

A Methodological Concept for Supporting the
Commercialization of Electric Vehicles towards Sustainable
Urban Freight Transport

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Abstract

Employment of Electric Commercial Vehicles (ECVs) constitutes a measure to achieve sustainable Urban Freight Transport (UFT). Despite a need for ECVs, the commercialization of ECVs in UFT has remained relatively low, which is reflected in the low market penetration. To increase the market penetration, much attention has been paid to four areas, which are the feasibility of ECVs, adaptations of logistics concepts, adaptations of vehicle concepts, and support of stakeholders. Besides studying these four areas, obtaining a satisfactory match between characteristics of ECVs and preferences of UFT is also an area for increasing the market penetration. However, due to the shortage of academic studies and appropriate tools that can systematically guide decision-makers in UFT to obtain a satisfactory match, little attention has been paid to this area.

The present dissertation proposed a methodological concept, namely Sustainable ECV-UFT Matching Concept, to deal with the outlined problem. This concept comprises two methodologies (methodology of assessment and methodology of determination). Since matching up the ECVs and UFT generates many possibilities (denoted as ECV-UFT combinations), the methodology of assessment was developed to help decision-makers to assess the diverse ECV-UFT combinations quantitatively in the economic, social, and environmental perspective. Subsequently, the methodology of determination was developed to analyze the assessment results and support decision-makers in determining the satisfactory match from the many possibilities. In addition, this dissertation implemented this methodological concept by designing a simulation platform, which includes an available database and corresponding mathematical expressions.

Three scenarios (DCV-, BEV-, and HEV-Express/post) were applied in the simulation platform to analyze the proposed methodological concept. The results confirmed that the Sustainable ECV-UFT Matching Concept is feasible in supporting decision-makers to determine the satisfactory match from the many ECV-UFT combinations. The benefits of obtaining a satisfactory match may inspire corresponding decision-makers to consider the employment of the appropriate ECVs in their UFT markets. This consideration may subsequently facilitate the market penetration of ECVs to achieve sustainable UFT. Overall, the main contribution of this dissertation is the development of a methodological concept to support the commercialization of ECVs for achieving sustainable UFT.

Zusammenfassung

Neben dem Einsatz im Bereich eines nachhaltigen Personennahverkehrs, werden elektrische Antriebsformen zukünftig auch für Nutzfahrzeuge (ECV – Electric Commercial Vehicle) einen wesentlichen Beitrag bei der Konzipierung und Realisierung eines nachhaltigen urbanen Gütertransports (UFT – Urban Freight Transport) leisten. Obwohl es heute bereits eine Vielzahl unterschiedlicher Ausprägungsformen sowohl im Bereich der Antriebe als auch bei den entsprechenden Fahrzeugen gibt, ist die Marktdurchdringung der Elektromobilität im innerstädtischen Güterverkehr noch sehr gering. Ziel der Arbeit ist die systematische Unterstützung der Entwicklung angemessener Konzepte für einen nachhaltigen innerstädtischen Gütertransport unter konsequenter Berücksichtigung des Potentials elektrisch angetriebener Nutzfahrzeuge. Hierbei werden Aspekte wie das Einsatzpotential elektrisch getriebener Fahrzeuge, die Anpassbarkeit von Logistikkonzepten, die Anpassbarkeit der Fahrzeugkonzepte und die Interessenlage der verschiedenen Stakeholder gleichermaßen betrachtet. Ein wesentlicher Beitrag der Arbeit liegt in dem systematischen Abgleich der Eigenschaften der Antriebskonzepte elektrisch betriebener Nutzfahrzeuge mit den bestehenden Anforderungen und Merkmalen innerstädtischer Güterverkehrskonzepte. Entsprechende Analysen und Vergleiche, die Entscheidungsträger im Bereich der Gestaltung nachhaltiger, innerstädtischer Güterverkehrskonzepte unterstützen, liegen bisher nicht vor.

Die vorliegende Dissertation entwickelt mit dem „Sustainable ECV-UFT Matching Concept“ einen Lösungsansatz, welcher auf eine Bewertungs- und eine Bestimmungsmethodik aufbaut. Da der Abgleich von ECVs und UFT viele Kombinationsmöglichkeiten aufweist, welche im Weiteren als ECV-UFT-Kombinationen bezeichnet werden, wird eine Bewertungsmethodik entwickelt. Diese hilft Entscheidungsträgern, die verschiedenen ECV-UFT-Kombinationen quantitativ in wirtschaftlicher, sozialer und ökologischer Perspektive zu bewerten. Ergänzend wurde eine Bestimmungsmethodik entwickelt, welche die Bewertungsergebnisse analysiert und Entscheidungsträger bei der Ermittlung einer passgenauen Kombination unterstützt. Darüber hinaus wurde eine Simulationsplattform entwickelt, die einen vorhandenen Datensatz und entsprechende mathematische Ausdrücke enthält, um das vorgeschlagene Konzept umzusetzen.

Die Anwendbarkeit des vorgeschlagenen Lösungsansatzes wurde an drei Teilszenarien simuliert. Die Ergebnisse bestätigen, dass das vorgeschlagene „Sustainable ECV-UFT Matching Concept“ Entscheidungsträgern bei der Identifikation und Auswahl fallspezifisch geeigneter ECV-UFT-Kombinationen unterstützen kann. Das vorgeschlagene Konzept leistet damit einen Beitrag für eine nachhaltigere Gestaltung zukünftiger Lösungsansätze im Bereich des innerstädtischen Güterverkehrs.

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1 Introduction

Electric Vehicles (EVs) is a well-known topic widely discussed in recent years. The attention on this topic primarily arises from the challenges of Internal Combustion Engine (ICE) vehicles. The ICE vehicles, which are designed to ignite fossil fuels to propel wheels, are the common means of transport. Since the fossil fuel is non-renewable energy and the exhaust gases of burning fossil fuels pollute the environment of the daily life, the EVs, which are partly or entirely powered by electric energy, are considered as an alternative to the ICE vehicles.

The development of EVs experienced the invention, the disappearance, and the reappearance. In 1828, the small-scale model car powered by an electric motor was invented (Chan, 2013). In the middle of the 19th century, the EVs became popular on the basis of their clean, quiet, as well as easy to start and drive. However, this popularity of EVs has switched to ICE vehicles since 1930. The main reasons for the disappearance include the demand for longer range vehicles, the reduction of gasoline price, the invention of the electric starter for ICE vehicles, the mass production of the ICE vehicles, and the increased number of gas stations (Chan, 2013). In the early 1970s, the EVs reappeared on account of the non-renewable fossil fuels. Additionally, since the attention is increasingly paid on the environmental protection and the concept of the sustainable development was proposed in 1987 (WCED, 1987), the EVs as a solution to address the outlined challenges have reappeared and become a widely discussed topic.

The studies of EVs commonly focus on passenger cars. These studies explored many areas of focus to solve the limitations of employing EVs for reducing the environmental pollution and the consumption of fossil fuels. These limitations mainly refer to the high purchase price, the long charging time, the limited driving range, and the insufficient charging stations (Chan, Bouscayrol, & Chen, 2010). Many areas of focus, such as battery systems (Lu, Han, Li, Hua, & Ouyang, 2013), fast charging (Anseán et al., 2016), arrangement of charging stations (Namdeo, Tiwary, & Dziurla, 2014), and customer preferences (Oliveira, Dias, & Santos, 2015; Ziegler, 2012), were considered in solving the limitations. However, in these studies, the electrification of commercial vehicles for addressing the environmental challenges of Urban Freight Transport (UFT) seems ignored.

Inconsistent with the passenger cars, commercial vehicles are one category of motor vehicles with at least four wheels designed and constructed for the carriage of goods (The European Parliament and of the Council, 2007). The role of driving commercial vehicles is to deliver goods for satisfying citizens and supporting the operations of logistic companies, whereas the drivers of passenger cars pursue convenient commute and the driving pleasure. To this effect, research on Electric Commercial Vehicles (ECVs) cannot be missing. In particular, these studies are

required to focus on not only same areas as electric passenger cars, such as the driving range, the charging time, the charging stations, and the purchase price, but also the other exclusive areas of ECVs, such as the payload capacity, the travel time, the travel distance, the profit, and the attitude of fleet managers. Given these points, the studies of ECVs in UFT is indispensable.

1.1 Motivation

Urban freight transport is a segment of freight transport. In this segment, road freight transport is the primary mode. The commercial vehicles constitute the means of UFT to deliver goods on the road. The goal of UFT is mainly to satisfy the needs of citizens. In recent years, this demand for necessities and services from commercial and domestic users in urban areas is increasing spurred by the rapid urbanization (Cui, Dodson, & Hall, 2015). To fulfill the demand, the UFT plays an increasingly significant role.

This significant role leads to challenges in UFT. Among these challenges, much attention is paid to environmental challenges, which arise from the ICE commercial vehicles. Saving energy and reducing Greenhouse Gas (GHG) emissions essentially constitute the environmental challenges of UFT. According to statistics in EU-28, road transport consumed 82.6% of the total energy consumption of transport (road, rail, domestic navigation, domestic aviation, and international aviation) in 2013. Similarly, road transport accounted for 94.4% of the total GHG emissions from transport in 2012 (Eurostat, 2015). These statistics indicate that road transport dominates the amount of energy consumption and GHG emissions. In addressing these environmental challenges to achieve sustainable UFT, the European Commission (European Commission, 2011) recommends developing and deploying new and sustainable fuels as well as propulsion systems for road transport.

Electric commercial vehicles constitute one category of vehicles recommended to address the outlined challenges towards sustainable UFT. As the one category, the ECVs are partly or entirely independent of fossil fuels and involves electric propulsion, such as electric motors and power converters (Chan, 2002; Chan et al., 2010). In terms of these features, the ECVs commonly consist of four types including Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs) (Chan et al., 2010). Besides classifying the ECVs, the features also contribute to decreasing noises, GHG emissions, and the amount of energy consumption.

In the perspective of commercial use, the ECVs appear suitable in the UFT due to conducive application environments. The UFT provides suitable conditions to employ the ECVs on account of the high use rates of fleet vehicles; route

predictability, as well as; the low commercial and industrial electricity rates (Lebeau, Macharis, & Mierlo, 2016; Pelletier, Jabali, & Laporte, 2016). Given these points, the environmental benefits resulting from ECVs and suitable prevailing conditions in UFT encourage stakeholders of the UFT to consider employing the ECVs.

Furthermore, some policies support the employment of ECVs in UFT. For example, the financial incentives, such as subsidies for the purchase price and setup of charging infrastructures as well as tax exemptions, stimulate the possibility to purchase and employ ECVs in UFT (Pelletier et al., 2016). Additionally, there are non-financial incentives offered to users of the ECVs in exclusion of other vehicles. The incentives such as preferential parking, initiating repair centers, permission to drive on high occupancy or bus lanes, and privileges to accessing to low emission zones in city centers, also facilitate the employment of ECVs in UFT (Pelletier, Jabali, et al., 2016; Taefi, Kreutzfeldt, Held, & Fink, 2016).

Despite the notable environmental benefits and supporting policies, yet the commercialization of ECVs for addressing the environmental challenges in UFT is relatively low. This low commercialization is reflected in the low market penetration of ECVs in UFT. According to the report of ICCT (International Council on Clean Transportation, 2017), in Europe, the light electric commercial vehicles (gross vehicle weight < 3.5t) including the BEVs, HEVs, and PHEVs, accounted for 0.7% of total sales of light commercial vehicles in 2016. In a similar manner, Navigant Research (Alexander & Jerram, 2017) forecasted that the market share of diesel medium – and heavy – duty trucks (gross vehicle weight $\geq 3.5t$) will remain the dominant in next decade. To this end, the outlined progresses imply that there is a low market penetration of ECVs, especially in the UFT. However, to address the environmental challenges, the commercialization of ECVs by increasing the market penetration is a potential solution to be considered. In this context, the conflict between a demand of commercialization and the low market penetration calls up for a need to address this problem.

1.2 Problem Statement

Much literature has studied the low market penetration. For example, works in (Pelletier, Jabali, et al., 2016; Sierzchula, 2014; Taefi, Kreutzfeldt, et al., 2015) have applied the survey and case study methods to explore and analyze factors related to cost, technology, infrastructures, sources of electricity, and incentives to increase an understanding of the problem. Other similar studies, which focus on reducing impacts resulting from the explored factors have also been carried out. For instance, the literature (Conrad & Figliozzi, 2011; Goeke & Schneider, 2015; Hiermann, Puchinger, Ropke, & Hartl, 2016; Schneider et al., 2014; Sevgi Erdog˘an, Miller-hooks, 2012) has proposed and formulated the Electric Vehicle

Routing Problem (EVRP) to minimize impacts concerning the limited driving range and charging infrastructures. Equally, to improve the battery systems in the ECVs, the literature (Kelouwani, Agbossou, Dubé, & Boulon, 2013; Lu et al., 2013) has addressed management of energy in batteries. Moreover, propositions on how to reduce impacts resulting from a need for fast charging (Anseán et al., 2016); retail infrastructure costs (Melaina, Sun, & Bush, 2014), and; spatial planning of public charging infrastructures (Namdeo et al., 2014) have been considered as well. On the whole, to increase the market penetration of ECVs in UFT, the existing works have studied the factors causing the low market penetration including the identification of factors and reducing the impacts of factors.

On top of the EVRP, battery systems, and charging infrastructures issues, the feasibility to employ the ECVs in UFT has been evaluated in different ways. It has been evaluated through modeling and simulation (Davis & Figliozzi, 2013; Feng & Figliozzi, 2013; Macharis, Van Mierlo, & Van Den Bossche, 2007) as well as tested by trials (Browne, Allen, & Leonardi, 2011; Melo, Baptista, & Costa, 2014). Similarly, the demonstrative projects such as the EU project FREVUE (“FREVIEW Objectives,” 2018) and the national project MELODYS (ALICE / ERTRAC Urban mobility WG, 2014) also have conducted the related evaluation. In the overall, studies on low market penetration are increasingly attracting attention and gradually making progress. In speeding up this progress, there is also a critical need to obtain a satisfactory match between product (ECVs) characteristics and customer (UFT) preferences (Oliveira et al., 2015).

This critical need regarding the satisfactory match has been considered in urban passenger transport systems (Camargo Pérez, Carrillo, & Montoya-Torres, 2015). The product in this satisfactory match refers to electric passenger cars or electric buses in urban passenger transport systems. The customer refers to individuals or bus operations. In this context, the product characteristics are commonly determined by the characteristics of each vehicle types. The customer preferences are reflected in the requirements, the interests, and the hobbies of individuals or bus operations. Accordingly, studies addressing the satisfactory match in urban passenger transport systems have focused on selecting suitable vehicle types in terms of the characteristics and increasing the understanding of customer preferences. For instance, Zubaryeva et al. (2012) and Mohamadabadi et al. (2009) have addressed issues regarding the suitable choice of electric passenger cars. Tzeng et al. (2005) and Vahdani et al. (2011) have concentrated on investigating the proper choice of electric buses. Oliveria et al. (2015) and Ziegler (2012) have conducted studies on customer preferences for electric passenger cars.

Compared to the literature on the choice of vehicles and customer preferences in urban passenger transport systems, few studies are addressing the same topic in the UFT systems. To obtain the satisfactory match in UFT, the product accordingly

refers to the ECVs and the customer mainly refers to the freight carriers in UFT. Similar to the urban passenger transport systems, the product characteristics are determined by the characteristics of each vehicle type. The customer preferences are presented in the requirements of freight carriers. Due to gaining insights into the ECVs (Section 2.3), there are four types of ECVs in terms of the differences concerning the configurations, propulsion systems, and energy storages (Chan et al., 2010). Additionally, the freight carriers have respective requirements depending on their various delivery tasks (Section 2.1). Five primary delivery tasks constitute five UFT markets (Abel & Karrer, 2005; CIVITAS, 2015; MDS Transmodal Limited, 2012). To this effect, matching up the four types of ECVs and the five UFT markets presents many possibilities. These possibilities reveal diversity in the employment of ECVs in UFT (Section 2.4). This diversity is denoted as ECV-UFT combinations in this dissertation.

Such diversity has been overlooked by the majority of the literature. In other words, there are few possibilities (ECV-UFT combinations) studied in the literature (Section 3.3). These few possibilities accordingly restrict the range of available ECV-UFT combinations for obtaining a satisfactory match. Moreover, the few possibilities studied in the literature limits the understanding concerning the employment of ECVs in UFT, namely lacking a comprehensive view of all possibilities. In this perspective, this limitation leads to a difficulty to thoroughly compare and assess different possibilities for determining the satisfactory match. Besides, the existing studies on the choice of ECVs and the identification of freight carriers' preferences have only completed a part of the task concerning the satisfactory match. For instance, Wątróbski et al. (2017) propose a multi-criteria analysis-based approach to select proper vehicle types of available BEVs for UFT. Lebeau et al. (2016) explore the battery electric vehicle choice behavior of transport companies. Although the articles studied the proper choice of ECVs and the identification of requirements in UFT, the studies to match up the ECVs and the UFT is missing.

Furthermore, no existing tools matched up the ECVs and the UFT by taking into account all possibilities along with the goal of obtaining a satisfactory match. The existing tools can be divided into vehicle-oriented (Burnham, 2016; Markel et al., 2002; TA Engineering, 2014) and logistics-oriented tools (ifeu Heidelberg, INFRAS Berne, & IVE Hannover, 2016; Institut für Transportlogistik TU Dortmund, 2018; Schmied, Knörr, Friedl, & Hepburn, 2012) according to their purposes. These two orientations reveal that there is no connection between the automotive and logistical parameters in the existing tools. On top of this, the criteria to determine the results in the existing tools are mainly economic and environmental criteria. Since the role of the satisfactory match is to facilitate the market penetration for ultimately achieving the sustainable UFT, the criteria to determine the satisfactory match are required to involve the three dimensions (economic, social, and environmental) of sustainability (Kates, Parris, &

Leiserowitz, 2005). The social criterion is missing in the existing tools. Given these points, in the context of lacking similar academic studies and appropriate tools, there is a need for a study, which may propose a systematic approach to guide decision-makers in UFT for assessing and determining the satisfactory match by taking into account the aforementioned missing elements.

On the whole, the problem statement of this dissertation phrases as follows: A methodological concept is required for obtaining the satisfactory match between the characteristics of ECVs and the preferences of UFT to increase the market penetration of ECVs towards sustainable UFT. Such a methodological concept has to consider the diversity in the employment of ECVs in UFT, the quantitative connection between ECVs and UFT, and the all three dimensions of sustainability to assess the diverse possibilities (ECV-UFT combinations) for supporting the determination of the satisfactory match.

1.3 Research Goal and Research Question

The research goal of this dissertation is to develop a methodological concept that supports decision-makers in UFT to facilitate the commercialization of ECVs for achieving sustainable UFT. In particular, this methodological concept helps decision-makers to: quantitatively assess diverse ECV-UFT combinations in economic, social, and environmental perspectives, as well as determine the satisfactory match by analyzing the assessed ECV-UFT combinations.

To accomplish the research goal, this dissertation mainly answers the following research question:

How can decision-makers obtain a satisfactory match to increase the market penetration of ECVs for achieving sustainable UFT?

