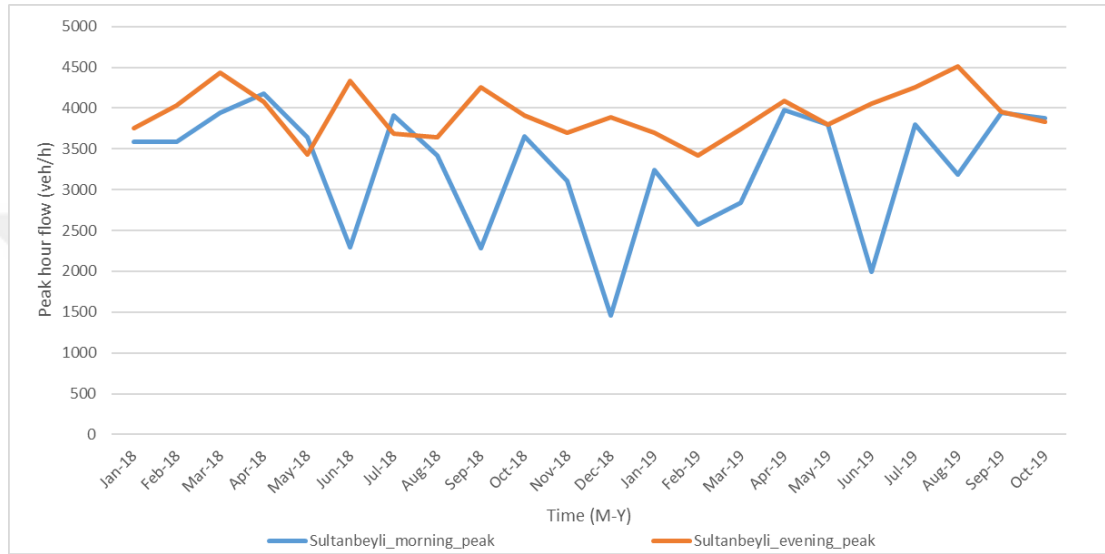


Figure 4.10 : Peak hour flow of Sultanbeyli between January 2018 and October 2019.

Sultanbeyli district, located on the transit route of Anatolian Highway (O-4) connecting Istanbul and Ankara, surrounded by Kartal in the southwest, Pendik in the east, and Sancaktepe in the northwest. This region is the last destination of the service fleet on the Asian side. The route consists of 3 traffic lanes in each direction. It can be concluded from the figure that flow rates at morning peak hours vary significantly between 4000 veh/hr and 1500 veh/h. However, flow rates ranging from 3500 veh/h to 4500 veh/h at evening peak hours are more stabilized compared to morning peak values.

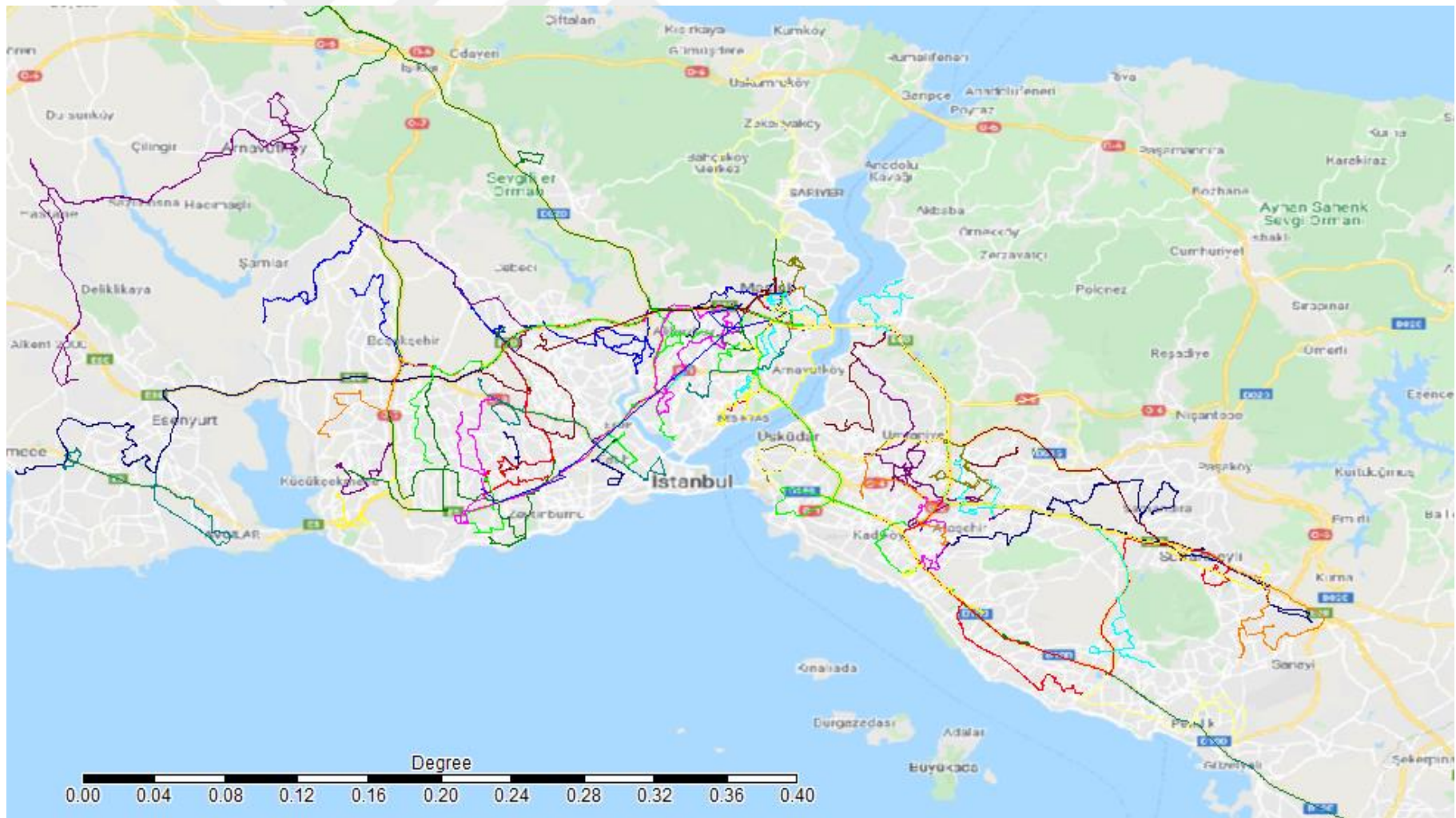


Figure 4.11 : Routes of bus fleet originated from Maslak district.

4.2.2 Description of real data

As service vehicles, there are 8 different models in the fleet and 42 service vehicles are employed in total. With these service vehicles, hundreds of academic and administrative staffs from several districts of Istanbul are served. All service vehicles in the fleet consume diesel fuel and, emission figures of vehicles comply with Euro 6 emission standards. The vehicles are divided into 3 classes with a seating capacity of 17, 27, and 47. During the predefined service period, buses with different capacities can be utilized for one route based on the monthly demand. The vehicle fleet is operated twice a day on weekdays, from 06:30 to 08:30 in the morning and from 17:30 to 19:30 in the evening. The vehicles in the fleet move in accordance with the speed regulations determined by the university administration within the campus, and they move in accordance with the speed regulations determined by the relevant authorities on the routes outside the campus. The data about service vehicles and their routes are given in Table 4.3 and Table 4.4, respectively.

Table 4.3 : The service vehicles data.

Vehicle type	Capacity	Number in Fleet
S1	46	2
S2	17	4
S3	17	5
S4	27	13
S5	17	4
S6	27	8
S7	17	3
S8	27	3

Table 4.4 : Service vehicle routes.

Origin	Destination	Origin	Destination	Origin	Destination
Maslak	Arıköy	Maslak	Esenyurt	Maslak	Mecidiyeköy
Maslak	Arnavutköy	Maslak	Fındıkzade	Maslak	Ortaçeşme
Maslak	Ataköy	Maslak	Göktürk	Maslak	Pendik
Maslak	Avcılar	Maslak	Göztepe	Maslak	Sarıyer
Maslak	Avrupa Konutları	Maslak	Gültepe	Maslak	Şerifali
Maslak	Ayazağa	Maslak	İçerenköy	Maslak	Sultanbeyli
Maslak	Bağcılar	Maslak	Kadıköy	Maslak	Tarabya
Maslak	Bahçelievler	Maslak	Kağıthane	Maslak	Tuzla
Maslak	Bayrampaşa	Maslak	Kartal	Maslak	Ümraniye
Maslak	Beşiktaş	Maslak	Kasımpaşa	Maslak	Üsküdar
Maslak	Beylerbeyi	Maslak	Kayaşehir	Maslak	Yakacık
Maslak	Bostancı	Maslak	Kızıltoprak	Maslak	Yenibosna
Maslak	Büyüçekmece	Maslak	Küçükçekmece	Maslak	Yenidoğan
Maslak	Çekmeköy	Maslak	Kurtköy	Maslak	Yeşilpınar

4.3 Scenario Development

In order to evaluate the effects of vehicle composition in terms of emission-related cost for environmental evaluation, three different situations are taken into consideration. In the first case, all vehicles in the fleet are considered as ICEVs. In the second case, half of the vehicles are considered as ICEVs and the other half are considered as EVs. In the final case, all vehicles in the fleet are considered as EVs. Considering ICEVs that are operated in the university campus, air pollutant emissions released from these vehicles are calculated using two different emission calculation models, Comprehensive Modal Emission Model (CMEM) and Computer Programme to calculate Emissions from Road Transport (COPERT) (Appendix A). Emissions values for the pollutants CO, CO₂, HC, and NO_x are obtained from the CMEM model and, emission values for SO₂ and PM are obtained from the COPERT model. The emission calculation is performed for the test vehicle used at ITU Ayazaga Campus for the shuttle operation.

The specifications of the selected test vehicle can be listed as follows: vehicle capacity of 21 seats and 31 standing, 190 hp maximum engine power, 510 Nm maximum net torque, Euro VI emission class, diesel fuel type, 35.3% climbing

ability, and 6.45 m turning radius. The parameters considered in the emission calculation are provided in Table 4.5.

Table 4.5 : Parameters used in the emission calculation process.

Average travel time (sec)	3533
Average travel distance (km)	49.08
Average vehicle speed (km/h)	50
Maximum upgrade slope (%)	13.27
Maximum downgrade slope (%)	13.26
Average upgrade slope (%)	1.93
Average downgrade slope (%)	1.80

Table 4.6 : Emission values of air pollutants.

Air pollutant emissions	CO	CO₂	NO_x	HC	SO₂	PM
Total emissions in one cycle (g/km)	0.71	242.21	2.63	0.34	0	0.21

The environmental assessment for determined situations is based on comparing the monetary values of pollutants emitted from the vehicles. The unit costs calculated by Bruyn et al. (2018) for 2015 and environmental impacts considered in the calculation process are given separately for each pollutant in Table 4.7. Considering a constant value of 3.5% increase per annum, unit costs to be used in the calculation of the monetary values of vehicle emissions in 2020 are calculated and given in Table 4.8. In (Bruyn et al., 2018), it is stated that economic valuation of emissions and other environmental effects are performed based on the framework given in Figure 4.12.

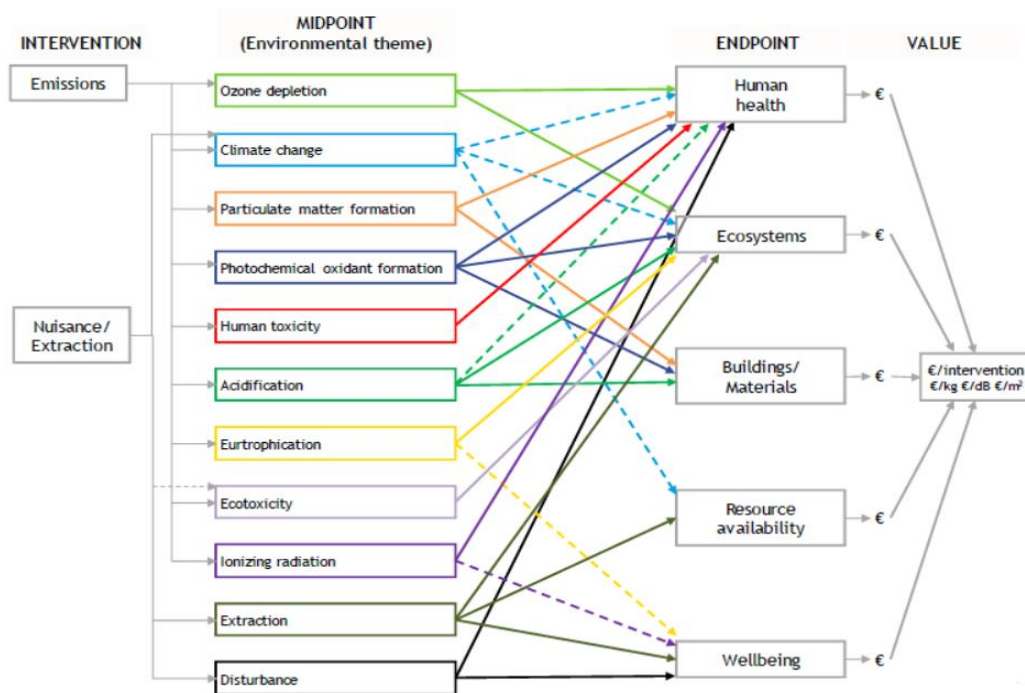


Figure 4.12 : Employed framework showing relationship between intervention, midpoints, endpoints, and valuation by Bruyn et al. (2018).

Table 4.7 : Environmental prices for fundamental air pollutant emissions (EUR/kg) in 2015 (Bruyn et al., 2018).

			CO ₂	NO _x	HC	CO	PM	SO ₂
Environmental (EUR/kg)	unit	costs	0.057	34.7	2.1	0.0958	59.55	24.9
Relevant midpoints								
PM formation				x			x	x
Smog formation				x	x	x	nc	x
Acidification				x				x
Climate change			x	nc				nc
Ozone layer								
Human toxicity								
Eutrophication				x				
Endpoints								
Human health			nc	x	x	x	x	x
Ecosystem services			nc	x	x			x
Materials/Buildingd			nc	x	x		x	x

nc: not calculated. The unit costs are used for 2015 emissions. For the economic valuation calculation, unit costs are increased with a constant value of 3.5% per year.

Table 4.8 : Monetary equivalents for fundamental air pollutant emissions (EUR/kg) at the end of the fleet's service life of 20 years.