Specifically, the answer to this research question is acquired by analyzing the following three questions step by step:

- *Q1: What are the challenges and requirements of obtaining the satisfactory match between the characteristics of ECVs and the preferences of UFT?*
- *Q2: How can decision-makers assess and determine the satisfactory match by addressing the challenges and satisfying the requirements?*
- *Q3: To what extent does the methodological concept support the decision-makers?*

According to the challenges and requirements identified in Q1, two methodologies including the *methodology of assessment* and the *methodology of determination* are proposed to constitute the methodological concept for answering the Q2. The

methodology of assessment is designed to quantify and calculate the economic, social, and environmental performance of diverse ECV-UFT combinations. The methodology of determination is designed to systematically compare and analyze the assessed ECV-UFT combinations for determining the satisfactory match. These two methodologies shape the methodological concept – *Sustainable ECV-UFT Matching Concept* in this dissertation. After developing the concept by answering the Q2, the implementation and the evaluation of this concept are conducted to answer the Q3. A simulation platform is designed to implement the two methodologies. Six alternatives in three scenarios are evaluated by applying the simulation platform to exemplify how the developed methodological concept supports the decision-makers to determine the satisfactory match and illustrate the extent of this support. In the end, the main research question can be answered by synthesizing the solutions of the three sub-questions.

1.4 Research Methodology

The research methodology for carrying out the entire dissertation is structured by:

1. Identifying the challenges of obtaining a satisfactory match (literature review) and specifying the corresponding requirements;
2. Proposing a methodological concept based on the Multi-Criteria Decision Making (MCDM) method and the approaches for supporting in analyzing and determining the satisfactory match (sensitivity analysis, ternary plot, and calculation of equivalent points);
3. Designing a simulation platform based on mathematical expressions, the Monte-Carlo method, and the 10-fold cross validation, to convert the proposed methodological concept from theoretical to practicable guidance;
4. Evaluating the proposed methodological concept in the simulation platform.

A Systematic Literature Review (SLR) is firstly conducted to increase the understanding regarding the state of the art in the field of employing ECVs in UFT. This state of the art supports to identify what areas of focus have been considered in the literature and what the challenges hinder efforts for obtaining the satisfactory match. The requirements are accordingly specified by analyzing the identified challenges.

To address the identified challenges and satisfy the specified requirements, the methodological concept is proposed to guide decision-makers to obtain their satisfactory match. In this concept, the methodology of assessment is developed based on the MCDM. Since the objectives of the three criteria (economic, social, and environmental) in the assessment are conflicting, the MCDM is then applied in this methodology to deal with decision problems under the presence of a number of

conflicting decision criteria (Triantaphyllou, Shu, Sauchez, & Ray, 1998; Wątróbski et al., 2017). Moreover, the methodology of determination is developed based on the sensitivity analysis, the ternary plot, and the calculation of equivalent points. The purpose of applying the sensitivity analysis is to reduce the number of available ECV-UFT combinations and simplify the decision of the satisfactory match. Additionally, the role of the ternary plot is to synthesize and visualize the assessed ECV-UFT combinations in a triangle. By observing the visualized ECV-UFT combinations in this triangle, decision-makers can visually compare them and quickly select the satisfactory match. In addition, the calculation of equivalent points is applied as the last step in the methodology of determination. The purpose of this step is to explore the differences between the satisfactory match selected from the ternary plot and the rest of ECV-UFT combinations assessed in the last two steps. The conclusions deduced from these equivalent points are considered as potential future research.

The simulation platform is designed to implement the proposed methodological concept. Formulation of mathematical expressions, the Monte-Carlo method, and the 10-fold cross validation are involved in this simulation platform. To quantitatively assess the ECV-UFT combinations, three mathematical expressions are formulated with respect to the three criteria. Furthermore, since the available data is scarce, the Monte-Carlo method is accordingly applied. The role of this method is to numerously create stochastic data for simulating the assessment of ECV-UFT combinations close to real conditions. Similarly, the 10-fold cross validation is introduced to numerously and repeatedly simulate the assessment for validating the methodological concept. Finally, the proposed methodological concept is evaluated by using six alternatives in the simulation platform.

1.5 Structure of Dissertation

Five elements constitute the present dissertation. The sequence of conducting these five elements shapes the structure of the dissertation (Figure 1). The first element in this structure refers to Chapter 1 (Introduction). In this chapter, the motivation for conducting this research, the statement of the existing problem, the research goal and the research questions, as well as the research methodology for solving this problem are outlined.

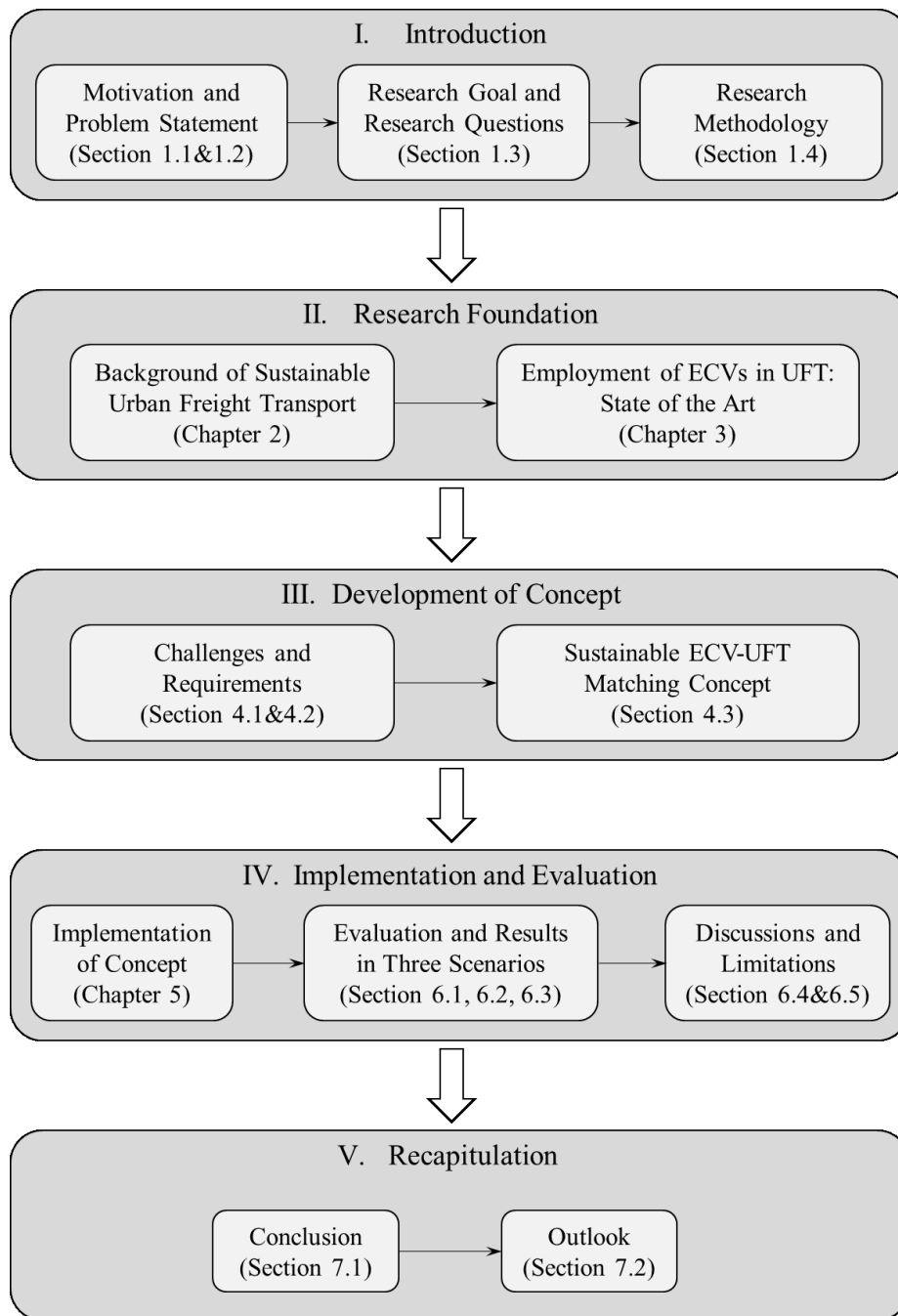


Figure 1: Structure of the dissertation

The second element involves Chapter 2 and 3. Chapter 2 mainly provides significant background knowledge including the definitions, the characteristics, and the development of ECVs, UFT, as well as sustainable UFT. On top of this background, Chapter 3 carries out a state of the art regarding the employment of ECVs in UFT. The primary areas of focus in the literature, the advantages and disadvantages of existing tools as well as the factors influencing the employment are illustrated in this chapter. In addition, a limitation of obtaining a satisfactory match is identified by reviewing the literature and tools. In essence, Chapter 2 and 3 provide the research foundation to increase the understanding and identify the research gap of this dissertation.

The third element of this structure (Chapter 4) focuses on proposing a concept to fill the identified research gap. In particular, the challenges, the main focus, the objective, and the requirements of proposing this concept are clarified in Section 4.1 and 4.2. Based on this groundwork, the Sustainable ECV-UFT Matching Concept including the methodology of assessment and determination is proposed in Section 4.3.

The fourth element in this structure deals with the implementation and the evaluation of the proposed methodological concept (Chapter 5&6). A simulation platform is designed by transforming the two methodologies into the computer for implementing the concept (Chapter 5). Moreover, six alternatives in three scenarios are introduced (Section 6.1&6.2) and entered into the designed simulation platform to evaluate the methodological concept. The evaluation results in these three scenarios are shown in Section 6.3. Besides, the discussions and the limitations of this methodological concept are presented in Section 6.4&6.5. Finally, this dissertation ends with the conclusion and the outlook (Chapter 7).

2 Background of Sustainable Urban Freight Transport

This chapter introduces the background of sustainable urban freight transport. In particular, the definition, the characteristics, and the environmental problems of urban freight transport are elaborated in Section 2.1. Furthermore, on account of these environmental problems, the concept: sustainable urban freight transport is introduced in Section 2.2. Besides these two sections, electric commercial vehicles as an essential measure of achieving sustainable urban freight transport are characterized in Section 2.3. On top of the background, this chapter also presents the challenges of employing electric commercial vehicles for achieving sustainable urban freight transport (Section 2.4). On the whole, this chapter describes the research foundation and outlines the research problem of this dissertation.

2.1 Urban Freight Transport

Urban Freight Transport (UFT) is an essential segment of freight transport to satisfy the needs of citizens. In turn, the rapidly increasing number of citizens accelerates the development of UFT. The rapidly increasing number of citizens results from rapid urbanization. As stated by the United Nations (2007; 2015), a shift of the population from dispersed small rural settlements to concentrated large and dense urban settlements is the process of urbanization. It implies that the dominant economic activity moves from agriculture towards industrial and service activities (Martine et al., 2007; United Nation, 2015). However, this movement keeps citizens away from their sources of necessities, such as food, consumer products, and waste disposal opportunities. Furthermore, the rapid urbanization spurs increasing demand for necessities and services from commercial and domestic users (Cui et al., 2015). To this effect, the UFT plays an increasingly significant role to deliver the necessities from sources to citizens and to fulfill the increasing demand.

Referring to the knowledge of Dablanc (2009), MDS Transmodal (2012), Comi et al. (2013), Taniguchi (2013), UFT is defined in this research as follows:

Urban freight transport: is a segment of road freight transport, which carries the goods by or for commercial entities into, out of and within urban areas, to satisfy the needs of citizens, support efficient economic, and social development.

To gain insight into the UFT, the means, the stakeholders, and the markets of UFT are mainly introduced in the following subsections. Additionally, this section presents the environmental challenges arisen in UFT.

2.1.1 Commercial Vehicles and Stakeholders of Urban Freight Transport

The commercial vehicle is the means of transporting goods on the road. The functions of these commercial vehicles vary depending on their size, weight, horsepower, and regional factors, such as the level of economic development, geography, and the shares of various sectors in the economy (International Energy Agency, 2017). In addition to the functions, the classification schemes of these commercial vehicles vary from country to country. Nevertheless, these countries essentially use the same parameter - Gross Vehicle Weight (GVW), which means the weight of the vehicle plus the maximum intended payload (International Energy Agency, 2017), to categorize their commercial vehicles. The classification schemes of commercial vehicles in the European Union and the United States exemplify two common schemes (Figure 2). Obviously, in the US, the classification is defined in more detail compared to the EU. Additionally, this classification in the US can also be generally categorized as light-duty (class 1-2), medium-duty (class 3-6), and heavy-duty (class 7-8) commercial vehicles. With the knowledge of these two classification schemes, the commercial vehicle category used in this research is defined as: *light-duty commercial vehicles* (<3.5t); *medium-duty commercial vehicles* (3.5t-12t), and; *heavy-duty commercial vehicles* (>12t).

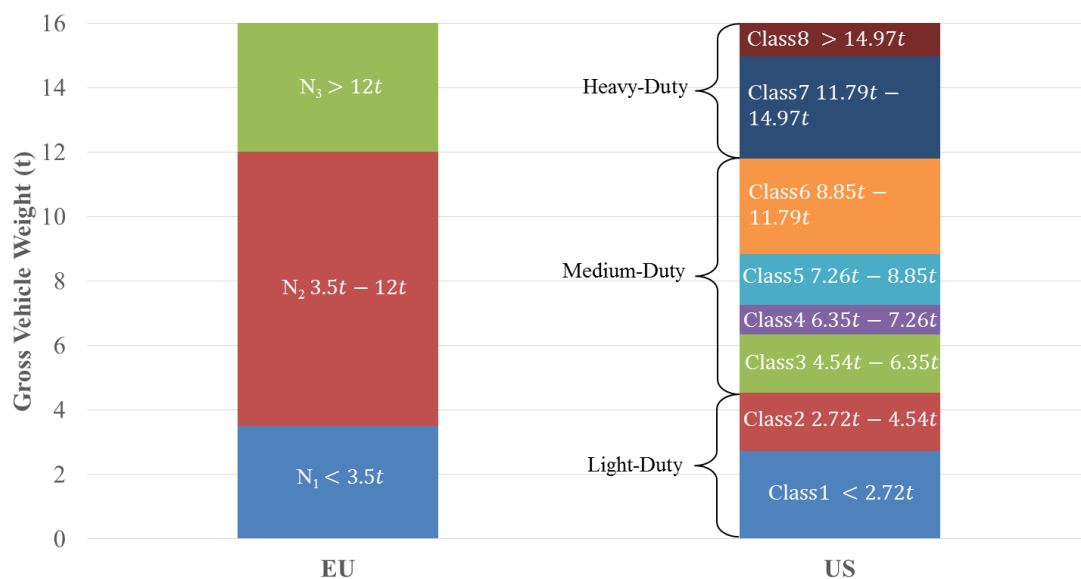


Figure 2: Classification schemes of commercial vehicles in the EU and the US (Alternative Fuels Data Centre, 2018; The European Parliament and of the Council, 2007)

On top of the commercial vehicles, the UFT comprises many stakeholders. In the perspective of the supply chain, the UFT stakeholders range from shippers, freight carriers, to receivers (Ma, 2014; MDS Transmodal Limited, 2012; OECD, 2003). Commonly, the task of shippers is to supply goods. Typical examples of shippers are manufacturers, wholesalers, and retailers. Succeeding suppliers are freight

carriers. Freight carriers perform the next task, which is to transport the goods. Some freight carriers are shippers because they transport their goods using their commercial vehicle fleets. Also, some freight carriers deliver goods by cooperating with Third-Party Logistics (3PL) providers. After that, receivers unload goods transported by the freight carriers. In urban areas, the primary receivers are the private households as well as the commercial receivers, such as shops, retail outlets, hotels, and restaurants. In addition to these three stakeholders from the perspective of supply chain, other stakeholders are the national/regional governments, urban motorway operators, city residents, and visitors (CIVITAS, 2015; Ma, 2014; Taniguchi, Kawakatsu, & Tsuji, 2000; Teo, Taniguchi, & Qureshi, 2012) from the perspectives of public authorities, resource supply, and participants

2.1.2 Urban Freight Transport Markets

The receivers and their requirements, such as the type of goods and the number of deliveries, determine the delivery tasks of freight carriers in UFT. Regarding the differences underlying the delivery tasks, the UFT can be classified into five markets, which are (Abel & Karrer, 2005; CIVITAS, 2015; MDS Transmodal Limited, 2012):

- *Retail market*: delivery of finished products mainly to shops and retail outlets;
- *Express/post market*: transport of letters, parcels, and provides express services for households and companies;
- *Ho(tel)Re(staurant)Ca(tering) market*: carry of food and beverage to hotels, bars, restaurants, canteens, and event catering;
- *Construction market*: delivery of a wide range of building material to building sites for infrastructural projects and residential constructions;
- *Waste collection market*: collection of municipal waste, industrial waste, hazardous waste, and construction waste to waste disposal facilities.

The characteristics of these five markets are summarized in Table 1 (MDS Transmodal Limited, 2012; OECD, 2003).

2 Background of Sustainable Urban Freight Transport

Table 1: Characteristics of five markets

UFT Markets	Characteristics
Retail	Using own account medium/heavy-duty commercial vehicles (retail chains); Frequent deliveries and diverse suppliers (independent retail); Using light-duty commercial vehicles with many stops (e-commerce)
Express/post	National postal operators and using hub-and-spoke networks (letter post); The high number of receivers per delivery tour with heterogeneous loads (courier, parcels, express)
HoReCa	Just-in-time supplies; Centralized procurement and less frequent deliveries (HoReCa chains); Frequent deliveries (independent HoReCa)
Construction	A wide range of building material; Fragmented industry; Project-based construction activity
Waste collection	A wide variety of material; Many stops (household waste); Frequent collection (industrial waste)

Retail market: The retail market contains retail chains, independent retail and e-commerce (MDS Transmodal Limited, 2012). The retail chains distribute goods to their stores by operating their medium- or heavy-duty commercial vehicles to increase delivery efficiency. The independent retailers, on the other hand, are commonly small or medium stores, to whom, diverse suppliers supply goods at a rate of three to ten times a week. Another emerging retail market is e-commerce. The e-commerce is typically focused on home delivery (Teo et al., 2012) to transport goods purchased online to recipients (homes, offices, or pickup points) by using couriers and parcel services (Visser, Nemoto, & Browne, 2014). These services apply commonly light-duty commercial vehicles to and within residential areas with the conduct of many stops on their routes (OECD, 2003).

Express/Post: The express/post market is constituted by the letter post-market as well as the courier, parcel, and express market. The national postal operators mainly conduct the letter post market in hub-and-spoke networks. The courier, parcel, and express market, similar to the home delivery in e-commerce, deliver heterogeneous goods to diverse receivers with many stops (70-90 deliveries per tour) (MDS Transmodal Limited, 2012).

HoReCa: The HoReCa market comprises HoReCa chains and independent HoReCa. The typical characteristic of this market is just-in-time supplies, requested in small quantities and fresh. Such characteristic leads to frequent deliveries. Nevertheless, this frequent delivery is specific to the independent

HoReCa market, since the HoReCa chains (such as large hotel and restaurant chains) intend to achieve economies of scale through centralized procurement as well as more consolidated and less frequent deliveries (MDS Transmodal Limited, 2012).