			CO ₂	NO _x	HC	CO	PM _{2.5}	SO ₂
Environmental (EUR/kg)	unit	costs	0.13	82.00	4.96	0.23	140.73	58.84

4.3.1 Scenario no 1: Bus fleet including 100% ICEVs

Considering the emissions values given in Table 4.6 and unit costs in Table 4.8, the monetary value of each air pollutant emissions are calculated for a single cycle of the considered service bus. The calculations for monetary equivalents of CO, CO₂, NO_x, HC, and PM are given below through Equations from (4.1) to (4.5). The total cost equivalents corresponding to total emissions are given in Equation (4.6):

$$CO = \frac{0.71}{1000} kg/km * 0.23EUR/kg = 0.000163 EUR/km \quad (4.1)$$

$$CO_2 = \frac{242.21}{1000} kg/km * 0.13EUR/kg = 0.031487 EUR/km \quad (4.2)$$

$$NO_x = \frac{2.63}{1000} kg/km * 82.00EUR/kg = 0.215660 EUR/km \quad (4.3)$$

$$HC = \frac{0.34}{1000} kg/km * 4.96EUR/kg = 0.001686 EUR/km \quad (4.4)$$

$$PM = \frac{0.21}{1000} kg/km * 140.73EUR/kg = 0.029553 EUR/km \quad (4.5)$$

$$Summation \text{ values of total emissions} = 0.278549 EUR/km \quad (4.6)$$

The bus fleet is operated twice a day and the total distance traveled by 42 buses in the fleet is 1047.5 km for one cycle. Considering the total traveled distance, the annual monetary value of total emissions released from the considered fleet:

$$\begin{aligned} \text{Monetary value of total emissions} &= 0.278549 EUR/ \\ km * 1047.5 km * 2 cyc * 365 &= 212,999.46 EUR/year \end{aligned} \quad (4.7)$$

Purchasing costs of internal combustion engine vehicles and electric vehicles, and emissions costs are considered in the comparison of scenarios. Assuming that the buses in the service fleet will be operated for 20 years, the monetary value of total emissions at the end of the fleet's service life:

$$\begin{aligned} & \text{Monetary value of total emissions at the end of the service life} & (4.8) \\ & = 212,999.46 \text{ EUR/year} * 20 \text{ years} = 4,259,989.20 \text{ EUR} \end{aligned}$$

For the sake of the simplicity in currency, the value calculated using Equation (4.8) is converted to Turkish Liras by taking into consideration the “Indicative Exchange Rates announced at 15:30 on 02/01/2020 by the Central Bank of Turkey” (Url-1). The total costs and comparisons of considered scenarios are presented in Table 4.9.

Table 4.9 : Total costs of considered scenarios.

Scenario	Total purchasing cost (TL) (Url-2; Url-3)	Total emission costs (TL)	Total cost (TL)	Improvement (%)
100% ICEVs	61,902,708.00	28,478,160.25	90,380,868.25	-
50% ICEVs; 50% EVs	66,066,894.71	14,239,080.13	80,305,974.83	11.15
100% EVs	70,231,081.41	0	70,231,081.41	22.29

To sum up, in case that the bus fleet consists of 100% ICEVs, total economic loss is equal to the sum of the purchasing costs of 42 vehicles in the fleet and costs of emissions caused by the operation of this fleet.

4.3.2 Scenario no 2: Bus fleet including 50% ICEVs and 50% EVs

In case that half of the internal combustion engine vehicles in the fleet are replaced by electric vehicles, there will be an improvement of 11.15% according to the first scenario during the service life of the fleet.

4.3.3 Scenario no 3: Bus fleet including 100% EVs

In case that all of the internal combustion engine vehicles in the fleet are replaced by electric vehicles, there will be no cost due to air pollutant emissions caused by traditional vehicles. The only cost considered in the relevant scenario is the purchasing costs of buses in the fleet. The considered scenario provides a 22.29% improvement according to the first scenario during the service life of the fleet.

4.4 Employment of Integrated Framework: Goals and Method Based Criteria Specification

This sub-section provides selected evaluation criteria, alternatives to be compared, and solution tables based on the hybrid decision-making framework employed.

4.4.1 Sub-problem no 1

As mentioned in the sub-section Section 3.1, the problem is to help decision-makers in the decision process of renewing the current shuttle service buses and determining the best vehicle for their intended use in the university campus. In the next sub-sections, selected evaluation criteria and vehicles selected as alternatives to be compared are provided.

4.4.1.1 Goal, grouping of criteria, and component criteria

The main criteria determined for the decision-making problem are: i) economic measures; ii) performance measures; iii) physical measures; iv) environmental measures; and, v) safety measures. For each main criterion, different numbers of sub-criteria are determined for the solution of the problem. The selected sub-criteria are shown in Table 4.10:

Table 4.10 : Selected main and sub-criteria.

Economic measures	Performance measures	Physical measures	Environmental measures	Safety measures
Purchasing cost	Motor power	Capacity	Carbon monoxide (CO) emission	Antilock brake system (ABS)
Taxing	Range	Vehicle weight	Carbon dioxide (CO ₂) emission	Automatic emergency brake system (AEBS)
Maintenance cost	Climbing ability	Turning radius	Nitrogen oxide (NO _x) emission	Forward collision warning system (FCWS)
Fuel cost	Torque		Hydrocarbon (HC) emission	Lane departure warning systems (LDWS)
Secondary market	Energy efficiency		Particulate Matter (PM) emission	Speed monitoring and warning systems (SMAWS)
Vehicle life				

As alternatives, 12 different vehicle types are determined including Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs), and Internal Combustion Engine Vehicles (ICEVs).

4.4.1.2 Scenario-based analysis

The decision matrices filled by 25 experts from different fields of study are analyzed and the consistency of the decision matrices is calculated based on the AHP method. According to the AHP method, expert evaluations with a consistency ratio of more than 10% are not taken into consideration in the calculation of the final weights of the evaluation criteria. However, based on the expert opinions of academicians working in the field of Management Engineering that evaluations with a consistency ratio of up to 20% can be included in this process, we calculate the final weights (priorities) of evaluation criteria considering expert evaluations with a consistency ratio of up to 20%. Calculation tables of criteria weights are provided for the AHP method and DEMATEL method in Appendix B and Appendix C, respectively. The final priorities of evaluation criteria calculated using the AHP method and DEMATEL method are given in Table 4.11 and Table 4.12, respectively. As it can be concluded from tables, where using the AHP method a scale of 1-9 for comparison is considered, safety measures criterion is the most important criterion in the selection of buses for school fleet according to the experts' evaluations, and the environmental measures criterion is the second most important criterion. In the DEMATEL method employing the 0-4 comparison scale, the physical measures criterion is the most important criterion in the selection of buses for the school fleet according to the experts' evaluations, and the performance measures criterion is the second most important criterion. The difference between the criterion weights obtained by using two different methods is probably due to the comparison scale and processing steps used by the methods. Influential-Relation Maps drawn for the main criteria and their sub-criteria are given in Appendix D.

Table 4.11 : Final weights of evaluation criteria calculated by AHP method.

	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight
Main criteria	Economic measures	0.150	Performance measure	0.118	Physical measures	0.102	Safety measures	0.448	Environmental measures	0.184
	Purchasing cost	0.032	Motor power	0.022	Capacity	0.058	ABS	0.139	CO emission	0.038
	Taxing	0.013	Range	0.022	Vehicle weight	0.017	AEBS	0.131	CO ₂ emission	0.028
Sub-criteria	Maintenance cost	0.024	Climbing ability	0.018	Turning radius	0.027	FCWS	0.073	NO _x emission	0.036
	Fuel cost	0.043	Torque	0.017			LDWS	0.051	HC emission	0.036
	Secondary market	0.017	Energy efficiency	0.039			SMAWS	0.054	PM emission	0.045
	Vehicle life	0.021								

Table 4.12 : Final weights of evaluation criteria calculated by DEMATEL method.