Construction: The construction market is a fragmented industry, which delivers a wide range of building material to building sites for infrastructural projects and residential constructions. These construction activities are project-based. However, the fragmented industry and the project-based construction activities may result in commercial vehicles running either empty or part-loads as well as consuming long waiting time to gain access to construction sites (MDS Transmodal Limited, 2012).

Waste Collection: The waste collection market in urban areas is mainly responsible for collecting municipal waste, manufacturing/industrial waste, hazardous waste, and construction waste. These wastes include a wide variety of materials, such as paper, food, glass, plastic, metal, medicaments, colors, batteries, and building material (Abel & Karrer, 2005). The delivery tasks in this market depend on the diverse types of waste. For instance, the collection of household waste is conducted weekly or every two weeks with many intermediate stops, whereas the collection of industrial waste is carried out daily and with less intermediate stops than the household waste collection (Abel & Karrer, 2005).

In these five UFT markets, Internal Combustion Engine (ICE) vehicles are the primary means employed to complete the delivery tasks. Nevertheless, this employment of ICE vehicles in UFT raises some environmental issues, such as noise, air pollution, and energy consumption (Russo & Comi, 2012). The air pollution in UFT refers to GHG emissions (CO₂, CH₄, N₂O, Hydrofluorocarbons, Perfluorocarbons, SF₆), CO, NO_x, Particulate Matter (PM) 10, PM_{2.5}, and VOC_{x1}. Among these elements of the air pollution, since the GHG emissions result in climate change (higher temperatures, rising sea levels, and more frequent weather extremes) and put many coastal communities, food security, human health, and ecosystems at risk (Eurostat, 2017), the attention regarding the air pollution is widely paid on the GHG emissions. Furthermore, due to the fact that the fossil fuel in ICE vehicles is non-renewable energy and the air pollution is generated by burning fossil fuels, reducing the energy consumption of ICE vehicles constitutes the environmental challenges in UFT.

As claimed by the Eurostat Statistics Explained (Eurostat, 2015), the road transport accounts for 94.4% of total GHG emissions in 2012 and consumes 82.6% of total energy consumption in 2013 from all transport modes (road rail, domestic navigation, domestic aviation, and international aviation). These proportions reveal that road transport mode is the main origin of the air pollution and the energy consumption in the transport sector. To address these environmental challenges, the UFT as a segment of road transport is required for solutions.

2.2 Sustainable Urban Freight Transport

This section introduces a concept called Sustainable Urban Freight Transport (sustainable UFT) for addressing the environmental challenges arisen in UFT. Section 2.2.1 focuses on introducing the definition of sustainable UFT. Section 2.2.2 presents existing works for achieving sustainable UFT.

2.2.1 Definition of Sustainable Urban Freight Transport

The concept named sustainable UFT stems from the term - *Sustainable Development (SD)*, which is defined as:

“development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987)

In order to achieve SD, the Sustainable Development Goals (2016) of the United Nations stated that it is crucial to harmonize three core elements: economic growth, social inclusion, and environmental protection. These three elements are also well-known as *three pillars (economic, social, and environmental) of SD* to expand the aforementioned definition (Kates et al., 2005).

Generally, the word *economic* means concerned with the organization of the money, industry, and trade of a country region, or society (Collins English Dictionary, 2017a); the word *social* means relating to society or to the way society is organized (Collins English Dictionary, 2017), and; the word *environmental* means concerned with the protection of the natural world of land, sea, air, plants, and animals (Collins English Dictionary, 2017b). On top of these basic explanations, there is a need for specifying the three dimensions to understand the SD in different perspectives.

In the perspective of urban transport, the SD and its three pillars can be specified as *sustainable urban transport*. The European Commission defined objectives of sustainable urban transport through an expert working group. The specific objectives of a sustainable urban transport system include (Behrends, Lindholm, & Woxenius, 2008):

- *“Ensuring the accessibility offered by the transport system to all categories of inhabitants, commuters, visitors, and businesses, in line with the objectives below;*
- *Reducing the negative impact of the transport system on the health, safety, and security of the citizens, in particular the most vulnerable ones;*
- *Reducing air pollution and noise emissions, GHG emissions, and energy consumption;*

- *Improving the efficiency and cost-effectiveness of the transportation of person and goods, taking into account the external costs;*
- *Contributing to the enhancement of the attractiveness and quality of the urban environment.”*

In this definition of sustainable urban transport, the purpose of the first item is to rephrase and specify the definition of SD for sustainable urban transport. The following items expand the description of the first item by specifying the three dimensions respectively. Given these points, the definition of sustainable urban transport involves the essential meaning of SD and specifies the three pillars to adapt to urban transport.

With the knowledge of the definition of UFT, SD, and sustainable urban transport, the sustainable UFT in this research is defined to fulfill the following objectives:

- ***prerequisite:** ensuring the ability of UFT to meet the present and future needs of citizens;*
- *from an **economic** perspective: improving the efficiency and cost-effectiveness of the transportation of goods, taking into consideration the external costs;*
- *from a **social** perspective: enhancing the attractiveness and quality of the urban environment, by avoiding accidents and ensuring the mobility and accessibility of citizens as well as goods;*
- *from an **environmental** perspective: reducing air pollution, noise emissions, GHG emissions, and energy consumption to levels without negative impacts on the health of citizens and nature.*

This definition of sustainable UFT refers to the structure of the definition of sustainable urban transport. The first item in this definition is the prerequisite formed by synthesizing the definitions of UFT and SD. The following items are objectives of three dimensions that are specified for adapting to the perspective of UFT. In particular, the economic dimension of sustainable UFT is concerned with costs, including internal (vehicle costs of ownership, and traffic crash costs) and external costs (congestion costs and environmental costs), as well as the efficiency and cost-effectiveness of transporting goods. The social dimension of sustainable UFT is concerned with a livable urban environment, which comprises safety, security, equity, mobility, and accessibility for citizens and goods. The environmental dimension of sustainable UFT is concerned with the environmental protection of citizens and nature. To this end, the sustainable UFT and its three

dimensions are defined explicitly as the concept to address the environmental challenges arisen in UFT.

2.2.2 Existing Works for Achieving Sustainable UFT

There are some existing works conducted for achieving sustainable UFT. A White Paper published by the European Commission (2011) is one of the existing works. This White Paper is a roadmap to a single European transport area towards a competitive and resource efficient transport system. In this White Paper, three primary measures are proposed for achieving sustainable UFT. The measures include: a). Optimizing the performance of multimodal logistic chains by making greater use of more energy efficient modes; b). Increasing the efficiency of transport and of infrastructure use with the help of information systems and market-based incentives, and; c). Developing and deploying new and sustainable fuels and propulsion systems. The following existing works for achieving sustainable UFT are introduced in line with these three measures.

Some existing works studied the issues related to the first two measures of the White Paper for achieving sustainable UFT. Taniguchi et al. (Taniguchi, Thompson, Yamada, & Duin, 2001) proposed a concept – city logistics. This is the process for entirely optimizing the logistics and transport activities by private companies with the support of advanced information systems in urban areas, while considering the traffic environment, congestion, safety, and energy savings within the framework of a market economy. Optimization and simulation are the main approaches for enhancing the practical applications of city logistics models (Taniguchi, Thompson, & Yamada, 2012). Besides, Figliozzi (2010) discussed the impacts of congestion on commercial vehicle tour characteristics and costs. Maden et al. (2009) applied traffic information with time-varying speeds to plan routes for reducing CO₂ emissions and comparing plans in terms of constant speeds and a general contingency allowance. Furthermore, Urban Consolidation Centers (UCCs) as one type of logistics facilities has been proposed and frequently discussed in recent years. It is initiated to reduce goods vehicle traffic, vehicle-related GHG emissions, and local air pollution (Allen, Browne, Woodburn, & Leonardi, 2012).

In addition to the studies regarding the first two measures, the third measure, which is replacing ICE vehicles with alternative fuel vehicles, has been studied in some existing works as well. For example, Tipagornwong et al. (2014) investigated the competitiveness of delivery services using electric-assisted trikes in urban areas. Besides, a number of regional and European Union (EU) projects have been initiated to investigate and demonstrate the feasibility of using alternative fuel vehicles in UFT, such as BESTUFS I II, CityMove, CityLog, DELIVER, FREVUE, FURBOT, MELODYS, SELECT, SMARTFUSION, SMILE, and V-FEATHE (ALICE / ERTRAC Urban mobility WG, 2014). According to the results of the projects CityMove and CityLog, freight operators in these projects

emphasized the significance of using smart, efficient, environmentally friendly and reliable vehicles in urban areas (Welfers et al., 2012). On top of using alternative fuel vehicles, using trams to deliver goods in urban areas is also a solution proposed and demonstrated in recent years. In Dresden, cargo trams have been applied to transport automobile components to avoid intense lorry traffic within the city. Similarly, in Zurich, the cargo trams have provided waste disposal service for bulky refuse and electrical as well as electronic goods (MDS Transmodal, 2012; Ma, 2014).

On the whole, to address the environmental challenges arisen in UFT, this section introduces the definition of sustainable UFT. Moreover, some theoretical and practical existing works are reviewed to present to what extent that sustainable UFT has been studied.

2.3 Electric Commercial Vehicles

Electric Commercial Vehicles (ECVs) constitute a means to achieve sustainable UFT. The ECVs are road vehicles, which involve electric propulsion systems for the carriage of goods (Chan, 2002; The European Parliament and of the Council, 2007). The categorization of ECVs can rely on differences regarding the configurations, propulsion systems, and energy sources. On account of these differences, the ECVs can be categorized into Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Fuel Cell Electric Vehicles (FCEVs) (Table 2).

Table 2: A summary of four types of ECVs (adapted from Chan et al., 2010)

Types	Characteristics	Strengths	Limitations
BEVs	Propulsion: electric motor drives; Energy storage: battery, supercapacitor; Infrastructure: charging stations	Zero local emissions; High energy efficiency; Independent of fossil fuels; Commercially available	Limited driving range; High initial cost; Insufficient charging infrastructures
HEVs	Propulsion: electric motor drives & internal combustion engines; Energy storage: battery, supercapacitor, fossil or alternative fuels; Infrastructure: gasoline stations	Low local emissions; High fuel efficiency; Long driving range; Commercially available	Dependent on fossil fuels; Higher cost than ICE vehicles; Control, optimization, and management of multiple energy sources

2 Background of Sustainable Urban Freight Transport

Types	Characteristics	Strengths	Limitations
PHEVs	Propulsion: electric motor drives, internal combustion engines; Energy storage: battery, supercapacitor, fossil or alternative fuels; Infrastructure: gasoline stations, charging stations	Low local emissions; High fuel efficiency; Long driving range; Commercially available	Dependent on fossil fuels; Higher cost than ICE vehicles; Control, optimization, and management of multiple energy sources; Insufficient charging infrastructures
FCEVs	Propulsion: electric motor drives; Energy storage: hydrogen tank; Infrastructure: hydrogen filling stations	Zero local emissions; High energy efficiency; Independent of fossil fuels; Satisfied driving range	High fuel cell cost; Difficulty of storage and transport of hydrogen; Insufficient hydrogen filling stations

The *BEVs* are powered entirely by electric energy stored in batteries. Electric motors convert the electric energy into mechanical energy to propel the vehicle wheels. Onboard batteries are rechargeable by plugging into an electric power source and regenerative braking energy (Alternative Fuels Data Center, 2018a). There are obvious strengths and limitations in the BEV. Without considering the raw material for producing electricity from the life cycle's perspective, BEVs emit zero tailpipe emissions and are independent of fossil fuels. Additionally, since there are no ICEs onboard, the noise of BEVs dramatically decreases in comparison with ICE vehicles. On the contrary, as a consequence of the limited battery capacity and high battery cost, the anxiety over driving range, high initial cost, and insufficient charging infrastructures constitute the limitations of the BEVs.

Inconsistent with the BEVs, the *HEVs* are powered by two propulsion devices, namely ICEs and electric motors. These two propulsion devices complicate the configuration of HEVs. Depending on the differences between the integration of the two propulsion devices, there are three basic configurations of HEVs including series hybrid, parallel hybrid, and series-parallel hybrid (Chan, 2007) (Figure 3). Among these configurations, the series hybrid vehicle is entirely powered by electric energy. The ICE in this configuration has no mechanical connection with the driveline. This decoupling indicates that the ICE mechanical output is exclusively converted into electricity by the generator. Then, the converted electricity can either charge the battery or directly propel the driveline. In comparison with the series hybrid, the parallel hybrid vehicle can be powered by ICE alone, by electric motors along, or by both of them. In this context, the mechanical connection between the ICE and the driveline replaces the connection between the ICE and electric motors. This replacement implies that the mechanical energy of the ICE can directly propel the driveline rather than converting this

mechanical energy into electric energy by generators. On top of these two configurations, the series-parallel hybrid vehicle is configured by integrating the two connections between ICE and drivelines as well as ICE and electric motors.

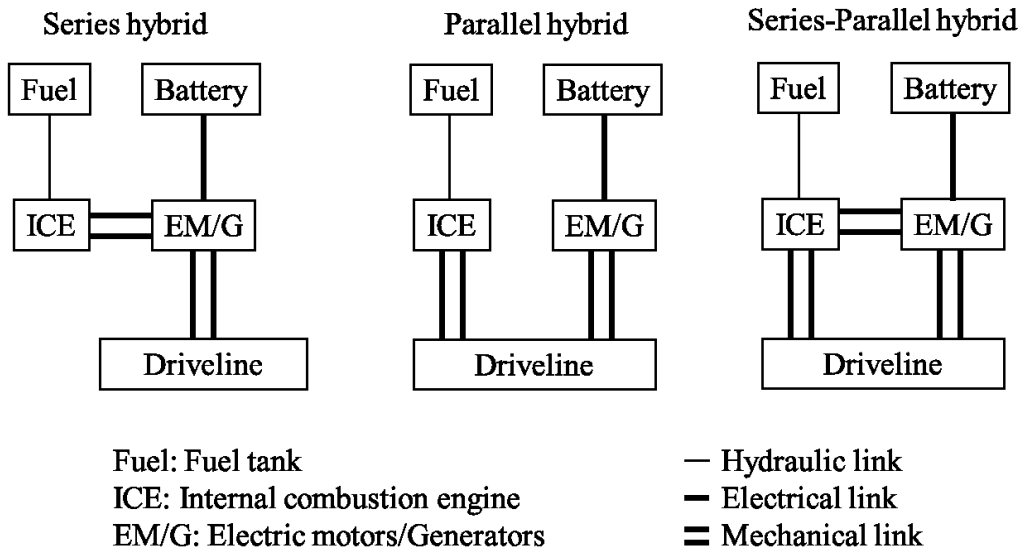


Figure 3: Configurations of HEVs (adapted from Chan, 2007)

On account of the two onboard propulsion devices, the HEVs may overcome some limitations of both ICE vehicles and BEVs (Chan, 2002). In comparison with ICE vehicles, the HEVs mitigate noise, tailpipe emissions, as well as energy consumption. By comparison with BEVs, the HEVs extend the driving range and have no demands on recharging by an external electric power source. Besides, on the basis of the optimized operation of the onboard ICE in the HEVs, the maintenance of the vehicle may be significantly reduced (Chan, 2007). Nevertheless, although the HEVs may improve some limitations of BEVs, since the ICE remains onboard, the HEVs still depend on fossil fuels. In addition, the cost of HEVs is higher than ICE vehicles because of the complex configurations and onboard energy storage systems.

Similar to the HEVs, the *PHEVs* are also powered by the two propulsion systems. The primary difference between HEVs and PHEVs is whether the on-board batteries can be recharged by external electric power sources. In the HEVs, the onboard batteries are commonly recharged by absorbing the power from the ICE and converting the regenerative braking energy. In the PHEVs, apart from the two modes of recharging batteries in the HEVs, the onboard batteries of PHEVs can be recharged by external electric power sources as well. In addition to the difference regarding recharging batteries, the PHEVs also differ from the HEVs in the size of battery capacity. Commonly, the battery capacity of PHEVs is larger than HEVs. This difference presents that the battery of PHEVs can propel vehicles longer than HEVs without the assistance of the ICE. On top of these differences, the strengths and limitations of PHEVs are same as HEVs.

2 Background of Sustainable Urban Freight Transport

The *FCEVs* are fueled with pure hydrogen gas stored directly on the vehicle (Alternative Fuels Data Center, 2018c). Hydrogen in the *FCEVs* plays the same role as gasoline or diesel in *ICE* vehicles. Using hydrogen, the fuel cell produces electric energy. The electricity from the fuel cell is either used to drive the vehicle or is stored in the battery pack (Chan, 2007). Since the byproducts of hydrogen are water and heat, the *FCEVs* emit zero tailpipe emissions. Moreover, the filling time of hydrogen is much shorter than the battery charging time and similar to the filling time of *ICE* vehicles. For instance, as introduced in Fuel Cell Electric Vehicles (2018b), the *FCEVs* can fuel in less than 10 minutes and have a driving range of around 300 miles (≈ 483 km). Nevertheless, since the cost of fuel cells is high, the storage and transport of hydrogen are difficult, and the hydrogen filling infrastructures are insufficient, the *FCEVs* still present relatively low availability nowadays.

In short, this section outlines four types of *ECVs* to in-depth illustrate to what extent that these types are available for being employed in UFT.

2.4 Summary

As introduced in this chapter, the relations between urbanization, UFT, *ICE* vehicles, *ECVs*, as well as sustainable UFT are portrayed in Figure 4. Since the urbanization determines the demands of goods in UFT, the rapid urbanization may stimulate the development of UFT. To pursue this development, the number of *ICE* vehicles is accordingly required to be expanded. Nevertheless, the *ICE* vehicles, which is powered by burning non-renewable fossil fuels, result in the environmental problems in UFT, such as air pollution and energy consumption. In this context, sustainable UFT is proposed to address these problems. The *ECV* is a measure for achieving sustainable UFT. As reviewed in Section 2.2.2, many studies and demonstration projects have considered the employment of *ECVs* to achieve sustainable UFT. In spite of this, the market penetration is relatively low underlying the intention of employing *ECVs*. According to the report of ICCT (International Council on Clean Transportation, 2017), in Europe, the light electric commercial vehicles ($GVW < 3.5t$) including the *BEVs*, *HEVs*, and *PHEVs*, accounted for 0.7% of total sales of light commercial vehicles in 2016. In a related perspective, Navigant Research (Alexander & Jerram, 2017) forecasted that the market share of diesel medium – and heavy – duty trucks (gross vehicle weight $\geq 3.5t$) will remain the dominant in next decade. Overall, although there are environmental benefits of employing *ECVs* and supporting policies for commercializing the *ECVs*, the statistics reveal that the market penetration of *ECVs* in UFT is still low.

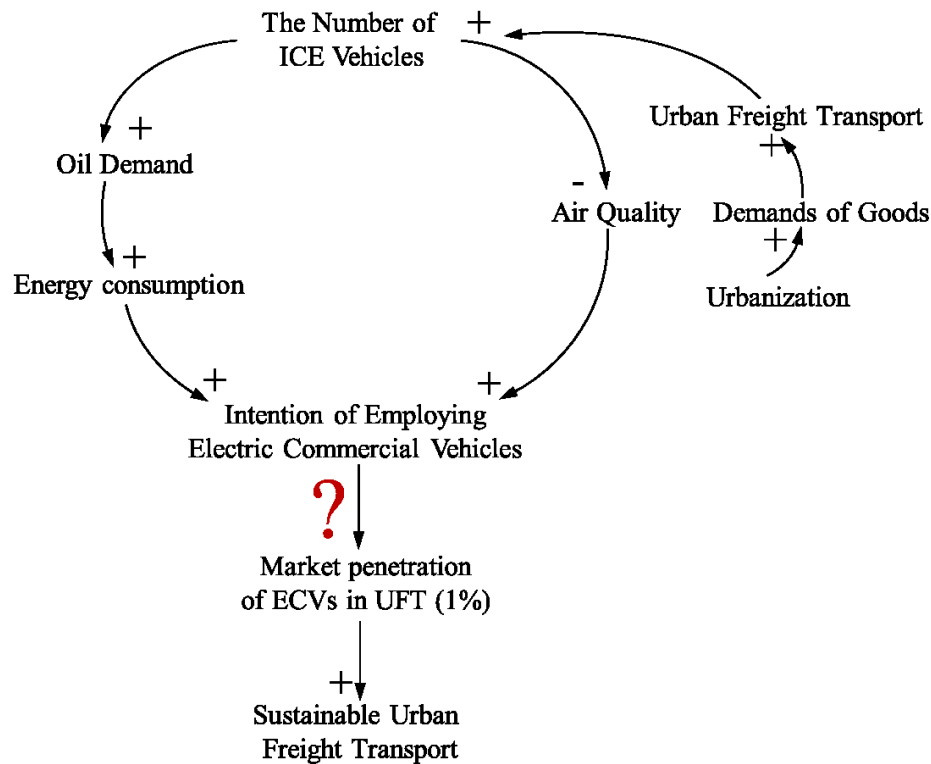


Figure 4: The conflict in employing ECVs to achieve sustainable UFT

In comparison with the intention of employing ECVs to achieve sustainable UFT, the current market penetration of ECVs raises a question: why there is a conflict between the intention and the real market penetration. To answer this question, the state of the art in this research field is reviewed in Chapter 3 to identify the limitations of the employment of ECVs in UFT and explain this conflict.

3 Employment of ECVs in UFT: State of the Art

This chapter focuses on reviewing the state of the art in the field of the employment of ECVs in UFT. The goal is to achieve in-depth knowledge in current studies so that to analyze and identify the limitations regarding such employment. Literature (Section 3.1) and existing tools (Section 3.2) as the current studies are reviewed in this chapter respectively. Moreover, the factors influencing the employment are extracted from the current studies and illustrated in Section 3.3. Finally, the limitations of the employment are analyzed and identified in Section 3.4 based on gaining insight into the state of the art.

3.1 Current Focus of Employing ECVs in UFT¹

This section presents the primary focus on the employment of ECVs in UFT. The role of this section is to answer the question: what has been considered in the literature to deal with such employment. A Systematic Literature Review (SLR) is applied following a sequence of activities: a. determining the objective of the SLR; b. selecting sources; c. selecting keywords; d. classifying the articles; e. summarizing the results. There are primarily four areas of focus appeared in the literature including the feasibility of ECVs, adaptations of logistics concepts, adaptations of vehicle concepts, and support of stakeholders. Subsequent subsections provide respective discussions about these four areas of focus.

3.1.1 Feasibility

In a standpoint of feasibility, the literature has identified the opportunities, limitations, and competitiveness of employing ECVs in UFT. The research methods in such literature mainly rely on surveys, case studies, and simulations. According to the identification of opportunities, there are environmental benefits (low emissions, noise, and energy consumption), social attitudes (drivers and freight operators) (Quak, & Nesterova, 2014; Quak, Nesterova, & Van Rooijen, 2016; Quak, Nesterova, Van Rooijen, & Dong, 2016; Wang, & Thoben, 2017b), and financial (subsidies, tax exemption) as well as non-financial incentives (preferential parking for ECVs, initiating repair centers for ECVs, allowing ECVs to drive on high occupancy or bus lanes, and privileges of accessing to low emission zones in city centers) (Pelletier et al., 2016; Taefi et al., 2016) discussed in the literature. These identified opportunities render the employment of ECVs in UFT feasible.

Besides such opportunities, the literature has also identified limitations, which hinder the employment of ECVs in UFT. The limitations include:

¹ This section has been published in (Wang et al., 2018)

3 Employment of ECVs in UFT: State of the Art

- Economic limitations, such as: high purchase price, battery price, and infrastructure costs (Iwan, Kijewska, & Kijewski, 2014; Quak, & Nesterova, 2014; Quak, Nesterova, & Van Rooijen, 2016; Quak, Nesterova, Van Rooijen, et al., 2016; Wang, & Thoben, 2017b);
- Technological limitations, such as: long charging time, limited driving range, payload capacity, and battery lifetimes (Iwan, Kijewska, et al., 2014; Morganti, & Browne, 2018; Quak, Nesterova, & Van Rooijen, 2016; Taefi, Kreutzfeldt, et al., 2015; Wang, & Thoben, 2017b), as well as;
- Infrastructural limitations: networks, diverse types of charging stations (battery charging with cables, battery swapping, or battery wireless charging), compatibility, and grid issues (Juan, Mendez, Faulin, De Armas, & Grasman, 2016; Quak, Nesterova, & Van Rooijen, 2016).

In addition to the outlined limitations, there are also other issues discussed in the literature. These issues comprise security, limited availability of vehicles, few proper business models and lack of a comprehensive understanding between freight operators and policymakers (Klumpp, Abidi, & Marner, 2014; Quak, Nesterova, & Van Rooijen, 2016; Quak, Nesterova, Van Rooijen, et al., 2016; Taefi, Kreutzfeldt, et al., 2016).

Furthermore, in this area of focus, the literature evaluates competitive advantages to employ ECVs in UFT, as compared to diesel commercial vehicles. The evaluation of this competitiveness focuses mainly on the economic and environmental perspectives. The economic perspective discusses the impact of the purchase cost, battery cost, fuel cost, and financial incentives for competitiveness. The environmental perspective is concentrated in the performance, such as CO₂ emissions and energy consumption. The results of the evaluation show that the competitive advantages of ECVs depend on their powertrains and Gross Vehicle Weight (GVW). In general, the light-duty BEVs are the most competitive vehicles to operate in some parts of UFT, such as express/post market (Lebeau, Macharis, Van Mierlo, & Lebeau, 2015; Macharis, Lebeau, Mierlo, & Lebeau, 2014; Melo et al., 2014). For the medium-duty vehicles, diesel commercial vehicles remain the most interesting solution from the financial point of view (Lebeau, De Cauwer, et al., 2015; Taefi, Stütz, & Fink, 2017). In the segment of heavy-duty vehicles, HEVs are more competitive with running in city areas rather than highways (Daw et al., 2013; Lebeau, De Cauwer, et al., 2015).

On the whole, the literature in the area of feasibility implies that the replacement of diesel commercial vehicles with ECVs in UFT appears possible. Additionally, some solutions and research perspectives have been suggested to address the issues raised by the studies on the feasibility. For example, from the economic point of view, the literature (Davis, & Figliozzi, 2013; Feng, & Figliozzi, 2013, 2012;

Lebeau, Macharis, Van Mierlo, et al., 2015; Taefi, Stütz, et al., 2017) proposes to reduce the battery cost and the purchase price; to raise the fuel price (diesel and petrol), and; increase vehicle utilization (traveled distance per year per vehicle). From the technological point of view, it is recommended to develop Information and Communications Technology (ICT), infrastructures (networks and inductive systems), as well as Electric Vehicle Routing Problem (EVRP) by taking into account fleet sizes and charging strategies (Iwan et al., 2014; Juan et al., 2016; Morganti & Browne, 2018; Pelletier et al., 2016; Quak, Nesterova, & Van Rooijen, 2016). From the policies' point of view, Taefie et al. (2016) suggest to implement a city toll on the long-term and allow drivers with a class B license to drive ECVs over 3.5t. In addition, Roumboutsos et al. (2014) suggest transferring leadership from central to municipal authorities for promoting the employment of ECVs in UFT.

3.1.2 Adaptions of Logistics Concepts

In order to fit characteristics of ECVs, some works in the literature have focused on adapting the existing logistics concepts, which are primarily designed for operating diesel commercial vehicles. The limited battery capacities of BEVs, as one of the characteristics, have been mainly discussed in this perspective of logistics. Schneider et al. (2014), Guo et al. (2017), and Panagiotis et al. (2016) have formulated the EVRP in the condition of recharging BEVs at depots and available charging stations en route. On the contrary, Conrad and Figliozzi (2011) as well as Aggoune-Mtala et al. (2015) proposed vehicle routing models to recharge BEVs at customer locations rather than recharging stations. In exclusion of these articles that focus on homogeneous fleets, Van Duin et al. (2013), Mirhedayatian and Yan (2018), as well as Rezgui et al. (2015) have investigated the EVRP with heterogeneous fleets. In addition to the literature addressing the EVRP, Deflorio and Castello (2017) studied a concept of charging-while-driving to assess traffic and energy performance of electric power systems for dynamically charging ECVs while driving. Schau et al. (2015) and Kretzschmar et al. (2016) adapted existing ICT systems to predict the range of BEVs for fitting the limitation of battery capacities. In short, to adapt the current logistics concepts to the limited battery capacities, the studies on the EVRP, the ICT, and the charging-while-driving have been discussed in the literature.

To further fit the characteristics of ECVs into UFT, some works focused on innovating logistics concept. The combinations of Urban Consolidation Centers (UCCs) and BEVs are one of the innovative logistics concepts. This concept suggested to constructing UCCs in relative proximity to the urban areas and replacing diesel commercial vehicles with BEVs to deliver goods in the cities (Browne et al., 2011; Leonardi, Browne, & Allen, 2012). In this context, the limited driving range of BEVs is not a restriction anymore, because the daily traveled distance is shorter than the driving range (Lebeau, Macharis, van Mierlo,

& Maes, 2013). Moreover, although the low payload capacity of BEVs led to more traffic, the total distance traveled, and CO₂ emissions were reduced by conducting this concept (Browne et al., 2011; Daniela, Paolo, Gianfranco, & Graham, 2014; Lebeau et al., 2013; Leonardi et al., 2012). In addition to the concept of UCCs, Faccio and Gamberi (2015) introduced an innovative distribution network to integrate the distribution of goods in a cluster of linked small cities. Furthermore, to decrease the congestion resulting from the limited parking spaces, Boussier et al. (2009) modeled a management process of the parking places sharing between car drivers and dedicated areas of goods deliveries. Besides, to reduce the total cost and increase the utilization of ECVs, Taefi (2016) proposed an innovative combination of the day and night delivery by using BEVs. Given these points, to support the employment of ECVs in terms of their existing limitations, some works are contributing to this support by adapting the existing logistics concepts.

3.1.3 Adaptions of Vehicle Concepts and Supporting Stakeholders

To improve existing limitations of ECVs for satisfying the requirement of UFT, there are some works focused on the area of adapting vehicle concepts. For example, to fit the diverse delivery tasks in UFT, Andaloro et al. (2015) defined and developed a flexible and modular light-duty BEVs with high payload capacity and a rolling chassis, which allows the integration with different powertrains and different upper bodies (vans or box vans). Molfino et al. (2015) designed a new architecture for light-duty BEVs to autonomously load and unload palletized or boxed goods. Clarembaux et al. (2016) improved the perception and control system of light-duty BEVs for parking/docking process. In addition, to adapt medium-duty HEVs to the parcel and delivery service, Lewis et al. (2017) studied a fuel cell HEV to properly size the fuel cell and battery by using real-world operational data and duty cycles. On the whole, to improve the limitations of ECVs for efficiently delivering goods in diverse UFT, the flexible and modular BEVs, the autonomous loading and unloading, the intelligent parking/docking, the high payload capacity, and the proper size of fuel cell and battery in HEVs have been studied in the adaption of vehicle concepts.

Besides the vehicle and logistics concept, the possible solutions for supporting stakeholders have been explored as well. For instance, to support authorities increasing their understanding on the limitations of adopting ECVs in UFT, Lebeau et al. (2015) investigated the choice behavior of transport companies for BEVs by applying survey and conjoint based choice analysis. To support transport companies selecting appropriate BEVs for UFT, Watróbski et al. (2017) proposed a unique approach in terms of multi-criteria analysis and discussed as well as ranked 36 available BEVs in the market. Furthermore, to support authorities employing ECVs in large scale, Cheng and Liu (2016) provided a business operating model, which respectively considered different practitioners (battery plants, energy supply companies, automobile companies) as individual operating

3.1 Current Focus of Employing ECVs in UFT

companies, to compare and discuss their advantages and disadvantages. To sum up, in the area of supporting stakeholders, the existing works studied the preferences of stakeholders for ECVs, proposed approaches of selecting proper ECVs, and discussed possible business models to facilitate the employment of ECVs in UFT.

On the whole, there are mainly four areas of focus, fifteen issues, and seven approaches or methods considered in the literature to deal with the employment of ECVs in UFT (Table 3).

Table 3: Four areas of focus

Area of Focus	Issue Addressed	Approach/Method
Feasibility	Limitations and opportunities	Review, survey, case study, the system of innovation
	Competitiveness of employing ECVs in UFT	Simulation, case study
	EVRP	Simulation
Adapting logistics concept	UCCs + BEVs	Simulation, case study
	ICT	Machine learning
	Charging-while-driving	Simulation
	Multi-city urban logistic model	Simulation
	Sharing parking places	Simulation
	Day and night delivery	Simulation
	New architecture	Simulation
Adapting vehicle concept	Improvement of the control system	Simulation
	Size of onboard energy for HEVs	Simulation
	Preferences of transport companies for ECVs	Survey
Supporting stakeholders	Business model	-
	Proper choice of ECVs for UFT	Multi-criteria analysis

According to the number of articles in each area, there are 32 articles (53%) studied the feasibility of ECVs, 20 articles (33%) adapted logistics concepts, 4 articles (7%) adapted vehicle concepts, and the rest of 4 articles (7%) explored

solutions for supporting stakeholders. These proportions reveal that many studies focus on addressing the feasibility of ECVs as the main area.

3.2 Tools for Employing ECVs in UFT

This section provides an analysis of existing tools regarding the employment of ECVs in UFT. The objective of this section is to identify which tools relate to such employment and what their purposes, strengths, and limitations are. The existing tools are examined by meeting the following criteria: a. the tools including alternative fuel commercial vehicles (light-, medium-, or heavy duty); b. taking into account the employment of these vehicles in UFT; c. assessing such employment in the economic, environmental, or social dimensions; d. running in English or German. In the end, six tools are selected for further analysis. Besides, in terms of the differences among the purposes of these six tools, the subsequent subsections present the tools from the vehicle-oriented and logistics-oriented point of view respectively.

3.2.1 Vehicle-Oriented Tools

AFLEET Tool

Alternative Fuel Life-Cycle Environmental and Economic Transportation is abbreviated as AFLEET Tool. It was supported by the Vehicle Technologies Office, U.S. Department of Energy. This tool allows clean cities stakeholders to estimate life-cycle petroleum use, life-cycle greenhouse gas emissions, air pollutant emissions in vehicle operation, and costs of ownership for light-duty vehicles and heavy-duty vehicles (Burnham, 2016). They investigated three types of light-duty vehicles and seven types of heavy-duty vehicles with using 16 available fuel types. Users can choose one or more vehicle categories and fuel types on the basis of their own cases.

There are several advantages of the AFLEET Tool. First of all, this tool can estimate and compare multiple vehicle categories and fuel types from economic and environmental perspectives. This advantage provides diverse options for users, who are involved in clean cities stakeholders, to select appropriate vehicle and fuel types in accordance with their own cases. Secondly, this tool takes into account the years of planned ownership to estimate the economic and environmental performance in the entire service years. This advantage reveals that the AFLEET Tool is a time-dependent tool, which can present results in current and future scenarios. In addition, the AFLEET Tool can calculate life cycle petroleum use, GHGs, and air pollutant emissions. Besides, all of the calculations in the AFLEET Tool are supported by a relatively full database.

On the other hand, there are two limitations for users to apply this tool. Firstly, this

tool estimates the petroleum use, GHGs, air pollutant emissions, and costs of ownership exclusive of considering the UFT and its logistical parameters. Secondly, the social dimension in sustainable UFT seems ignored in this tool. In this context, the conclusion of this tool cannot show the interaction between the calculated results (GHGs and TCO) and the changes of logistical parameters (transported weight and traveled distance). Moreover, the users of this tool cannot comprehensively understand their options from the sustainable point of view without considering the social dimension.

Heavy Truck Benefits Analysis Models

The Heavy Truck Benefits Analysis Models (HTBAMs) are developed by the Energy System Division at Argonne National Laboratory. It is applied for estimating energy, environmental, and economic benefits by using a market-based approach. The HTBAMs consists of three submodels. The Heavy Truck Energy Balance Dynamic (HTEBdyn) Model is one of the submodels. It calculates the fuel economy of medium-duty (Class 3-6) and heavy-duty (Class 7& 8) vehicles on the basis of vehicles' and engines' characteristics as well as drive cycles (Argonne National Laboratory, 2017). The intended purpose is to estimate the impact of technology improvements and innovations on heavy truck fuel consumption for a variety of duty cycles (TA Engineering, 2014). Therefore, hybrid electric trucks with integrating regenerative braking systems as one of the technology improvements and innovations are involved in this model. Furthermore, the rest of the models are the TRUCK model and the VISION model. The TRUCK model applies the results of HTEBdyn for estimating the market potential of associated technology changes and calculates the fuel economy of new truck fleets. The VISION model then uses sales projections and historical scrappage rates to project the future stock of heavy vehicle, the fuel economy of the in-use fleet, and total consumption of traditional as well as alternative transportation fuels (TA Engineering, 2012).

There are three advantages to this model. Firstly, the model incorporates drive cycles to calculate fuel consumption. It implies that the fuel consumption varies with the velocity at each time step so that the accumulated results are closer to real life. Secondly, this model has the capability of predicting future market of heavy trucks to present a long-term view. Finally, the calculation of total carbon-equivalent emissions covers the emissions from Well To Wheel (WTW).

Nevertheless, several limitations to this model need to be noted. Although the fact that this model took into account the advanced technologies, the alternative fuel types and vehicle categories are fewer in number than the AFLEET Tool. In addition, the HTBAMs estimate the change in fuel costs by applying advanced technologies, whereas the total costs for employing these advanced technologies are overlooked. Finally, similar to the AFLEET Tool, this model concentrates on

estimating the economic and environmental benefits from the automotive point of view without involving the perspective of UFT and its logistical parameters as well as the social dimension.

ADVISOR

ADVISOR is the abbreviation of Advanced Vehicle Simulator. It is an open source simulation tool, which is written in the MATLAB/Simulink environment and developed by the National Renewable Energy Laboratory. The role of this tool is to provide the vehicle engineering community with an easy-to-use, flexible, yet robust and supported analysis package for advanced vehicle modeling (Markel et al., 2002). The fuel economy, the performance, and the emissions of passenger and commercial vehicles with using conventional and alternative fuels can be quantified in this tool. Fuel cells, batteries, and ICE in hybrid configurations are the alternative technologies included in this tool.