	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight
Main criteria	Economic measures	0.198	Performance measure	0.215	Physical measures	0.238	Safety measures	0.160	Environmental measures	0.189
	Purchasing cost	0.028	Motor power	0.040	Capacity	0.071	ABS	0.028	CO emission	0.036
	Taxing	0.040	Range	0.042	Vehicle weight	0.088	AEBS	0.028	CO ₂ emission	0.043
Sub-criteria	Maintenance cost	0.031	Climbing ability	0.046	Turning radius	0.079	FCWS	0.031	NO _x emission	0.036
	Fuel cost	0.031	Torque	0.047			LDWS	0.051	HC emission	0.036
	Secondary market	0.037	Energy efficiency	0.039			SMAWS	0.054	PM emission	0.045
	Vehicle life	0.032								

The final decision on the vehicle selection problem is made based on the comparison of results obtained from two different hybrid frameworks, including AHP-TOPSIS and DEMATEL-MULTIMOORA methods. Decision tables are filled by experts based on the 1-9 scale in the AHP method. Following the calculation steps of the method, whose tables are provided in Appendix A, the weights of the evaluation criteria are obtained. Then, the decision table including evaluation criteria, criteria direction –whether they are maximized or minimized-, criteria weights, alternatives, and both positive and negative ideal solutions for alternatives are constructed for the TOPSIS method. The solution tables consisting of the ranking of alternatives are given as Table 4.13 and Table 4.14 for the TOPSIS and MULTIMOORA methods, respectively. In the tables, ICEVs, EVs, and HEVs are represented by A, B, and C, respectively.

Table 4.13 : Ranking of alternatives with TOPSIS method.

Alternatives	Vehicle type	S_i^*	S_i^-	C_i	Ranking
A1	ICEV	0.045	0.075	0.624	1
A2	ICEV	0.047	0.074	0.611	2
A3	ICEV	0.048	0.073	0.604	3
A4	ICEV	0.087	0.029	0.250	12
B1	EV	0.064	0.066	0.510	4
B2	EV	0.076	0.051	0.400	11
B3	EV	0.076	0.053	0.411	9
B4	EV	0.075	0.054	0.418	8
C1	HEV	0.063	0.060	0.491	6
C2	HEV	0.062	0.062	0.499	5
C3	HEV	0.075	0.051	0.405	10
C4	HEV	0.065	0.060	0.483	7

Table 4.14 : Ranking of alternatives with MULTIMOORA method.

Alternatives	Vehicle type	Ratio System	Reference Point Approach	Full Multiplicative Form	FINAL
A1	ICEV	3	2	6	4
A2	ICEV	4	1	5	5
A3	ICEV	2	1	7	3
A4	ICEV	9	2	12	9
B1	EV	1	2	1	1
B2	EV	6	2	3	4
B3	EV	5	2	2	2
B4	EV	7	2	4	6
C1	HEV	11	4	10	10
C2	HEV	8	2	8	7
C3	HEV	12	2	11	11
C4	HEV	10	3	9	8

4.4.1.3 Sensitivity analysis

A sensitivity analysis is carried out in this sub-section by changing the evaluation criteria weights to determine the influences of experts' individual judgments on the ranking of selected alternatives obtained by the proposed hybrid framework. Sensitivity analysis is performed for two different methods using four different scenarios in total. The first scenario includes that each sub-criterion belonging to a main criterion has the same weight. There are five main criteria in total and each main criterion contains different numbers of sub-criteria. The priority calculation for the first case can be performed using the formula given by Equation (4.9):

$$\text{criterion weight} = \frac{\frac{1}{n}}{m} \quad (4.9)$$

where, n represents the number of main criteria, and m represents the number of sub-criteria under each main criterion.

The second scenario is determined such that each sub-criterion has the same weight. There are twenty-four sub-criteria in total. Thus, the priority calculation for the second case can be performed using the formula given Equation (4.10):

$$\text{criterion weight} = \frac{1}{m} \quad (4.10)$$

where, m represents the total number of sub-criteria.

The weight values obtained by using AHP and DEMATEL methods of the evaluation criteria are provided in Table 4.11 and 4.12, respectively. To provide a clear comparison of the weights used in the calculation, the criteria weights considered in the sensitivity analysis are presented in Appendix E.

For the first scenario, the solution tables, which are obtained by changing the criteria weights and which include the ordering of the alternatives, are given in Table 4.15 and Table 4.16 for the TOPSIS and MULTIMOORA methods, respectively.

Table 4.15 : Ranking of alternatives with TOPSIS method for the first scenario.

Alternatives	Vehicle type	S_i^*	S_i^-	C_i	Ranking
A1	ICEV	0.046	0.061	0.571	2
A2	ICEV	0.046	0.061	0.567	3
A3	ICEV	0.046	0.061	0.571	2
A4	ICEV	0.069	0.043	0.383	9
B1	EV	0.044	0.069	0.608	1
B2	EV	0.056	0.056	0.499	5
B3	EV	0.058	0.058	0.502	4
B4	EV	0.058	0.056	0.490	6
C1	HEV	0.065	0.040	0.379	10
C2	HEV	0.060	0.045	0.431	7
C3	HEV	0.072	0.034	0.319	11
C4	HEV	0.065	0.044	0.404	8

It can be concluded that the ranking of alternatives obtained by the TOPSIS method is effected by criteria weight. In the base case, in which the criteria weights are calculated using the MCDM method, the best three alternatives are ICEVs. Assuming each sub-criterion weight under main criteria are equal to each other, the ranking is slightly changed such that while the best alternative is EV, the second best and third best alternatives are ICEVs.

Table 4.16 : Ranking of alternatives with MULTIMOORA method for the first scenario.

Alternatives	Vehicle type	Ratio System	Reference Point Approach	Full Multiplicative Form	FINAL
A1	ICEV	2	1	5	3
A2	ICEV	3	1	6	6
A3	ICEV	2	1	7	4
A4	ICEV	9	1	12	11
B1	EV	1	1	1	1
B2	EV	6	1	4	7
B3	EV	4	1	2	2
B4	EV	5	1	3	5
C1	HEV	10	1	10	10
C2	HEV	7	1	8	8
C3	HEV	11	1	11	12
C4	HEV	8	1	9	9

It is shown from the solution table obtained by the MULTIMOORA method that changing criteria weight does not influence the ranking of the alternatives, especially ranking of the best four alternatives does not change in case that sub-criteria under each main criterion have the same weight.

For the second scenario, the solution tables, which are obtained by changing the criteria weights and which include the ordering of the alternatives, are given in Table 4.17 and Table 4.18 for the TOPSIS and MULTIMOORA methods, respectively.

Table 4.17 : Ranking of alternatives with TOPSIS method for the second scenario.

Alternatives	Vehicle type	S_i^*	S_i^-	C_i	Ranking
A1	ICEV	0.049	0.061	0.556	2
A2	ICEV	0.049	0.061	0.553	3
A3	ICEV	0.050	0.061	0.551	4
A4	ICEV	0.073	0.041	0.361	11
B1	EV	0.047	0.069	0.597	1
B2	EV	0.058	0.058	0.500	7
B3	EV	0.059	0.062	0.510	5
B4	EV	0.058	0.061	0.509	6
C1	HEV	0.064	0.041	0.391	10
C2	HEV	0.063	0.045	0.416	9
C3	HEV	0.076	0.030	0.281	12
C4	HEV	0.065	0.047	0.421	8

To sum up, the ranking of alternatives obtained by the TOPSIS method is affected by in case that each evaluation sub-criterion has equal weight. In the base case, in which the criteria weights are calculated using the MCDM method, the best three alternatives are ICEVs. However, in the considered case, the ranking is slightly changed such that while the best alternative is EV, other the best three alternatives are ICEVs.