Users can benefit from two advantages of this tool. First of all, same as the HTBAMs, this tool calculates the fuel economy in accordance with drive cycles, which constitutes a series of vehicle speeds as a function of time. Moreover, the regenerative braking system is integrated into this calculation of fuel economy. Secondly, ADVISOR contains a wide range of vehicle and fuel types so that some stakeholders, such as component suppliers, automobile manufacturers, future governments, and academic researchers, can benefit from the simulation results.

In spite of this, users cannot directly apply this tool for simulating the employment of ECVs in UFT because of the following limitations. Firstly, this tool analyzes the various technologies simply from an environmental point of view. The expenditure and the social impact of using ECVs are paid no attention. Secondly, the UFT and its logistical parameters are excluded from this tool. It results in a difficulty for users to employ appropriate types of ECVs to replace conventional vehicles in UFT.

3.2.2 Logistics-Oriented Tools

Calculating GHG Emissions for Freight Forwarding and Logistics Services

This is a guidance, which is published by the European Association for Forwarding, Transport, Logistics and Customs Services (CLECAT). The purpose of this guide is to provide a practical tool for logistics service providers that seek to make use of the European standard EN 16258 “Methodology for calculation and declaration of energy consumption and greenhouse gas emissions of transport services”, in order to determine their environmental footprint and seek ways to reduce it (Schmied et al., 2012). The readers can calculate the energy consumption and GHG emissions in compliance with sample calculations by applying standard

values. The energy consumption of the lorries, trains, ships, aircraft as well as buildings, warehouses and handling are involved in this guide.

This guide contributes to providing explicit methods for calculating the energy consumption and the GHG emissions by taking into consideration logistical parameters and diverse transport modes. The corresponding equations and WTW standard values are provided in accordance with the EN 16258. The role of these standard values is to transfer different units of energy consumption and GHG emissions into standardized unit mega joule (MJ) and CO₂ equivalent kilogram (kg). In short, this guide supports the freight forwarding and logistics services to analyze their own cases from the environmental dimension easily and efficiently.

Nonetheless, there are several limitations for readers to follow this guide. Firstly, although this guide involves logistical parameters and diverse transport modes, the UFT markets are unspecified. Secondly, in comparison with the vehicle-oriented tools, the total energy consumption and GHG emissions in this guide are calculated independent of the time (drive cycles or planned service years). Furthermore, the economic and social dimensions are not involved in this guide. This limitation leads to an incomprehensive assessment from a sustainable point of view. Finally, the electric vehicles, which has the capability of saving energy and reducing emissions to achieve sustainable UFT, are excluded from this guide.

Calculation and Allocation of UFT

Calculation and allocation of UFT (German original name Straßengüterverkehr Berechnung und Allokation: SBuA) is one module of a tool called CO₂-Method Kit. This tool is developed by Institut für Transportlogistik at the Technical University of Dortmund. The objective of this tool is to help small and medium-sized logistics enterprises with balancing their energy consumption, carbon dioxide emissions as well as GHG emissions (Institut für Transportlogistik TU Dortmund, 2018). This module focuses on the commercial vehicles of using conventional diesel, biodiesel, biodiesel 4%, 5%, 6%, and 7% blend. The energy consumption, CO₂ emissions, and CO₂ equivalent emissions from TTW and WTW are calculated by inputting the goods types, vehicle categories, fuel types, gradient, running road, actual transported weight, and actual traveled distance. The methods of calculation and the standard values are applied in compliance with the guide introduced in the last subsection.

There are two advantages in this module for supporting this dissertation. First of all, this module involves logistical parameters, such as goods types, transported weight, and traveled distance, to estimate the energy consumption and CO₂ equivalent emissions. Furthermore, this module takes into account the calculations from the perspective of TTW and WTW. This advantage may contribute to the users numerically and comprehensively understanding their transport operations

from the environmental point of view.

However, several limitations render this module unsatisfied for users to employ ECVs in UFT from a sustainable point of view. Firstly, this module only examines the environmental parameters. The differences in the expenditure are unclear from the economic point of view. In addition, the social dimension is also lacking in this module. Secondly, the vehicle categories and the fuel types are fewer in number than the AFLEET Tool and the relevant automotive parameters are overlooked. The logistical parameters are involved in this module, but these parameters describe unspecified UFT markets. Finally, this module is time-independent.

EcoTransIT

EcoTransIT World is an abbreviation of Ecological Transport Information Tool – Worldwide. It is free of charge internet application, which shows the environmental impact of freight transport on any route in the world and any transport mode (ifeu Heidelberg et al., 2016). This application aims to support the forwarding companies, carriers, logistics providers, political decision-makers, consumers, and non-governmental organizations. The purpose is to assist them in calculating the corresponding environmental parameters and comparing them thoroughly from logistic concepts including all transport modes (road, rail, air, maritime, and so on). This application provides two input modes. The standard input mode allows users to estimate energy consumption and GHG emissions quickly and efficiently. The extended input mode provides users some options to adapt their own cases with standardized units, such as changing the goods types, running routes, transport modes, vehicle categories (light-, medium-, and heavy-duty), fuel types (diesel, CNG, LNG, BEV), emission standards, load factors, and empty trip factors.

This application transformed the standard EN 16258 into an effective tool. The diverse transport modes and logistical parameters assist the relevant stakeholders in calculating and comparing their own cases. Nevertheless, same as the limitations of the guide, this application is independent of the time factor. Besides, few fuel types, few automotive parameters, unspecified UFT markets, and lack of consideration about economic and social impacts hinder users to apply this tool.

3.2.3 Benefits and Limitations of Existing Tools

A summary of purposes, strengths, and limitations of the six tools are illustrated in Table 4. On observing the vehicle-oriented tools, the typical advantages present in the wide range of vehicle categories and fuel types, the time-dependent, as well as the estimation of the economic and environmental performance from WTW. In particular, the wide range of vehicle categories and fuel types provides users more options to determine their satisfactory employment of ECVs in UFT. Moreover,

the estimation with taking into account the time-dependent feature, the economic and environmental performance, as well as the perspective of WTW may support users to understand the different options more comprehensively. In spite of this, the unspecified UFT markets, lack of logistical parameters, and the little attention to the social dimension hinder the decisions of users to employ ECVs in UFT from a sustainable perspective.

Table 4: Purposes, advantages, and limitations of existing tools

	Tools	Purposes	Advantages	Limitations
Vehicle-Oriented Tools	AFLEET	To estimate and compare multiple vehicle categories and fuel types from economic and environmental perspectives for clean cities stakeholders	Wide range of vehicle categories and fuel types; Time-dependent; Relatively full database; WTW	No logistical parameters; No social dimension
	HTBAMS	To estimate energy, environmental, and economic benefits for heavy trucks	Time-dependent; Future market; WTW	Few vehicle categories and fuel types; No logistical parameters; No social dimension
	ADVISOR	To provide the vehicle engineering community an analysis package for advanced vehicle modeling	Time-dependent; Wide range of vehicle categories and fuel types	No logistical parameters; No social and economic dimension
Logistics-Oriented Tools	CLECAT	To provide a practical tool for logistics service providers to determine their environmental footprint and seek ways to reduce it	Easy and clear methods; Logistical parameters; Diverse transport modes; WTW	Time-independent; No social and economic dimension; Few vehicle categories and fuel types; Unspecified UFT markets
	SBuA	To help small-and medium-sized logistic enterprises balancing their environmental parameters	Logistical parameters; WTW	Time-independent; No social and economic dimension; Few vehicle categories and fuel types; Unspecified UFT markets
	EcoTransIT	To assist freight transport stakeholders calculating environmental parameters and comparing them from	Logistical parameters; Diverse transport modes; WTW	Time-independent; No social and economic dimension; Few fuel types; Unspecified UFT

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Tools	Purposes	Advantages	Limitations
	logistic concepts including all transport modes		markets

Furthermore, in comparison with the vehicle-oriented tools, the logistics-oriented tools benefit from the logistical parameters and the estimation of the environmental performance in a wide range of transport modes from WTW. However, few vehicle categories and fuel types, few automotive parameters, unspecified UFT markets, and exclusive of social as well as economic dimensions are limitations for the logistics-oriented tools. These limitations imply that a diversity in the employment of ECVs in UFT has been overlooked. Besides, the study of sustainable UFT is incomprehensive. In conclusion, since the existing tools are either vehicle- or logistics-oriented tools, no existing tools can completely illustrate the employment of ECVs in UFT from a sustainable point of view.

3.3 Factors Influencing the Employment

This section extracts the factors influencing the employment of ECVs in UFT with respect to the three dimensions (economic, social, and environmental) of sustainable UFT. These factors refine the opportunities and limitations in the existing works and specify potential parameters for supporting the development of the methodological concept in Chapter 4.

3.3.1 Economic Factors

The factors in the economic dimension primarily focus on costs. These costs influence the decisions of purchasing ECVs and expanding ECVs in use. Normally, freight carriers (users) estimate and compare the Total Costs of Ownership (TCO), including the purchase price, insurance, registrations fees, fuel costs, maintenance costs, and depreciation costs, to determine whether a freight vehicle is appropriate to be purchased in large. Additionally, specific to the employment of ECVs, the financial incentives provided by governments are also involved in this decision.

In the economic perspective, the financial incentives, low energy costs, and low maintenance costs are considered as positive factors to facilitate the employment of ECVs in UFT. Specifically, the financial incentives are used to reduce the ownership costs of ECVs and their charging equipment (Pelletier et al., 2016). In addition, since the low energy and maintenance costs mitigate the high TCO, which results from the high purchase price, they constitute triggers for employing ECVs in UFT.

Financial Incentives

There are three aspects supported by the financial incentives (Pelletier et al., 2016). The first aspect is the purchase of ECVs, which is incentivized by purchase subsidies granted on buying ECVs. The vehicle based and the battery energy based subsidies are two categories of the purchase subsidies (Hou, Wang, & Ouyang, 2014). The vehicle based subsidies mean a constant amount of subsidy for buying one electric vehicle. For instance, the city of Amsterdam provides a 5,000 euro subsidy per vehicle for fully electric cars, delivery vans and taxis registered by companies (Tietge, Mock, Lutsey, & Campestrini, 2016). On the other hand, the battery energy based subsidies indicate that there is a constant amount of subsidy per kWh for buying one ECV. The total amount of subsidies depends on the traction battery capacity. For example, in China, an ECV, which has the traction battery capacity less than 30 kWh, receives 1,500 yuan ($\approx 192\text{€}^2$) per kWh; an ECV, which has the traction battery capacity between 30 kWh and 50 kWh, receives 1,200 yuan ($\approx 154\text{€}$) per kWh, and; an ECV, which has the traction battery capacity more than 50 kWh, receives 1,000 yuan ($\approx 128\text{€}$) per kWh (MIIT of PRC, 2016). In short, the purchase subsidy is a positive factor to reduce the TCO for users and to promote the consideration of employing ECVs from the economic point of view.

The second aspect supported by the financial incentives is charging infrastructures. From 2007 to 2013, the TEN-T program of the EU invested more than 4 million euros funding in 155 fast charging stations along the main motorways in northern Europe (Tietge et al., 2016). In addition to the EU's program, there are also specific subsidies of charging infrastructures in line with the regional and national policies. For instance, in the UK, the private chargers can apply for the Electric Vehicle Homecharge Scheme to cover a maximum of 75% of the total installation cost (Office for Low Emission Vehicles, 2016). In Poitou-Charentes, businesses with less than 500 employees and nonprofit organizations could receive a 50% subsidy of equipment and installation costs up to 20,000 euros in total (Tietge et al., 2016). These examples show that the subsidies of charging infrastructures are a positive factor in the economic dimension to mitigate the financial burden of charging ECVs.

Besides, taxes are the third aspect supported by the financial incentives. These taxes may be exempted from the Value Added Tax (VAT), vehicle registration taxes, fuel consumption taxes, company car taxes, and so on (Pelletier et al., 2016). For example, in Germany, BEVs registered between 2016 and 2020 are exempted from the road tax for five years. Moreover, in Norway, the taxes of BEVs are exempted from registration taxes, VAT, and company car taxes (Tietge et al., 2016). Given these points, these tax exemptions may support the reduction of the

² 1€=7.8yuan (02.01.2018)

TCO and facilitate the consideration of employing ECVs in UFT.

Energy and Maintenance Costs

In addition to the financial incentives, low energy and maintenance costs are also positive factors in the economic dimension. Nevertheless, these two positive factors are mainly of benefit to BEVs, since the reduction of energy and maintenance costs of HEVs, PHEVs, and FCEVs is not as dramatically as BEVs. As introduced in Section 2.3, HEVs and PHEVs are powered not only by on-board batteries but also by internal combustion engines. These two propulsion systems result in the energy costs of HEVs and PHEVs including fossil fuel costs and electricity costs. Hence, the energy costs of HEVs and PHEVs are not as low as BEVs. Furthermore, as studied by Melaina et al. (2014), total fuel costs per mile for BEVs and PHEVs are respectively 21% lower and 13% lower than that for FCEVs under the home-dominant scenario. It implies that the FCEVs have lower competitiveness in comparison with BEVs with regard to the energy costs. In the perspective of maintenance costs, BEVs have an advantage over HEVs, PHEVs, and FCEVs, since the configuration of BEVs is simplified and without using ICE. Consequently, the low energy and maintenance costs are mainly positive factors for promoting the employment of BEVs in UFT.

Purchase Price

Aside from the positive factors, there are some economic factors frequently discussed as negative factors in existing works (Iwan et al., 2014; Pelletier et al., 2016; Sierzchula, 2014). High purchase costs are one of the negative factors in the economic dimension. Taking the BEVs as an example, the purchase price of one delivery step van, which is entirely powered by electricity, is \$150,000, whereas a diesel delivery step van costs \$65,000 (Burnham, 2016). In terms of the federal tax credits for all-electric vehicles in the U.S., this BEV can receive up to \$7,500 subsidy depending on its battery capacity (“Federal Tax Credits for All-Electric and Plug-in Hybrid Vehicles,” 2017). Nevertheless, despite the fact that the regional and national policies provide financial incentives, such as this subsidy, the purchase price of BEVs is still high in comparison with diesel commercial vehicles.

Battery Costs

Additionally, high battery costs is also a research focus on studying the employment of ECVs in UFT. As stated by Pelletier et al. (2016), the projections of lithium-Ion battery pack cost will reduce from \$700/kWh in 2015 to \$200/kWh in 2030. This reduction indicates that the battery costs currently still dominate the purchase price, since the on-board battery capacity of one battery electric truck is mostly equal to or greater than 80 kWh. Furthermore, the battery costs have also

influence on the TCO. Commonly, the ownership of a commercial vehicle is planned for more than ten years, whereas the battery life is between six to eight years (Electrification Coalition, 2010; Lebeau et al., 2015). This difference reveals that the battery pack needs to be replaced with a new one, if this battery electric truck is planned to be used more than eight years. In this case, high battery costs lead to high battery replacement costs. Moreover, high battery replacement costs increase the TCO of employing ECVs in UFT. On the whole, the high battery costs are a negative factor influence on the purchase price and the TCO.

Charging Infrastructure Costs

The costs of charging infrastructures is an extra expenditure for freight carriers, who intend to use ECVs in their fleets. For conventional commercial vehicles, the public fuel stations are the main approach to refuel vehicles. Nevertheless, on account of insufficient public charging infrastructures, the freight carriers need to install their own charging infrastructures. According to the database of AFLEET tool (Burnham, 2016), a public charger for recharging BEVs and PHEVs costs \$5,500 and a public station for refueling FCEVs costs \$1,353,401. Therefore, the costs of charging infrastructures as an extra cost become a negative factor in the employment of ECVs in UFT.

In conclusion, on account of the high purchase price, battery replacement costs, and charging infrastructure costs, the positive factors in the economic dimension (financial incentives as well as low energy and maintenance costs) currently have limited contributions to the competitiveness of ECVs in comparison to diesel commercial vehicles.

3.3.2 Social Factors

The social dimension in sustainable UFT involves a wide range of factors. As defined in Section 2.2, the factors, which influence the attractiveness and quality of the urban environment, can be considered as social factors. In this perspective, social factors can relate to health, safety, security, mobility, and accessibility. Among these factors, the primary attention has been paid to the accessibility in the literature. In this research, the accessibility is considered as goods' ability to reach required services and destinations (Litman & Burwell, 2006), namely the accessibility of using ECVs to deliver goods in UFT. To this effect, the studies on the accessibility in this dissertation have shifted to focus on the access incentives, driving range, as well as charging infrastructures of ECVs in UFT.

Prioritized access incentives are a positive factor from the social point of view. The objective of these incentives is to encourage the use of freight ECVs. There are three types of prioritized access incentives (Pelletier et al., 2016). The first type of incentives grants freight BEVs access to high occupancy lanes or bus lanes, which

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has been done in Utrecht, Lisbon, and Trondheim. The second type of incentives proposes a concept - low emission zones in city centers. ECVs are allowed in the zone and have privileges, such as exempt from a charge, enter the city center at night, and exempt from restrictions on the maximum weight of vehicles allowed in city centers. The third type of incentives is preferential parking for ECVs either in allocating free spaces or designated loading and unloading. In conclusion, the prioritized access incentives improve the goods' ability to reach the required services and destinations by giving privileges to the use of ECVs.

Although the prioritized access incentives improve the accessibility, the driving range of ECVs, as well as the locations and the number of charging infrastructures, are still the issues for ECVs to reach required services and destinations. As stated by NOW (2013), BEVs' driving range is normally between 150 and 250 km, FCEVs' driving range is between 400 and 600 km, whereas ICE vehicles' driving range is between 800 and 1200 km. Obviously, the driving range of ICE vehicles has an advantage over BEVs and FCEVs. This strength of ICE vehicles indicates that the accessibility of using BEVs and FCEVs to transport goods is not as good as the accessibility of ICE vehicles. Therefore, the limited driving range constitutes a negative factor leading to the low accessibility in the social dimension.

To improve the driving range, the attention has been paid increasingly on the installation of public charging and hydrogen refueling infrastructures. The objective of installing the infrastructures is to mitigate the anxiety of the limited driving range and improve the low accessibility. The locations and the number of infrastructures are significant for freight carriers to plan their routes (Afrodit, Boile, Theofanis, Sdoukopoulos, & Margaritis, 2014; Conrad & Figliozzi, 2011; Schneider et al., 2014; Sevgi Erdogan, Miller-hooks, 2012). Nevertheless, the insufficient number of public infrastructures render the charging and refueling ECVs as well as the route plan difficult. For instance, in Norway, 2.4 public charging points on average are available for every 1,000 cars registered³ (Tietge et al., 2016). This data implies that the number of public charging infrastructures in Norway may not match the increasing number of electric vehicles in use. As a result, the insufficient number of infrastructures, which are applied to solve the limited driving range and to improve the accessibility, is considered as a negative factor in the social dimension.

To summarize, although the regional and national policies support and facilitate the employment of ECVs in UFT by proposing the prioritized access incentives, the limited driving range of ECVs as well as the locations and number of charging infrastructures are still issues for improving accessibility in the social dimension.

³ Including ICE and electric passenger cars

3.3.3 Environmental Factors

The factors in the environmental dimension, which have been studied in the literature and existing tools regarding the employment of ECVs in UFT, mainly focus on the issues of pollution and energy consumption. Among these factors, the pollution commonly refers to air pollution, noise pollution, as well as the production and disposal of batteries. The energy consumption includes the amount of consuming fossil fuels from Tank to Wheel (TTW) and from Well to Wheel (WTW).

In the perspective of pollution, air pollution has been frequently discussed in the literature. The conventional commercial vehicles are the main source of the air pollution in urban areas. As stated in Section 2.1, air pollution involves many elements. Among these elements, the attention is widely paid to the GHG emissions. Employing ECVs in UFT has been recommended as a measure to reduce GHG emissions. For instance, according to the study of den Boer et al. (2013), in the scenario where 50% of total EU ton kilometers are transported by ECVs in 2050, GHG emissions would decrease by 8% compared to 2012 in the perspective of WTW. Furthermore, simplified configurations of ECVs without using internal combustion engines reduce the noise pollution not only for the urban areas but also for drivers.

The low energy consumption of ECVs is a positive factor in the environmental dimension. As introduced in Section 2.3, the ECVs are partially or entirely powered by electric energy. This feature indicates that the ECVs may save more fossil fuels in comparison with diesel commercial vehicles from the perspective of TTW. The amount of energy saving by ECVs depends on vehicle types. For example, BEVs is independent of fossil fuels. It implies that there are no fossil fuels consumed on board. Additionally, since HEVs and PHEVs remain two propulsion systems on board (ICE and electric motors), they are then still dependent on fossil fuels and may save energy more than diesel commercial vehicles. Besides, the amount of energy saving of ECVs is also dependent on the load carried and the driving conditions (Alternative Fuels Data Center, 2018b). In short, the low energy consumption is a positive factor attracting the employment of ECVs in UFT.

In addition to considering the on-board energy consumption and the GHG emissions from the tailpipe, the attention regarding the energy consumption and pollution of ECVs from the perspective of WTW has to be paid as well. In this perspective, energy consumption involves not only on-board fuel consumption but also the consumption of energy sources. For example, although the electric energy generated by batteries is regarded as the green energy used in ECVs, the electricity, which is provided for charging infrastructures, can be produced by petroleum, gas, coal, biomass fuel, or renewable energy. It indicates that the energy consumption

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of ECVs from life cycle's point of view may not as low as the consumption from the tank to wheel. Similarly, the total GHG emissions of employing ECVs would increase from well to wheel, if the electricity and hydrogen are produced by fossil fuels. Accordingly, the benefits of using ECVs, such as low energy consumption and GHG emissions, may reduce in the perspective of WTW. Likewise, as a significant component of ECVs, the life cycle assessment of batteries from the production to the disposal should be studied as well in the environmental dimension.

Given these points, the low energy consumption, GHG emissions, and noise of ECVs may attract more attention for considering the employment of ECVs in UFT. Furthermore, the life cycle assessment of energy consumption, GHG emissions, as well as batteries is also worth being considered, particularly before the future commercialization of ECVs.

In the end, exclusive of the factors in the three dimensions, there are several factors influence the employment of ECVs in UFT from the perspective of freight carriers, such as their corporate social responsibility, their public image, the pressure from government regulations, the first mover advantage, and testing new technologies (Sierzchula, 2014; Visser et al., 2014).

To distinctly illustrate the factors considered in the existing works regarding the employment of ECVs in UFT, Table 5 shows a summary of these positive and negative factors respectively in economic, social, and environmental dimensions. There are two contributions to studying these factors. One contribution is to gain insight into the strengths and limitations of employing ECVs in UFT. Additionally, the study of the factors also contributes to exploring potential parameters for supporting the development of the methodological concept in Chapter 4.

Table 5: A summary of factors in three dimensions

Dimensions	Positive Factors	Negative Factors
Economic	Financial incentives: <ul style="list-style-type: none"> • Purchase subsidies of ECVs; • Subsidies of charging infrastructures; • Tax exemptions; Low energy costs; Low maintenance costs	High purchase costs; High battery costs; High costs of charging infrastructures;
Social	Prioritized access incentives	Low accessibility
Environmental	Environmentally friendly: <ul style="list-style-type: none"> • Low energy consumption; • Low GHG emissions; • Low noise 	Energy sources; Production and disposal of batteries

In conclusion, although a group of positive factors is supporting the employment, the negative factors summarized from the literature and existing tools are still the primary limitations for the employment of ECVs in UFT. In other words, although these limitations have been discussed to deal with the issues in the employment of ECVs in UFT, the market penetration of ECVs is still low in our daily life.

3.4 Limitations of the Employment

This section provides a different perspective to illustrate a potential limitation of the employment of ECVs in UFT. As stated in Section 2.4, there is a conflict between the intention of employing ECVs in UFT and the real market penetration of ECVs. To analyze the potential limitation leading to the conflict, this section introduces a feature in the employment of ECVs in UFT (Section 3.4.1) and reviews the corresponding state of the art (Section 3.4.2).

3.4.1 Diversity in the Employment

Oliveria et al. (2015) have stated that, towards increasing the market share of a product, it is crucial to obtain a satisfactory match between product characteristics and consumer preferences. Concordant to a context of this dissertation, increasing the number of ECVs employed in UFT requires satisfying the match between characteristics of ECVs and requirements of markets in UFT. As introduced in Section 2.1 and 2.3, there are five UFT markets and four types of ECVs. In this perspective, these diverse types of ECVs and various UFT markets complicate the process of obtaining a satisfactory match.

This complication can be visualized as shown in Figure 5. The four types of ECVs (x_1, x_2, x_3, x_4) as the products have their own characteristics. The freight carriers in the five UFT markets (y_1, y_2, y_3, y_4, y_5) as consumers have their respective requirements. In this context, matching up the four types of ECVs and five UFT markets generates many possibilities. These possibilities present a diversity in the employment of ECVs in UFT. Accordingly, this diversity complicates the selection of a satisfactory match.

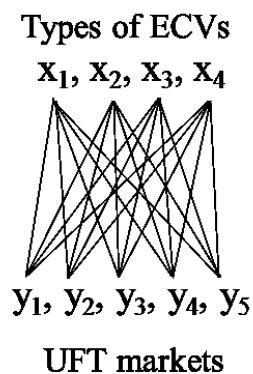


Figure 5: The possibilities of employing ECVs in UFT

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To further understand the diversity and figure out the number of possibilities, this dissertation denotes this diversity in employing ECVs in UFT as the ECV-UFT combinations. The set V is defined to hold the four types of ECVs:

$$V = \{\text{BEVs, HEVs, PHEVs, FCEVs}\} \quad (1)$$

The number of subsets in the set V is 16 (2^4) including the empty set and V itself. These subsets of set V are shown as follows: \emptyset , {BEVs}, {HEVs}, {PHEVs}, {FCEVs}, {BEVs, HEVs}, {BEVs, PHEVs}, {BEVs, FCEVs}, {HEVs, PHEVs}, {HEVs, FCEVs}, {PHEVs, FCEVs}, {BEVs, HEVs, PHEVs}, {BEVs, HEVs, FCEVs}, {BEVs, PHEVs, FCEVs}, {HEVs, PHEVs, FCEVs}, {BEVs, HEVs, PHEVs, FCEVs}.

The set M is defined to hold the five markets in UFT:

$$M = \{\text{Retail, Express/Post, HoReCa, Construction, Waste}\} \quad (2)$$

The number of subsets of M is 32 (2^5). The formation of subsets in set M is the same as the set V . Among these subsets, the empty subsets of V and M indicate the unspecified types of ECVs and unspecified markets in UFT, respectively. Next, the set of the ECV-UFT combinations is given by the Cartesian product of the sets V and M as indicated in Eq. 3:

$$C_{\text{ECV-UFT}} = V \times M = \{(v, m) \mid v \in V, m \in M\} \quad (3)$$

Accordingly, the number of subsets in the set $C_{\text{ECV-UFT}}$, namely the total number of ECV-UFT combinations, is 512. This result is calculated by the product of the subsets' numbers of V and M ($2^4 \cdot 2^5$). In consideration of the many subsets in $C_{\text{ECV-UFT}}$, Table 6 shows a group of subsets in the set $C_{\text{ECV-UFT}}$ as an example to explain the formation of the ECV-UFT combinations.

Table 6: Examples of the subsets in $C_{\text{ECV-UFT}}$

Subsets in $C_{\text{ECV-UFT}}$	Subsets in $C_{\text{ECV-UFT}}$
BEVs – Unspecified	(BEVs, HEVs) - Unspecified
BEVs – Retail	(BEVs, HEVs) - Retail
BEVs - Express/post	(BEVs, HEVs) - Express/post
BEVs - (Retail, Express/post)	(BEVs, HEVs) - (Retail, Express/post)
HEVs - Unspecified	Unspecified - Unspecified
HEVs – Retail	Unspecified - Retail

Subsets in $C_{ECV-UFT}$	Subsets in $C_{ECV-UFT}$
HEVs - Express/post	Unspecified - Express/post
HEVs - (Retail, Express/post)	Unspecified - (Retail, Express/post)

This group of subsets refers to all possibilities in the combinations between two types of vehicles (BEVs and HEVs) and two UFT markets (retail and express/post) including the empty set (unspecified). The total number of the subsets in this group is derived from the product of the subsets' numbers of two vehicle types and two UFT markets ($2^2 \cdot 2^2 = 16$). The brackets in some subsets represent that the elements in the brackets are one subset. For instance, in the subset: (BEVs, HEVs) - Retail, the two vehicle types are considered as one subset in the set V and the retail market is the subset in the set M. This subset presents a situation that the two vehicle types can be simultaneously employed in the same UFT market. Following this example, the combinations between four types of ECVs and five UFT markets generate 512 possibilities in the set $C_{ECV-UFT}$. This number implies that obtaining a satisfactory match for increasing the market penetration of ECVs has to consider the diversity outlined in this subsection.

There are 16 ECV-UFT combinations appeared in the literature (Table 7). The check marks in this table refer to the ECV-UFT combinations that were considered in the four areas of focus extracted in Section 3.1, whereas the cross marks refer to the ECV-UFT combinations excluded in these areas. This table can be read in two perspectives. In the perspective of combinations, some articles considered only one vehicle type in one UFT market, such as BEVs-Retail and HEVs-Express/post. On the contrary, some articles discussed diverse vehicle types in various UFT markets, such as (BEVs, HEVs, PHEVs)-(Retail, Express/post). In the perspective of the areas of focus, the study regarding the feasibility has considered the most number of the 16 ECV-UFT combinations (75%) appeared in the literature in comparison with the other three areas.

Table 7: ECV-UFT combinations in four areas of focus

ECV-UFT Combinations	Feasibility	Logistics	Vehicles	Stakeholders
BEVs-Unspecified	√	√	√	√
BEVs-Retail	√	√	×	√
BEVs-Express/post	×	√	×	×
BEVs-(Retail, Express/post)	√	√	√	×
HEVs-Unspecified	√	×	×	×

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ECV-UFT Combinations	Feasibility	Logistics	Vehicles	Stakeholders
BEVs-(Retail, Express/post, HoReCa, Construction, Waste)	√	×	×	×
HEVs-Express/post	×	×	√	×
BEVs-Waste	√	×	×	×
BEVs-(Retail, HoReCa)	×	√	×	×
BEVs-(Retail, Express/post, Construction)	√	×	×	×
BEVs-(Retail, Express/post, HoReCa, Waste)	√	×	×	×
(BEVs, HEVs)-Unspecified	√	×	×	×
(BEVs, PHEVs)-Unspecified	√	×	×	×
(BEVs, HEVs, PHEVs)-(Retail, Express/post)	×	√	×	×
(BEVs, HEVs, PHEVs)-(Retail, HoReCa)	√	×	×	×
(BEVs, HEVs, PHEVs, FCEVs)-Unspecified	√	×	×	×

To render the 16 ECV-UFT combinations comparable with the number of total ECV-UFT combinations (512), the all possible subsets in these 16 ECV-UFT combinations are further derived. The procedure of deriving the subsets is the same as the formation of the 512 ECV-UFT combinations introduced below Eq.3. For instance, the combination of the three vehicle types (BEVs, HEVs, PHEVs) and the two UFT markets (Retail, Express/post) constitutes 32 ($2^3 \cdot 2^2$) possible subsets including empty sets. In total, there are 236 possibilities derived from the calculation of all possible subsets in each of the 16 ECV-UFT combinations. Since some subsets are repeatedly calculated, there are finally 82 possible ECV-UFT combinations derived from the existing 16 ECV-UFT combinations exclusive of the repeated subsets. The details of the 82 possible ECV-UFT combinations are shown in Appendix 1. In comparison with the total number of ECV-UFT combinations, the 82 possible ECV-UFT combinations account for only a small portion of this total number (16%). This percentage indicates that the literature has paid the least attention to many other possible ECV-UFT combinations (approximately 84%).

The least attention paid by the literature may lead to the low market penetration of ECVs. In other words, the results derived from few specific ECV-UFT combinations in the literature may only contribute to understanding and solving

few specific scenarios. This limited understanding and few solutions about the ECV-UFT combinations hinder the decision-makers to obtain the satisfactory match. For instance, there were few ECV-UFT combinations examined in the area of feasibility. This few examinations lead to the limited understanding concerning the feasibility of the rest of ECV-UFT combinations. This shortage of comprehensive understanding may result in a difficulty for decision-makers to determine the satisfactory match.

Given these points, the little diversity considered in the literature may constitute a challenge of obtaining a satisfactory match. In this perspective, Lebeau et al. (2015), Watróbski et al. (2017), and Christensen et al. (2017) in Table 3 have considered this challenge to emphasize the significance of taking into account such diversity. In particular, Lebeau et al. (2015) revealed the opportunities for reducing costs of UFT by including different fuel types of commercial vehicles in a fleet. Watróbski et al. (2017) stated the importance of considering the specificity of the delivery tasks in UFT to properly choose BEVs. Christensen et al. (2017) noticed the significance of the diversity and investigated the suitable commercial sectors of UFT to employ BEVs. In conclusion, the diversity is a feature in the employment of ECVs in UFT. However, little attention on this feature leads to a difficulty of obtaining a satisfactory match for increasing the market penetration of ECVs in UFT.

3.4.2 Satisfactory Match

This subsection focuses on the study of the satisfactory match in urban transport. The purpose is to gain insight into the state of the art about the satisfactory match and discuss the challenges of obtaining such a match. Besides, the methods of Multi-Criteria Decision Making (MCDM) are briefly reviewed in this section to support further understanding of the challenges regarding the satisfactory match in the perspective of methods.

Due to the fact that the satisfactory match has been few considered in UFT, this subsection, therefore, focuses on increasing the understanding of the satisfactory match by extending the research field to Urban Passenger Transport (UPT). There are some literary works studied regarding the satisfactory match in the UPT systems. For instance, Zubaryeva et al. (2012) and Mohamadabadi et al. (2009) have addressed issues regarding the suitable choice of electric passenger cars. Tzeng et al. (2005) and Vahdani et al. (2011) have concentrated on investigating the proper choice of electric buses. In addition to the selection of vehicles, Oliveira et al. (2015) and Ziegler (2012) have studied customer preferences for electric passenger cars. Given these points, compared to the literature on the choice of vehicles and customer preferences in UPT, few studies have addressed the same topic in UFT (see Section 3.1).

Furthermore, to select proper vehicles, the study regarding the satisfactory match in urban transport prefers to apply MCDM. The MCDM is a branch of Operation Research (OR) models, which deal with decision problems under the presence of a number of decision criteria (Triantaphyllou et al., 1998). The MCDM is widely applied to solve various real-life decision problems, such as addressing issues in logistics, environment, manufacturing, architecture, marketing, service, industry, sports, tourism, health-care, and higher education (Ho, 2008; Ho, Xu, & Dey, 2010; Pohekar & Ramachandran, 2004; Wong & Li, 2008). In the perspective of obtaining the satisfactory match, the decision problem refers to the selection of proper vehicle types, the alternatives for the decision refer to the different vehicle types, and the multiple criteria in the decision refer to the customer preferences.

There are many methods in the MCDM to deal with decision problems. The *Weighted Sum Model (WSM)* is a commonly used method in single-dimensional cases. The score of the best alternative by applying this method is calculated by the following expression (Triantaphyllou et al., 1998):

$$A_{WSM} = \max\{\sum_{j=1}^N a_{ij} \cdot w_j \mid i = 1, 2, 3, \dots, M\} \quad (4)$$

where A_{WSM} is the WSM score of the best alternative, N is the number of decision criteria, M is the number of alternatives, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of the j^{th} criterion.

Similar to the WSM, the *Weighted Product Model (WPM)* is another MCDM method by replacing the addition in Eq.4 with multiplication (Eq.5) (Triantaphyllou et al., 1998).

$$R\left(\frac{A_k}{A_L}\right) = \prod_{j=1}^N (a_{kj}/a_{Lj})^{w_j} \quad (5)$$

where A is the score of each alternative, N is the number of criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion.

On the basis of the structure in Eq. 5, the WPM can eliminate the units of the actual values to rank the alternatives in multi-dimensional decision-making cases. The better alternative can be identified by the result $R(A_k/A_L)$. If this result is greater than one, then the alternative A_k is better than A_L and vice versa. If this result is equal to one, the alternative A_k and A_L show identical performance.

Analytic Hierarchy Process (AHP) is a method, which has the capability of solving the single- and multi-dimensional MCDM problems (Triantaphyllou et al., 1998). This method decomposes complex MCDM problems into hierarchical systems and ranks the priority of alternatives through pairwise comparisons. The priority scales that measure intangibles in relative terms are derived from the judgments of

experts (Saaty, 2008). There are four steps to generate priorities (Saaty, 2008). The first step is to define the MCDM problem and determine the kind of knowledge sought. Secondly, a hierarchical structure (Figure 6) is developed with the top level (the goal of the decision), the intermediate levels (a set of criteria and sub-criteria), and the lowest level (a set of alternatives).

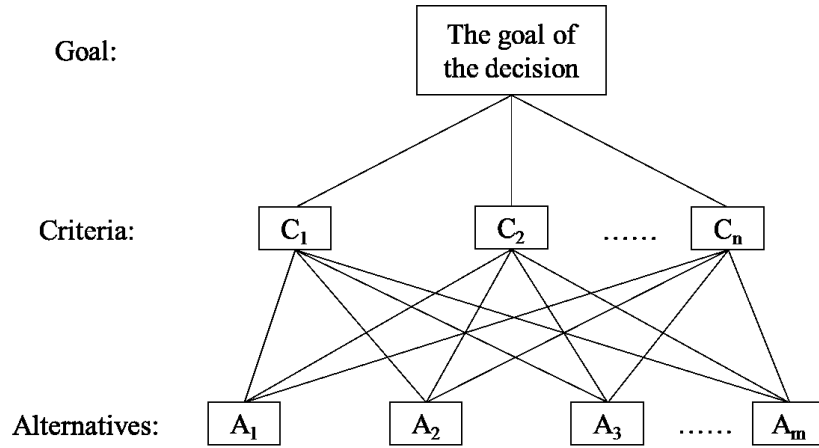


Figure 6: A hierarchical structure of AHP

Thirdly, a set of pairwise comparison matrices is constructed with respect to the goal and the criteria. Each element in an upper level is used to compare the elements in the level immediately below with respect to this element in the upper level. A scale of numbers from 1 to 9 is used to indicate the importance of elements. The experts, who select the numbers, determine the priorities (Wang & Thoben, 2016). Finally, after comparing all of the elements, the weights of each element including the criteria and alternatives with respect to their parent elements are derived. The global priority, namely scores of each alternative, is then calculated by using the equations in the last column of Table 8. Consequently, the decision-makers may determine the ranking of alternatives depending on the calculated scores.