Table 4.18 : Ranking of alternatives with MULTIMOORA method for the second scenario.

Alternatives	Vehicle type	Ratio System	Reference Point Approach	Full Multiplicative Form	FINAL
A1	ICEV	2	1	5	2
A2	ICEV	4	1	6	5
A3	ICEV	3	1	7	4
A4	ICEV	11	1	12	9
B1	EV	1	1	1	1
B2	EV	7	1	4	6
B3	EV	5	1	2	2
B4	EV	6	1	3	3
C1	HEV	10	1	10	8
C2	HEV	9	1	8	7
C3	HEV	12	1	11	9
C4	HEV	8	1	9	7

The solution table obtained by the MULTIMOORA method shows that changing criteria weight impacts the ranking of alternatives slightly. While the best two

alternatives are EVs and other the best two alternatives are ICEVs in the original case, the best three alternatives are determined as EVs in the second case where each evaluation sub-criterion has equal weight.

4.4.1.4 Discussions

As it can be concluded from Table 4.13 and Table 4.14, the ranking of alternatives may vary based on different evaluation and comparison methods. In the first framework including the integration of AHP and TOPSIS methods, it is determined that the most suitable three vehicles are internal combustion engine bus alternatives. The fourth most suitable vehicle is determined as the electric bus. The second framework combining DEMATEL and MULTIMOORA methods figures out that the most suitable two vehicles are electric buses and the third most suitable vehicle is the internal combustion engine vehicle.

When the sensitivity analysis is performed using different criteria weights obtained from AHP and DEMATEL method, different rankings are obtained based on the designed scenario. Firstly, the weights of the main criteria are assumed as equal. In this case, the most suitable vehicle is determined as the electric bus, and the second and third most suitable vehicles are obtained as internal combustion engine buses with the TOPSIS method. Similar results are obtained with the MULTIMOORA method for the first scenario. When it is assumed that each sub-criterion has the same weight, similar results are obtained with the TOPSIS method. However, different from the original weights and the first scenario, one of the hybrid buses is determined as the third most suitable vehicle with the MULTIMOORA method, where the most suitable vehicle is determined to be an electric vehicle.

The solution tables obtained with the proposed integrated solution framework provide consistent results with the objectives of the Istanbul Transport Master Plan, i.e., to provide sustainable transportation minimizing the ecological harm to the environment, and to create a more liveable urban environment.

Moreover, the results support the expected benefits from long-term and mid-term transport plans either completed or under the planning/construction process, in which the elimination of air pollution and environmental problems caused by heavy traffic is aimed.

As sustainable transportation aims to balance the economic and social benefits of transportation and the need to protect the environment, it can be concluded that the integrated decision-making framework proposed for the solution of the considered problem provides results in accordance with the sustainable transportation concept. To this end, although hybrid vehicles have less negative impacts on the environment compared to the internal combustion engine vehicles, the fact that they are not among the most suitable options confirms this inference.

Considering the purchasing costs and emissions costs of buses in the service fleet, three different scenarios are evaluated: i) the fleet including 100% internal combustion engine vehicles; ii) the fleet including 50% internal combustion engine vehicles and 50% electric vehicles; and, iii) the fleet including 100% internal electric vehicles. At the end of the scenario analysis, it has been concluded that the third scenario shows an improvement of approximately 20% comparing the first scenario while the second scenario shows an improvement of approximately 10% in terms of environmental and economic aspects.

4.5 Overall Discussion on Performance of Integrated Decision Making Framework

MCDM methods take an important role in the solution of many real-world problems, however, such methods may not be accepted as accurate all the time. As calculating weights of evaluation criteria depends on the individual judgments and experts' preferences in MCDM methods, the accuracy of the solution may differ significantly especially in the assessment of qualitative criteria. To eliminate this unfavorable situation, the consistency check, which calculates the consistency ratio of individual preferences, is utilized in the AHP method. Moreover, employing different MCDM methods and comparing the results obtained by these methods, more accurate and robust solutions are achieved for the decision-making problems.

The solution tables show that MCDM methods may provide different solutions for the same decision-making problem. This results due to the nature of these methods. Since MCDM methods do not provide certain solutions for decision-makers, who will make the final decision, and only guide the decision-makers in their judgments, decision-makers should make their final decisions considering both the results obtained from MCDM methods and their own experiences.

The proposed hybrid framework including four different MCDM methods in total has minor differences in the ranking of the alternatives. Similar results have been confirmed by sensitivity analysis comparing the results obtained by the proposed integrated framework. Thus, it is concluded that these differences may not have critical importance on the final ranking.





5. CONCLUSIONS AND FUTURE DIRECTIONS

The conclusions drawn dependent on the findings from the study are summarized in this section, which is separated into two: first, results obtained from the proposed hybrid framework is presented; and, then, future research objectives are explained.

5.1 Findings

The aim of the current study has been to employ an integrated MCDM framework in order to determine the most suitable vehicle for a bus fleet currently serving in a complex urban area and to provide environmentally sustainable transportation. On this purpose, twelve vehicle alternatives belonging to three different vehicle groups (ICEVs, HEVs, and EVs) are evaluated based on a total of twenty-four criteria determined under the main headings of economic, performance, physical, environmental and safety measures using the proposed hybrid decision-making framework including AHP, TOPSIS, DEMATEL, and MULTIMOORA methods.

The first hybrid framework combining AHP and TOPSIS methods provides that the most suitable three vehicles are internal combustion engine bus alternatives and the fourth is determined as the electric bus alternative. The second hybrid framework integrating DEMATEL and MULTIMOORA methods concludes that the most suitable two vehicles are electric buses and third is the internal combustion engine vehicle. In both frameworks, hybrid vehicles are not among the best three alternatives in the ranking. This may result from that; i) hybrid vehicles have higher purchasing costs than other alternatives; and, ii) economic measures the main criterion is the third important criterion in the TOPSIS method and the second important in the DEMATEL method.

In the Istanbul Transport Master Plan, a number of targets have been set so as to minimize the ecological harm to the environment and create a more liveable urban environment in order to ensure the environmental sustainability of the transportation system. Furthermore, with long-term and mid-term transport plans, which are either completed or under the design/construction process and aim to eliminate air pollution

and environmental problems caused by heavy traffic, sustainability has been tried to be accomplished.

Based on the knowledge that sustainability tries to create a balance between economic, social and environmental requirements, which are the three main components, and the goals set in transportation projects and in the Istanbul Transportation Master Plan, it can be concluded that the integrated decision-making framework proposed to the solution of the problem of determining the most suitable vehicle for the considered bus fleet gives results compatible with the sustainability targets.

Carrying a majority of passengers and goods and providing access to other modes of transport, road transport takes an important part in both the economy and society. New developments in automation and environmental principles as well as increased awareness in environmental issues have been caused to seek alternatives to enhance transportation sustainability and the quality of road operation. This thesis presents a wide range of studies on: i) involvement of environmental issues into transport-related decision making; ii) participation of experts from different study areas and road users in transport-related issues; iii) tools/approaches used in the evaluation of transport-related pollution including air, water, land, noise, etc.; iv) application of these tools transportation-based problems worldwide; and, v) development of the transportation sector in terms of environmental sustainability. The strengths of the integrated framework suggested can be listed such that it enables sustainability assessment under both qualitative and quantitative criteria, includes many experts' points of view in the process, and produces a final ranking of alternatives based on different approaches instead of only one approach. Giving the opportunity of considering many different criteria consisting of economic, performance, physical, safety, and environmental, the framework developed for the evaluation of transportation sustainability has been seen to be applicable in the decision-making process of determining the most suitable vehicle to be operated along a complex urban area.

5.2 Future Research Directions

As a future extension of the present study, it is suggested that since it allows consideration of both tangible and intangible factors in the decision-making process,

the proposed framework could also be used in processes such as transportation project evaluation and appraisal instead of Cost-Benefit Analysis, which is one of the most common methods.

Moreover, in order to deal with evaluation criteria with qualitative or unknown structure better, the proposed integrated decision-making framework could also be applied in a fuzzy environment.





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APPENDICES

APPENDIX A: Emission Models

APPENDIX B: Calculation Matrices of AHP Method

APPENDIX C: Calculation Matrices of DEMATEL Method

APPENDIX D: Influential-Relation Maps of Evaluation Criteria Obtained from DEMATEL Method

APPENDIX E: Criteria Weights Considered in the Sensitivity Analysis

APPENDIX A

Comprehensive Modal Emissions Model (CMEM)

CMEM is an emission model developed with a project which was started by University California, University of Michigan, and Lawrence Berkeley National Laboratory in 1995 and completed in four years. The model has been developed in order to obtain reliable emission data of light-duty vehicles and to create a function depending on the vehicle driving style (acceleration, deceleration, idling) (Boulter et al., 2007). Three elements including time-dependent catalyst pass fraction, engine emission indices, and fuel rate are used in order to model the tailpipe emissions (Scora ve Barth, 2006). The emission values of HC, CO, CO₂, and NO_x can be calculated using CMEM.

Computer Programme to Calculate Emissions from Road Transport (COPERT)

COPERT, a computer program developed on behalf of the EEA, is an updated version of the CORINAIR 1985 emission inventory (Eggleston et al., 1993). The model is used to calculate emission values of many air pollutants (CO, NO_x, VOC, PM, CO₂, CH₄, N₂O, NH₃, SO₂, heavy metals, PAH and POP) emitted by different vehicle types (cars, light-duty vehicles, heavy-duty vehicles, buses, mopeds, and motorcycles). In the COPERT model, emission calculations are carried out in two different ways (Ntziachristos ve Samaras, 2000):

Calculation based on emission types: Total emissions are calculated as the sum of emissions emitted from three different sources, including hot engine, cold-start, and evaporation emissions.

Calculation based on different driving conditions: Total emissions are calculated as the sum of three different situations, including emissions from rural, urban, and highway driving.

APPENDIX B

Table B.1 : Final pairwise comparison matrix of main criteria.

	Economic measures	Performance measures	Physical measures	Safety measures	Environmental measures
Economic measures	1.00	1.48	1.33	0.33	0.77
Performance measures	0.68	1.00	1.34	0.27	0.62
Physical measures	0.75	0.74	1.00	0.22	0.59
Safety measures	2.99	3.71	4.50	1.00	2.47
Environmental measures	1.29	1.62	1.70	0.40	1.00
SUM	6.71	8.56	9.87	2.23	5.45

Table B.2 : Normalization matrix of main criteria.

	Economic measures	Performance measures	Physical measures	Safety measures	Environmental measures
Economic measures	0.149	0.173	0.135	0.150	0.142
Performance measures	0.101	0.117	0.136	0.121	0.113
Physical measures	0.112	0.087	0.101	0.100	0.108
Safety measures	0.445	0.434	0.456	0.448	0.453
Environmental measures	0.192	0.189	0.172	0.181	0.183

Table B.3 : Priority calculation matrix of main criteria.

	Economic measures	Performance measures	Physical measures	Safety measures	Environmental measures	PRIORITIES
Economic measures	0.149	0.173	0.135	0.150	0.142	0.150
Performance measures	0.101	0.117	0.136	0.121	0.113	0.118
Physical measures	0.112	0.087	0.101	0.100	0.108	0.102
Safety measures	0.445	0.434	0.456	0.448	0.453	0.448
Environmental measures	0.192	0.189	0.172	0.181	0.183	0.184

Table B.4 : Weighted sum calculation matrix of main criteria (Vector product of original judgments with criteria weights).

Original judgments					Priorities	Weighted sum
1.00	1.48	1.33	0.33	0.77	0.150	0.750
0.68	1.00	1.34	0.27	0.62	0.118	0.589
0.75	0.74	1.00	0.22	0.59	0.102	0.510
2.99	3.71	4.50	1.00	2.47	0.448	2.243
1.29	1.62	1.70	0.40	1.00	0.184	0.921

Table B.5 : Consistency calculation matrix of main criteria.

Weighted Sum	Priorities	W. Sum/Priorities	Consistency	
0.750	0.150	5.013	N	5
0.589	0.118	5.013	R.I.	1.12
0.510	0.102	5.013	C.I.	0.003
2.243	0.448	5.013	C.R.	0.003
0.921	0.184	5.013	CONSISTENT	
SUM		25.06		
$\lambda_{\max}$		5.01		

APPENDIX C

Table C.1 : Final pairwise comparison matrix of main criteria.

	Economic measures	Performance measures	Physical measures	Safety measures	Environmental measures	SUM
Economic measures	0.00	4.00	3.60	0.91	2.10	10.60
Performance measures	2.02	0.00	4.00	0.80	1.84	8.66
Physical measures	4.00	3.95	0.00	1.18	3.13	12.27
Safety measures	2.66	3.30	4.00	0.00	2.20	12.16
Environmental measures	3.05	3.82	4.00	0.95	0.00	11.82
SUM	11.72	15.07	15.60	3.84	9.26	15.60

Table C.2 : Normalized direct-influence matrix (C) of main criteria.

	Economic measures	Performance measures	Physical measures	Safety measures	Environmental measures
Economic measures	0.00	0.26	0.23	0.06	0.13
Performance measures	0.13	0.00	0.26	0.05	0.12
Physical measures	0.26	0.25	0.00	0.08	0.20
Safety measures	0.17	0.21	0.26	0.00	0.14
Environmental measures	0.20	0.24	0.26	0.06	0.00

Table C.3 : Difference of normalization matrix and identity matrix for main criteria (I-C).

	Economic measures	Performance measures	Physical measures	Safety measures	Environmental measures
Economic measures	1.00	-0.26	-0.23	-0.06	-0.13
Performance measures	-0.13	1.00	-0.26	-0.05	-0.12
Physical measures	-0.26	-0.25	1.00	-0.08	-0.20
Safety measures	-0.17	-0.21	-0.26	1.00	-0.14
Environmental measures	-0.20	-0.24	-0.26	-0.06	1.00

Table C.4 : Inverse matrix of difference matrix $(I-C)^{-1}$.

	Economic measures	Performance measures	Physical measures	Safety measures	Environmental measures
Economic measures	1.36	0.65	0.63	0.19	0.41
Performance measures	0.43	1.38	0.59	0.16	0.36
Physical measures	0.61	0.71	1.51	0.22	0.50
Safety measures	0.56	0.68	0.72	1.15	0.46
Environmental measures	0.56	0.69	0.70	0.20	1.32

Table C.5 : Total influence matrix of main criteria (Vector product of normalized matrix (C) with inverse matrix $(I-C)^{-1}$).

	Economic measures	Performance measures	Physical measures	Safety measures	Environmental measures	Di
Economic measures	0.36	0.65	0.63	0.19	0.41	2.24
Performance measures	0.43	0.38	0.59	0.16	0.36	1.92
Physical measures	0.61	0.71	0.51	0.22	0.50	2.54
Safety measures	0.56	0.68	0.72	0.15	0.46	2.57
Environmental measures	0.56	0.69	0.70	0.20	0.32	2.47
Ri	2.52	3.10	3.14	0.92	2.06	

Table C.6 : Priority calculation matrix of main criteria.