Table 8: Decision matrix of AHP

Alternatives	Criteria				Results
	C ₁	C ₂	...	C _N	
A ₁	a ₁₁	a ₁₂	...	a _{1N}	$r(A_1) = \sum_{j=1}^N a_{1j} \cdot w_j$
A ₂	a ₂₁	a ₂₂	...	a _{2N}	$r(A_2) = \sum_{j=1}^N a_{2j} \cdot w_j$
⋮	⋮	⋮	⋮	⋮	⋮
A _M	a _{M1}	a _{M2}	...	a _{MN}	$r(A_M) = \sum_{j=1}^N a_{Mj} \cdot w_j$

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In Table 8, A_m represents the alternatives, M is the number of alternatives, C_n is the criteria, N is the number of criteria, a_{MN} is the relative value of the alternative A_M when it is considered in terms of decision criterion C_N , w_j is the weight of importance of the j^{th} criterion, and $r(A_M)$ is the score of the alternative A_M .

On the whole, the AHP is a method, which constructs hierarchical structures to conduct pairwise comparisons by using a scale of numbers from 1 to 9 exclusive of units. The experts, who have the intuition, the experience, and the judgment with regard to the field of decision problems, subjectively select numbers from the scale and determine the ranking of alternatives.

In addition to the aforementioned methods (WSM, WPM, and AHP), the Elimination and Choice Translating Reality (ELECTRE, French original name), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), and the multi-criteria optimization and compromise solution (VIKOR, Serbian original name), are also the methods commonly used in MCDM (Pohekar & Ramachandran, 2004; Triantaphyllou et al., 1998).

The principle of MCDM and its methods have been applied and adapted in the studies about the satisfactory match in urban transport. For example, since there is a need to combine multiple criteria (demography, environment, economy, energy, and transport) to rank different potential EV market drivers, a Geographic Information System (GIS)-based multi-criteria decision support process with fuzzy measures was developed in Zubaryeva et al. (2012) to identify potential lead markets for electric passenger cars (BEVs and PHEVs) in Europe. Moreover, to evaluate the alternative-fuel buses (diesel, hydrogen, electric, hybrid electric) for the urban areas in Taiwan, Tzeng et al. (2005) applied the AHP to determine the relative weights of evaluation criteria (including social, economic, technological, and transportation aspects) and TOPSIS as well as VIKOR to determine the best compromise alternative fuel mode. Besides, in the perspective of UFT, Watróbski et al. (2017) applied PROMETHEE II and fuzzy TOPSIS to select proper vehicle types of available BEVs under the technical and economic criteria. Given these points, the MCDM has been considered to solve the decision problems regarding the satisfactory match in the literature.

3.5 Summary

This chapter illustrates the opportunities and the limitations of the employment of ECVs in UFT by reviewing the literature and existing tools (Section 3.1-3.3). Although these limitations discussed to deal with the issues in such employment, the market penetration of ECVs is still low. Accordingly, Section 3.4 provides a different perspective to analyze low market penetration.

On the basis of gaining insight into such employment, a feature – diversity in the employment of ECVs in UFT as the perspective was proposed and defined in this chapter. The potential limitation (exclusive of the limitations studied in the literature) leading to the low market penetration was analyzed. Since obtaining a satisfactory match between the characteristics of ECVs and the requirements of UFT is a solution to increase the market penetration, the many possibilities resulted from the diversity (512 ECV-UFT combinations) has become a limitation for decision-makers to select their satisfactory match. Moreover, in the literature and existing tools, little attention has been paid on the diversity and the satisfactory match. In other words, the decision-makers cannot derive appropriate and systematic solutions from academic studies to support themselves in better understanding the diversity. This incomprehensive understanding may result in a difficulty of determining the satisfactory match for increasing the market penetration of ECVs in UFT. Therefore, the potential limitation can be outlined that there is a need for a systematic solution to guide and support decision-makers in obtaining their satisfactory match based on a comprehensive understanding of the diversity.

To deal with this limitation, the next chapter focuses on proposing a methodological concept by refining the challenges and the requirements of obtaining a satisfactory match.

4 Sustainable ECV-UFT Matching Concept

A methodological concept named Sustainable ECV-UFT Matching Concept is proposed in this chapter to deal with the limitation identified in Chapter 3. Four sections constitute this chapter. In Section 4.1, the challenges of obtaining a satisfactory match are refined according to the state of the art reviewed in Chapter 3. In Section 4.2, the main focus, the objective, and the requirements for the methodological concept are specified. Subsequently, to address the challenges and meet the requirements, the Sustainable ECV-UFT Matching Concept is accordingly proposed. In particular, two methodologies including the methodology of assessment (Section 4.3.1) and the methodology of determination (Section 4.3.2) constitute this concept. Among them, the methodology of assessment is designed to assess diverse ECV-UFT combinations quantitatively under the economic, social, and environmental dimensions. The methodology of determination is proposed to support decision-makers to analyze the assessment results and determine the satisfactory match. By following this methodological concept, decision-makers may assess the ECV-UFT combinations that they are interested in under the three dimensions and determine their satisfactory match. Finally, a summary of this chapter is shown in Section 4.4.

4.1 Challenges of Obtaining a Satisfactory Match

This section refines the challenges of obtaining a satisfactory match according to the identified limitation of the employment of ECVs in UFT (Section 3.4). With gaining insight into this research field, such challenges mainly result from three elements, namely the diversity (many ECV-UFT combinations), the multiple criteria (economic, social, and environmental dimensions), and the multiple factors (see Section 3.3). Figure 7 provides an example to portray how the three elements cause challenges.

4 Sustainable ECV-UFT Matching Concept

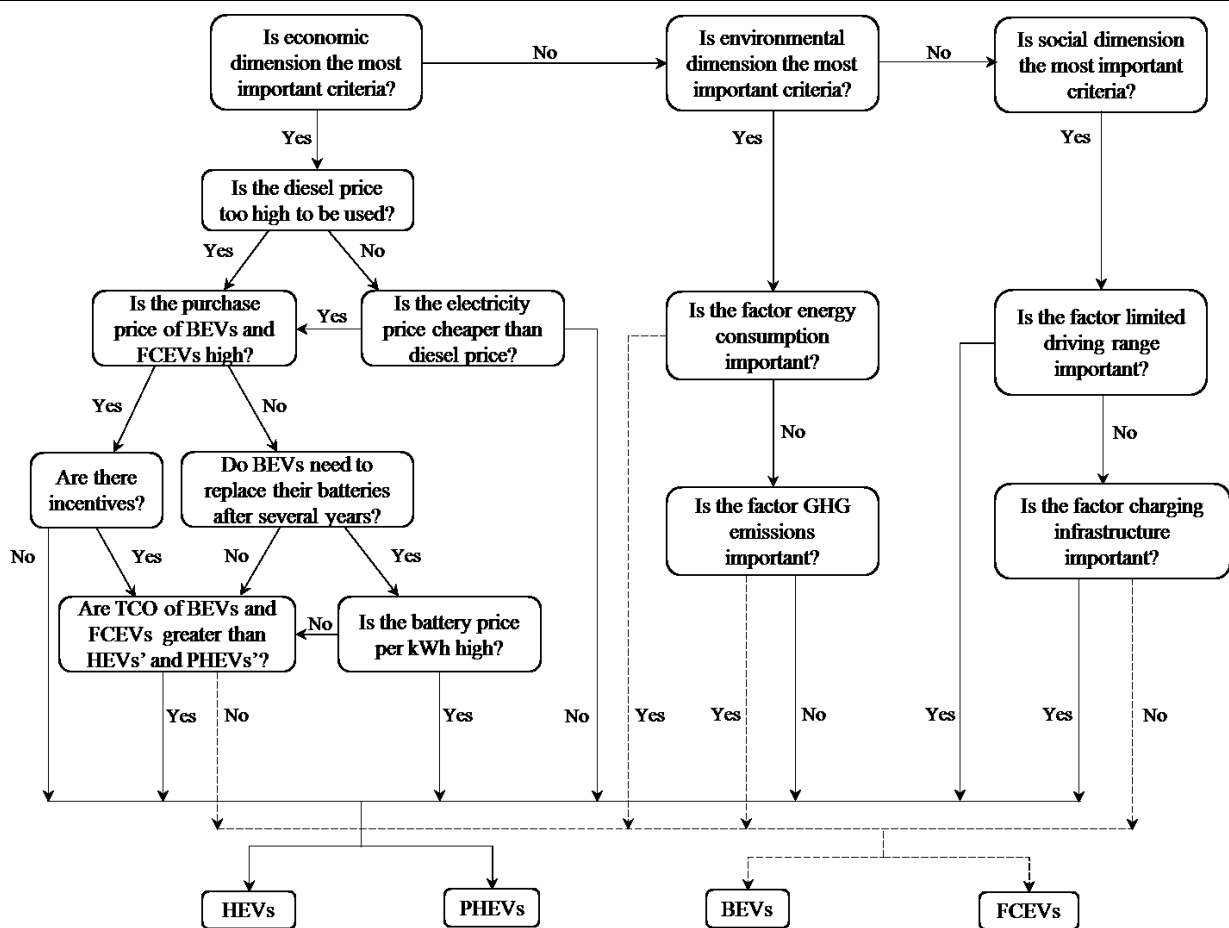


Figure 7: A tree diagram for explaining the formation of the challenges

In this diagram, the three dimensions of sustainable UFT are considered as the criteria. The factors extracted from studies influence the determination of the satisfactory match. Moreover, the UFT markets are assumed identical. It means that the ECV-UFT combinations refer to the four vehicle types in this example. There are two groups of these vehicle types classified regarding the similarity of their characteristics. One group is constituted by HEVs and PHEVs using solid lines. The other group consists of BEVs and FCEVs using dashed lines.

This tree diagram reveals a typical MCDM problem. The multiple criteria and factors complicate the determination of the satisfactory type of ECVs in an identical UFT market. Additionally, the objectives of the multiple criteria are conflicting (Wątróbski et al., 2017). For instance, reducing the TCO is one of the objectives in the economic criteria. However, the objective of replacing diesel commercial vehicles with ECVs to reduce GHG emissions in the environmental criteria may increase the TCO from the perspective of economic criteria. In this context, the complication and the conflict render the determination of the satisfactory match difficult. Moreover, this difficulty is formed in the condition of four ECV-UFT combinations. If conditions expand to including all ECV-UFT combinations (512), the extent of the difficulty will be more considerable. To this

effect, there is a need for a solution to support decision-makers assessing the diverse ECV-UFT combinations and determining the satisfactory match.

Nevertheless, no existing tools have provided such solutions. First of all, as discussed in Section 3.2, to obtain a satisfactory match, it is crucial that the solution in the tools can involve all possibilities of ECV-UFT combinations. Moreover, since the satisfactory match refers to matching up the characteristics of ECVs and the requirements of UFT markets, the automotive and logistical parameters, which can represent the characteristics and the requirements, should be both considered in the existing tools. Furthermore, due to the fact that the employment of ECVs is an emerging measure for achieving the sustainable UFT, the time-dependent parameters are required to be taken into account in the existing tools for comprehensively understanding the future scenarios. Besides, there is also a need for including all three dimensions of sustainable UFT in the existing tools for determining the satisfactory match. However, few ECV-UFT combinations, lack of the automotive and logistical parameters as well as their connections, independent of time parameters, and little attention to the social dimension hinder the existing tools to accomplish the assessment and the determination of the satisfactory match.

In addition, although the literature and existing tools provide some methodologies and different methods of MCDM are applied in urban transport to study the satisfactory match (see Section 3.4.2), there is still no methodology suitable to the task of obtaining the satisfactory match in the outlined context. For instance, the methodology applied in AFLLET Tool presents a procedure including choosing the vehicle and fuel types, which are intended to be assessed; calculating their TCO and life-cycle petroleum use as well as air pollution, and; graphically showing the outputs. The methodology of EcoTransIT shows a system of choosing the vehicle and fuel types; entering data of logistical parameters; calculating the TTW and WTW energy consumption and GHG emissions, and; graphically illustrating the results. In addition, the methodology in Watróbski et al. (2017) includes setting the criteria and alternatives of MCDM; determining and modeling preferences; applying PROMETHEE II and fuzzy TOPSIS method; ranking the vehicle types of BEVs under the technical and economic criteria, and; analyzing robustness and sensitivity of obtained solution. Using these three methodologies can partially complete the task of obtaining a satisfactory match, such as the acquisition of the satisfactory vehicle or fuel type, which has the best economic or environmental performance. Nevertheless, few ECV-UFT combinations, lack of the connection between the automotive and logistical parameters, as well as little attention to the social dimension are still the difficulty of obtaining the satisfactory match by using these methodologies.

Given these points, the challenges of obtaining a satisfactory match are refined as follows:

4 Sustainable ECV-UFT Matching Concept

There is no appropriate methodology conducted the assessment of the diverse ECV-UFT combinations and the determination of the satisfactory match by taking into consideration:

- *time-dependent parameters;*
- *automotive and logistical parameters as well as their connections, and;*
- *economic, social, as well as environmental dimensions,*

to increase the market penetration of ECVs for achieving sustainable UFT.

4.2 Requirements for the Methodological Concept

In this section, the main focus, the objective, and the requirements of the methodological concept are specified to support in addressing the refined challenges. There are two aspects of the main focus outlined from the challenges. One aspect is to assess the diverse ECV-UFT combinations, and the other aspect is to determine the satisfactory match from the diverse ECV-UFT combinations regarding the assessment results. In this perspective, the objective of developing the methodological concept is to propose appropriate methodologies for quantifying the assessment and numerically supporting decision-makers to determine the satisfactory match. Furthermore, to develop an explicit concept for addressing the challenges, the requirements are specified. Four phrases in the challenges are significant for specifying the requirements. These four phrases include diverse ECV-UFT combinations; time-dependent; automotive and logistical parameters; as well as the three dimensions. The details of these requirements are elaborated as follows.

The first requirement is specified that the proposed concept should allow involving all of the ECV-UFT combinations. As defined in Section 3.4.1, there are a total of 512 ECV-UFT combinations in consideration of the four vehicle types of ECVs and five UFT markets. However, the state of the art presents that the literature has paid attention only to a small portion of the ECV-UFT combinations, while many other possible ECV-UFT combinations have been overlooked. In this context, the least attention paid by the literature contributes to incomprehensive understanding and few specific solutions. This lack results in the difficulty for decision-makers to determine the satisfactory match. Therefore, the first requirement of developing the concept is to consider all the possibilities of the ECV-UFT combinations.

The second requirement is specified to take into account the time-dependent parameters including the planned service years of ECVs and the drive cycles. The planned service years refer to the years of planned ownership of commercial vehicles for freight carriers. This parameter allows to assess and predict the current

as well as the future performance of the ECV-UFT combinations. In this context, the performance presents a clear view for supporting the decision-makers in determining the satisfactory match, which is suitable for current and future scenarios.

Furthermore, drive cycles, which are applied for measuring fuel economy, also constitute a time-dependent parameter in the second requirement. Commonly, there are three ways, which comprise using chassis dynamometers, real-world data, and custom drive cycles, to measure the fuel economy. Applying the chassis dynamometer is a measurement to test the fuel economy according to a standard drive cycle in the laboratory. This test is exercised by a driver following a prescribed speed trace on the test aid monitor to calculate the fuel consumption by using gravimetric approach or the carbon balance method back-calculating (Lammert et al. , 2012). The second way of measuring fuel economy refers to the collection of real-world data, which is recorded from in-use vehicles. Among the data, the result of the division of total traveled distance by total used fuel is the fuel economy. Using custom drive cycles is the third way to measure the fuel economy. These custom drive cycles are generated by processing and aggregating real-world data. This data is collected by operating vehicles in a specific market of UFT for several weeks or months. Hence, the custom drive cycles present the typical characteristics of real operations in this specific market. The fuel economy in this context is derived by using the custom drive cycles into the chassis dynamometers or simulation models.

The custom drive cycles as the time-dependent parameters are required in the development of the methodological concept to measure the fuel economy close to the real operation conditions. In comparison with the fuel economy measured by the standard drive cycle in the laboratory and real-world data, there is a significant difference (approximately 45%) between them (T. T. Taefi, 2016). In other words, the fuel economy measured in the real-world is commonly much higher than in the laboratory. This difference indicates that it is difficult to test fuel economy close to the real operation conditions by using the standard drive cycle. Accordingly, the fuel economy measured by the chassis dynamometers in the laboratory regarding the standard drive cycle is excluded from this research. Moreover, since the ECV is an emerging technology, the real-world data is scarce. In this context, the fuel economy measured by real-world data is also unfeasible. In this perspective, due to the custom drive cycles present the typical characteristics of specific UFT markets and may better reflect the real operation conditions to a certain extent in comparison to standard drive cycles, the custom drive cycles as the time-dependent parameters are considered in the second requirement.

The third requirement for developing the methodological concept is specified to involve both automotive and logistical parameters. As discussed in Section 3.4, the existing tools either used automotive parameters to assess different types of ECVs

4 Sustainable ECV-UFT Matching Concept

in vehicle-oriented tools or used logistical parameters to assess UFT in logistics-oriented tools. Since none of these tools included both automotive and logistical parameters as well as their connections, this limitation results in the difficulty of assessing the ECV-UFT combinations by directly applying these existing tools. Moreover, these tools were not developed in identical conditions and the markets of UFT were unspecified. Hence, these existing tools cannot be synthesized to assess the ECV-UFT combinations. In spite of this, the principles for developing these tools are considered in developing the concept. To summarize, the methodological concept requires both automotive and logistical parameters.

Furthermore, it is worth pointing out that the data, with regard to the time-dependent, the automotive, and the logistical parameters, plays a significant role to assess the ECV-UFT combinations. Hence, the methodological concept should not only include the aforementioned parameters, but also provide a database, which contains corresponding data to support the quantitative assessment of the diverse ECV-UFT combinations. The data may be collected from published reports, articles, existing databases, or real-time measurements. On the whole, the fourth requirement for the methodological concept is specified to provide a database to quantify the assessment of ECV-UFT combinations.

Finally, the three dimensions (economic, social, and environmental) and their harmonization are required to be considered as the final requirement for supporting the determination of the satisfactory match. As observed in Chapter 3, the majority of studies focused on economic and environmental dimensions. The parameters, such as the TCO from the economic perspective and the GHG emissions from the environmental perspective, are discussed frequently. However, little attention has been paid to the social dimension and its parameters. Hence, to determine the satisfactory match from a comprehensive view, all three dimensions are required in the methodological concept. Besides, since a harmonized development of the three dimensions is the path of achieving the sustainable UFT (United Nation, 2016), it is then crucial to harmonize the results of these three dimensions derived by assessing ECV-UFT combinations to determine the satisfactory match. Given these points, the final requirement for developing the methodological concept is specified to cover and harmonize the economic, social, and environmental dimensions.