Criteria	Di+Ri (Prominence)	Di-Ri (Relationship)	$\frac{(Di+Ri)^2 + (Di-Ri)^2}{2}$	Weights
Economic measures	4.75	-0.28	4.76	0.198
Performance measures	5.02	-1.19	5.16	0.215
Physical measures	5.68	-0.60	5.71	0.238
Safety measures	3.48	1.65	3.85	0.160
Environmental measures	4.53	0.41	4.55	0.189
TOTAL			24.03	

APPENDIX D

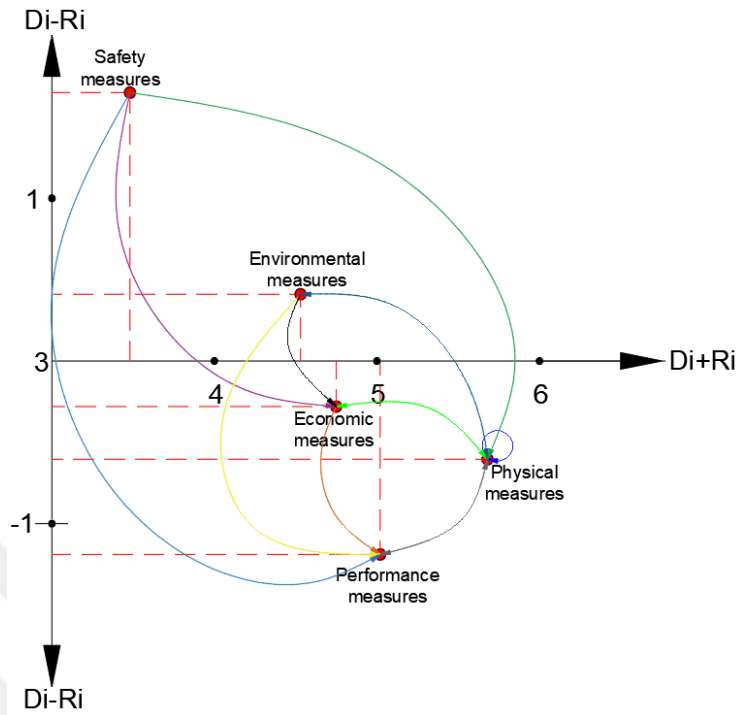


Figure D.1 : Influential-relation map of main criteria.

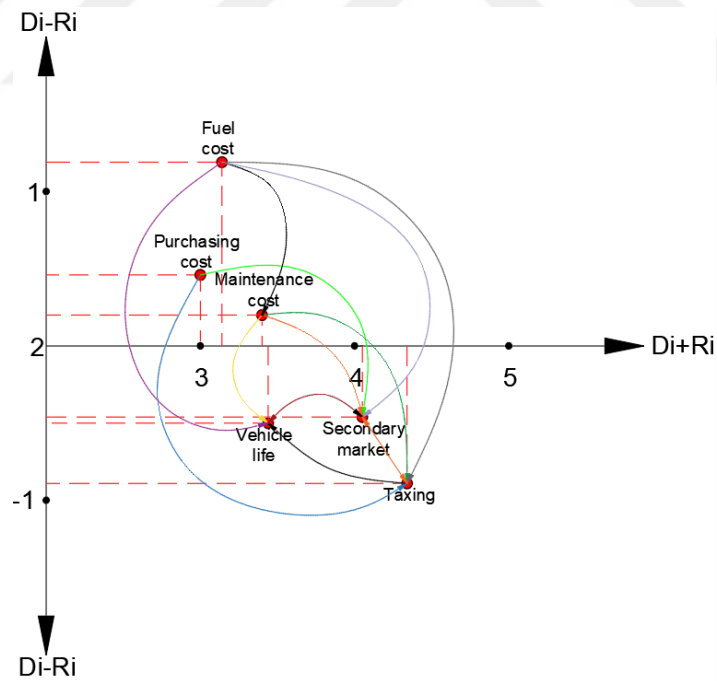


Figure D.2 : Influential-relation map of sub-criteria of economic measures main criterion.

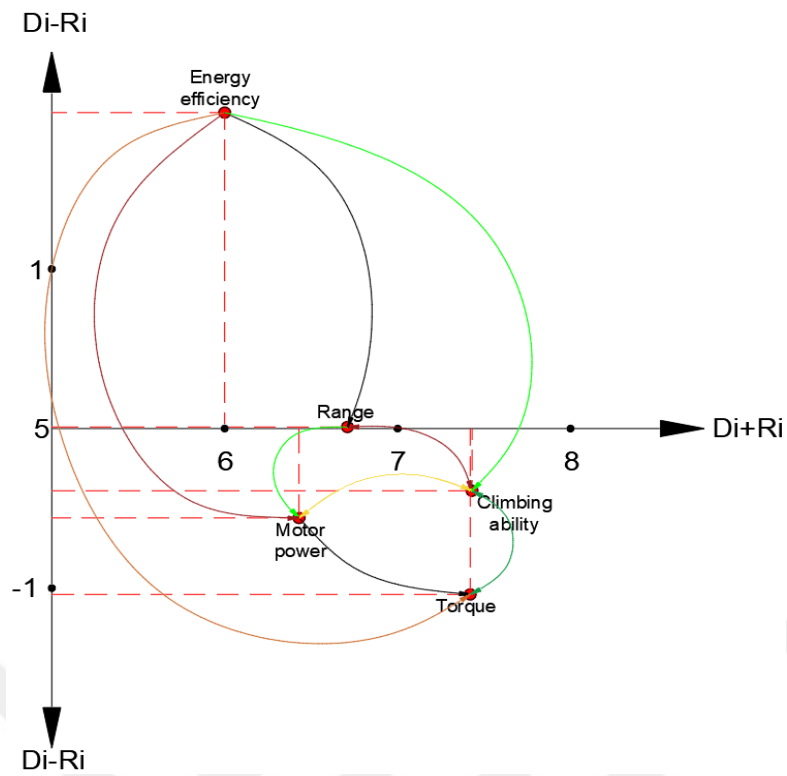


Figure D.3 : Influential-relation map of sub-criteria of performance measures main criterion.

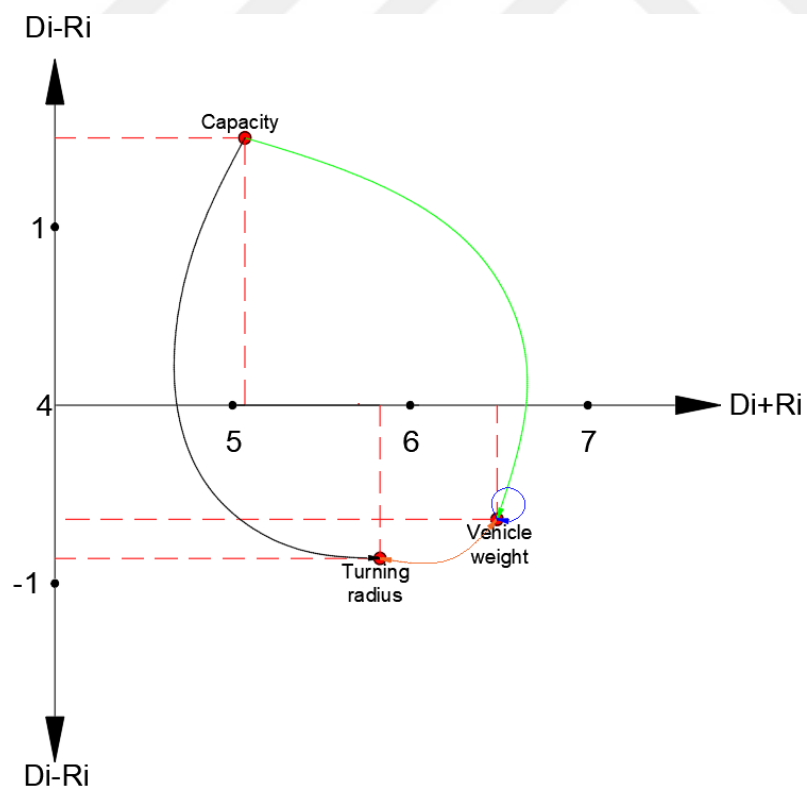


Figure D.4 : Influential-relation map of sub-criteria of physical measures main criterion.

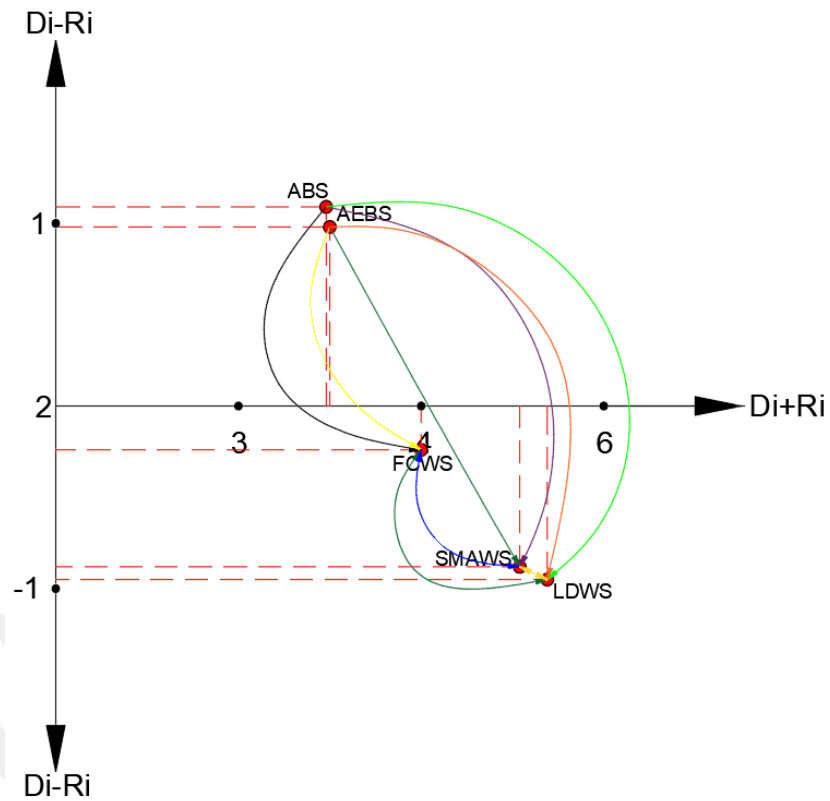


Figure D.5 : Influential-relation map of sub-criteria of safety measures main criterion.

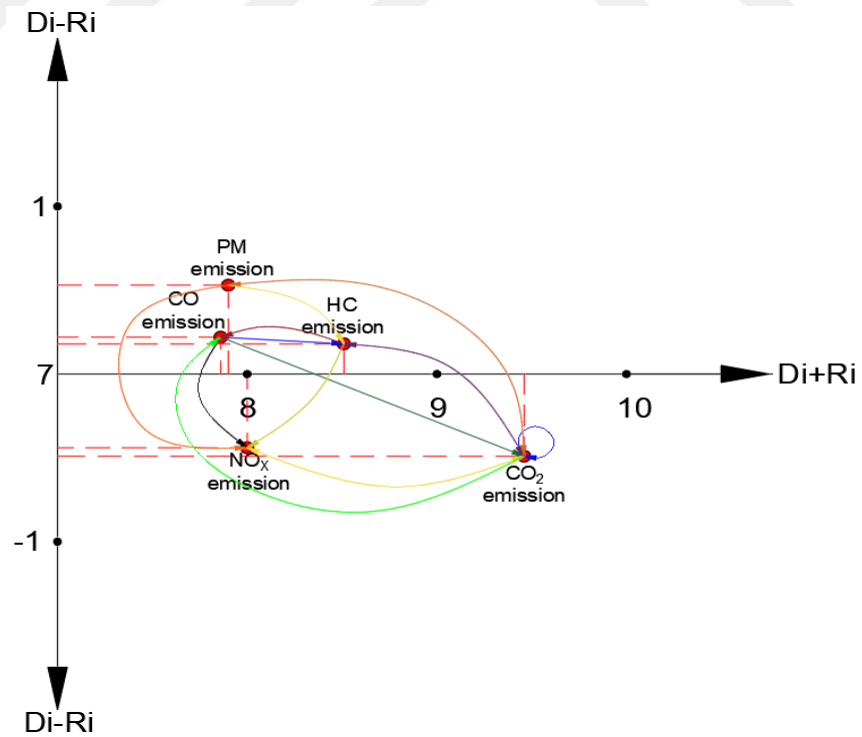


Figure D.6 : Influential-relation map of sub-criteria of environmental measures main criterion.

APPENDIX E

Table E.1 : Weights of evaluation criteria considered in the sensitivity analysis (first scenario - TOPSIS and MULTIMOORA methods).

	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight
Main criteria	Economic measures	0.198	Performance measure	0.200	Physical measures	0.201	Safety measures	0.200	Environmental measures	0.200
	Purchasing cost	0.033	Motor power	0.040	Capacity	0.067	ABS	0.040	CO emission	0.040
Sub-criteria	Taxing	0.033	Range	0.040	Vehicle weight	0.067	AEBS	0.040	CO ₂ emission	0.040
	Maintenance cost	0.033	Climbing ability	0.040	Turning radius	0.067	FCWS	0.040	NO _x emission	0.040
	Fuel cost	0.033	Torque	0.040			LDWS	0.040	HC emission	0.040
	Secondary market	0.033	Energy efficiency	0.040			SMAWS	0.040	PM emission	0.040
	Vehicle life	0.033								

Table E.2 : Weights of evaluation criteria considered in the sensitivity analysis (second scenario - TOPSIS and MULTIMOORA methods).

	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight	Criterion name	Criterion weight
Main criteria	Economic measures	0.250	Performance measure	0.210	Physical measures	0.126	Safety measures	0.210	Environmental measures	0.210
	Purchasing cost	0.042	Motor power	0.042	Capacity	0.042	ABS	0.042	CO emission	0.042
	Taxing	0.042	Range	0.042	Vehicle weight	0.042	AEBS	0.042	CO ₂ emission	0.042
Sub-criteria	Maintenance cost	0.042	Climbing ability	0.042	Turning radius	0.042	FCWS	0.042	NO _x emission	0.042
	Fuel cost	0.042	Torque	0.042			LDWS	0.042	HC emission	0.042
	Secondary market	0.042	Energy efficiency	0.042			SMAWS	0.042	PM emission	0.042
	Vehicle life	0.042								



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Akti, S. & Celikoglu, H.B. (2020). An Integrated Decision-Making Framework for Shuttle Bus Selection Using DEMATEL and MULTIMOORA Methods. In Moreno-Díaz et al. (Eds.): *EUROCAST 2019* (LNCS 12014, pp. 1-9). Springer Nature Switzerland AG 2020. (doi: 10.1007/978-3-030-45096-0_20).