Synthesizing the main focus, the objective, and the requirements, the methodological concept is required to have the capability of *assessing diverse ECV-UFT combinations including the time-dependent, the automotive, and the logistical parameters from the economic, social, and environmental dimensions. An available database is required in this methodological concept to support the assessment and the determination of the satisfactory match by harmonizing the results in the three dimensions.*

4.3 Methodological Concept

In this section, a methodological concept called Sustainable ECV-UFT Matching Concept is proposed to support decision-makers to obtain their satisfactory match. Figure 8 shows the process of obtaining a satisfactory match from the diverse ECV-UFT combinations by satisfying the outlined requirements. In particular, this concept is constituted by two methodologies, namely methodology of assessment and methodology of determination.

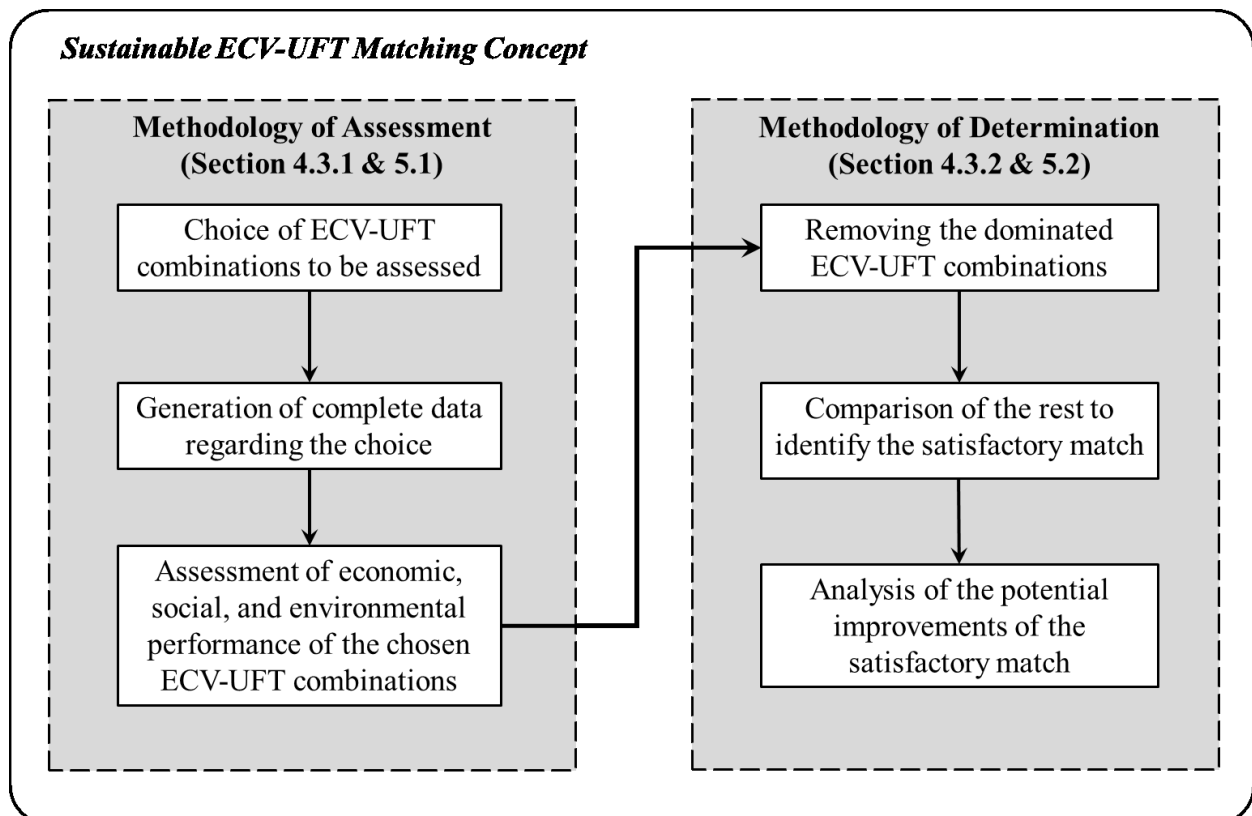


Figure 8: The methodological concept

Among these methodologies, the decision-maker plays an essential role. There are three groups of decision-makers considered in this methodological concept. These groups include users, automobile manufacturers, and regional as well as national governments. The users in this concept are primarily freight carriers, who conduct logistics business in urban areas. Since the market of UFT is commonly fixed for these freight carriers, the satisfactory match for these decision-makers mainly refers to assessing and determining a satisfactory type of ECVs to match their markets. The benefit of employing this satisfactory type may facilitate freight carriers to consider this type of ECVs in their own business. Accordingly, the market penetration of this type of ECVs may increase. Automobile manufacturers as the second group of decision-makers are commonly interested in the performance of employing their ECVs in different markets of UFT. This methodological concept contributes to the automobile manufacturers paying

attention to the differences regarding the performance of their products in different markets. These differences may help automobile manufacturers to adapt their products to be more suitable and competitive for specific UFT markets. Finally, the regional and national governments as a decision-maker may concern about the comprehensive understanding of the satisfactory match to make policies. In other words, this methodological concept supports governments to determine which type of ECVs is more suitable to be introduced into which UFT market from a short-term and a long-term point of view. In the perspective of these decision-makers, the following subsections portray each step of the two methodologies respectively.

4.3.1 Methodology of Assessment

This subsection focuses on elaborating the process of assessing ECV-UFT combinations under the economic, social, and environmental criteria. There are three steps in this methodology of assessment. First of all, decision-makers are required to choose the ECV-UFT combinations, which they intend to assess regarding their conditions. Secondly, a set of complete data is accordingly generated to support the quantitative assessment of the chosen ECV-UFT combinations. Finally, the economic, social, and environmental performance of these chosen ECV-UFT combinations is assessed by using the complete data.

The first step allows this methodological concept to assess all the possibilities of employing ECVs in UFT to meet the first requirement specified in Section 4.2. In other words, all ECV-UFT combinations are given in this step for the choice conducted by decision-makers. Regarding the different purposes and conditions, decision-makers can choose the ECV-UFT combinations, which they are interested in. For instance, the freight carrier, who transports goods purchased online to recipients (Express/post market), may intend to assess and compare the ECV-UFT combinations constituted by different types of ECVs, such as BEV-Express/post, HEV-Express/post, and PHEV-Express/post, to fit their business. On the contrary, the regional or national governments may intend to consider comprehensive ECV-UFT combinations for making appropriate policies, such as BEV-Retail, HEV-HoReCa, or PHEV-Waste collection. To this end, the first step is required to comprise all possibilities of the employment to give decision-makers the autonomy to explore different ECV-UFT combinations and decide their satisfactory match.

The second step focuses on generating a set of complete data regarding the choice of decision-makers in the first step. The purpose of including this step is to support the quantitative assessment of the chosen ECV-UFT combinations. As stated in the requirements (Section 4.2), a database is required in this concept to generate complete data. This database should contain the data related to the time-dependent, the automotive, and the logistical parameters. Furthermore, since the data regarding the employment of ECVs in UFT is insufficient, the data sources may include a wide range of related publications. Besides, the decision-makers are also

considered as a data source to provide specific data. The database finally stores all this data from different sources. In this context, the complete data is generated from the database according to the chosen ECV-UFT combinations.

By using the complete data, the assessment of the chosen ECV-UFT combinations under the economic, social, and environmental criteria is carried out in the third step. To address the challenges and satisfy the requirements specified in Section 4.1 and 4.2, the economic, social, and environmental performance is quantified and the performance of each ECV-UFT combination is calculated as the results of the assessment. After deriving such results, a validation is then required to estimate the accuracy of the results and confirm a range in which the results are credible to support making trustworthy decisions. The validated results are then analyzed in the next methodology for determining the satisfactory match. Overall, the third step in this methodological concept allows decision-makers to assess the chosen ECV-UFT combinations by using the complete data from the economic, social, and environmental dimensions.

The three steps of this methodology are summarized and visualized in Figure 9. This diagram mainly illustrates the outcomes after conducting each step. For instance, according to the choice conducted by decision-makers, the list of the chosen ECV-UFT combinations is the outcome of the first step. The complete data, which is generated regarding the choice, refers to the outcome of the second step. Using this complete data, the chosen ECV-UFT combinations are assessed under the economic, social, and environmental criteria. The table of the assessment results is the outcome of the third step.

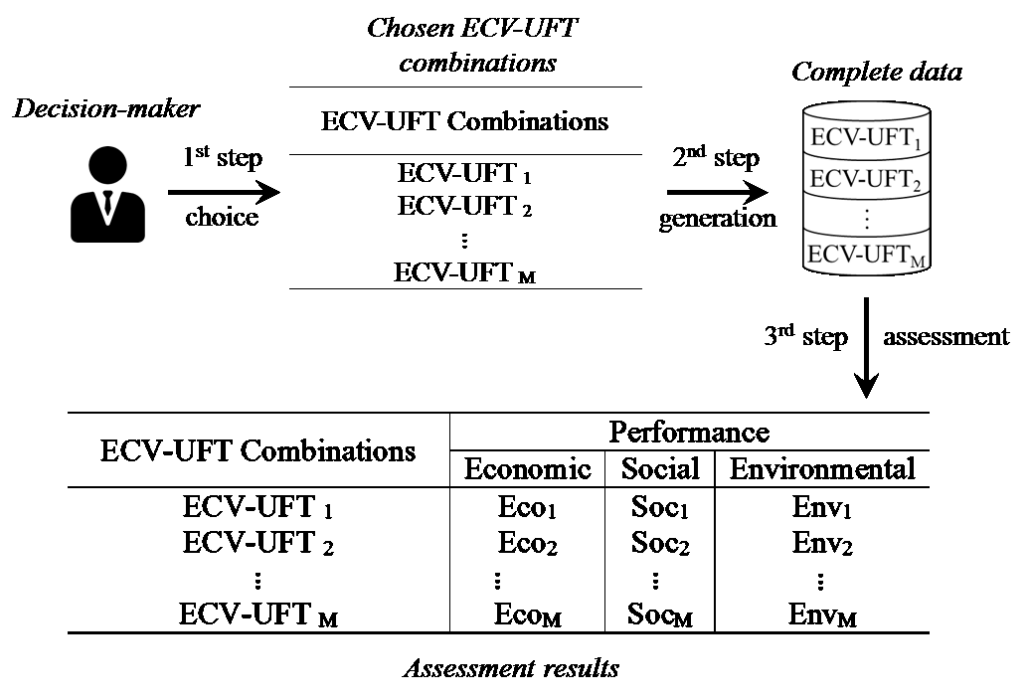


Figure 9: The methodology of assessment

On the whole, these three steps constitute the methodology of assessment and satisfy the requirements. The details of implementing this methodology, such as the user interface for the choice of ECV-UFT combinations, the methods applied for the assessment and validation, are introduced in Chapter 5.

4.3.2 Methodology of Determination

After assessing the performance of the chosen ECV-UFT combinations, the methodology of determination provides a system of methods to analyze the assessment results, determine the satisfactory match, and suggest future research. The requirement of harmonizing the economic, social, and environmental performance is satisfied in this methodology to support the determination from a sustainable perspective.

The methodology of determination is comprised of three steps. The first step of this methodology focuses on analyzing the assessment results to narrow the range of available ECV-UFT combinations for simplifying the determination of the satisfactory match. In other words, the role of this step is to remove the ECV-UFT combinations, which are dominated by the others. The process of identifying the dominated ECV-UFT combination is adapted from Pareto optimal in Konak et al. (2006). For instance, there are two ECV-UFT combinations assessed in the last methodology. If the results show that the ECV-UFT₁ expends more costs and consumes more energy in comparison to the ECV-UFT₂, in this context, the ECV-UFT₁ with the worse performance under the three criteria is preliminarily considered to be dominated by the ECV-UFT₂. Furthermore, it is crucial to analyze and establish whether the performance of this “dominated” ECV-UFT combination can be improved and better than the other one in any of the three criteria by changing the values of the parameters. If no, the ECV-UFT combination with the worse performance is said to be dominated by the other one. Then, this dominated ECV-UFT combination is removed from the available ECV-UFT combinations. In conclusion, this predetermination in the first step helps decision-makers to identify the available ECV-UFT combinations.

The second step in the methodology of determination is to compare the available ECV-UFT combinations and support decision-makers in determining the satisfactory match. Three performance of each available ECV-UFT combination is required to be synthesized in this step. This synthesized performance of each available ECV-UFT combination is compared subsequently. Moreover, the synthesized performance can present the extent of harmonization of the three criteria in each of ECV-UFT combinations. This extent may help decision-makers to identify the extent of sustainability for each ECV-UFT combination. In other words, the higher the extent of harmonization is, the more sustainable the ECV-UFT combinations will be. Furthermore, the rule in determining the satisfactory match depends on the decision-makers. This means that the most sustainable ECV-

UFT combination may be or may not be the satisfactory match for decision-makers. For example, if a decision-maker demands an ECV-UFT combination, which can harmonize the performance of the three criteria, the most sustainable ECV-UFT combination is then the satisfactory match for this decision-maker. If a decision-maker demands an ECV-UFT combination, which expends the least costs and has acceptable energy consumption, the ECV-UFT combination, in which the synthesized performance satisfies these demands, is the satisfactory match. In short, this step supports decision-makers in comparing the available ECV-UFT combinations. Moreover, according to the results in the comparison, the identification of the satisfactory match is determined by the demands of decision-makers.

The final step focuses on analyzing the potential improvements of the satisfactory match to suggest future research. The potential improvements in this step refer to the differences between the satisfactory match and the other available ECV-UFT combinations. For instance, the satisfactory match determined by decision-makers in the last step may have the best economic performance and normal environmental as well as social performance. To in-depth understand the limitations leading to such environmental and social performance, the differences in each parameter between this satisfactory match and the ECV-UFT combination, which has the best environmental and social performance, are analyzed. Finally, the potential improvements are suggested regarding the analyzed limitations.

The outcomes of each step in this methodology of determination are outlined in Figure 10. The list of the available ECV-UFT combinations ($X \leq M$) is the outcome of the first step after removing the dominated ECV-UFT combinations. The satisfactory match ($ECV-UFT_y'$) is the outcome of the second step after comparing the performance of the available ECV-UFT combinations. In the end, the potential improvements are the outcomes of the third step after analyzing the differences of each parameter between the satisfactory match and the other available ECV-UFT combinations.

4 Sustainable ECV-UFT Matching Concept

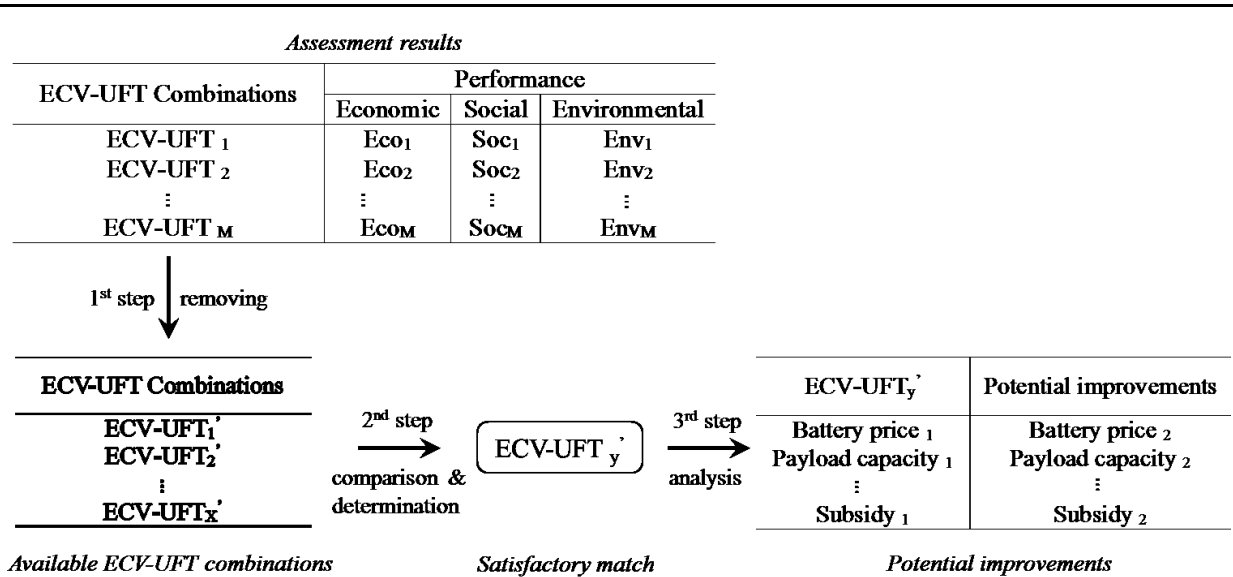


Figure 10: The methodology of determination

In short, the methodology of determination provides decision-makers with a process of analyzing the assessment results and determining the satisfactory match. The corresponding methods for implementing this methodology are introduced in Chapter 5.

4.4 Summary

This chapter has proposed a methodological concept - Sustainable ECV-UFT Matching Concept as a systematic solution to guide and support decision-makers in obtaining their satisfactory match. The challenges of obtaining such a satisfactory match were firstly identified to clarify what issues should be addressed in this methodological concept. Moreover, the main focus and the objective of the concept as well as the requirements for proposing the concept were specified to explicitly present how the concept was formed by meeting such requirements. To this end, two methodologies were proposed to constitute the Sustainable ECV-UFT Matching Concept.

These two methodologies include the methodology of assessment and the methodology of determination. The methodology of assessment was developed to help decision-makers to understand the diversity in the employment by assessing the diverse ECV-UFT combinations quantitatively under the three dimensions. The methodology of determination was formed to analyze the assessment results and support decision-makers in determining their satisfactory match from the diverse ECV-UFT combinations.

To convert the methodological concept from the theoretical to the practical guidance, a simulation platform is designed in the next chapter to implement the concept.

5 Implementation

This chapter elaborates the implementation of the Sustainable ECV-UFT Matching Concept. Four sections constitute this chapter. Since the proposed methodological concept contains two methodologies, this chapter introduces the implementation of the methodology of assessment (Section 5.1) and the methodology of determination (Section 5.2) respectively. In Section 5.1, the primary goal is to provide feasible methods for decision-makers to assess diverse ECV-UFT combinations quantitatively under the three criteria. After deriving the assessment results from Section 5.1, Section 5.2 presents the methods to support decision-makers to understand the assessment results better and determine the satisfactory match. Finally, a simulation platform is designed in Section 5.3 to implement this methodological concept holistically in the MATLAB environment. Decision-makers as the users to apply this simulation platform may obtain their satisfactory match and explore the potential improvements for future research. A summary of this implementation is shown at the end of this chapter (Section 5.4).

5.1 Implementation of the Methodology for Assessment

This section focuses on implementing the methodology of assessment to help decision-makers to assess the diverse ECV-UFT combinations quantitatively in the economic, social, and environmental criteria. The methods for generating a set of complete data and assessing ECV-UFT combinations are introduced in subsequent subsection respectively.

5.1.1 Generation of Complete Data

This subsection illustrates the procedure of generating complete data for the chosen ECV-UFT combinations. Required parameters, data collection, and database are three essential elements in this procedure. The connections between the essential elements are shown in Figure 11. In the first step, before collecting the data, the parameters required for the assessment is identified. After this identification, the values of these parameters are collected from decision-makers or related publications. In this research, the data collected from the related publications is considered as a set of background data. A database, which is constituted by the required parameters and their values, is established by storing and processing the data from decision-makers and related publications to ultimately provide a set of complete data for the assessment.

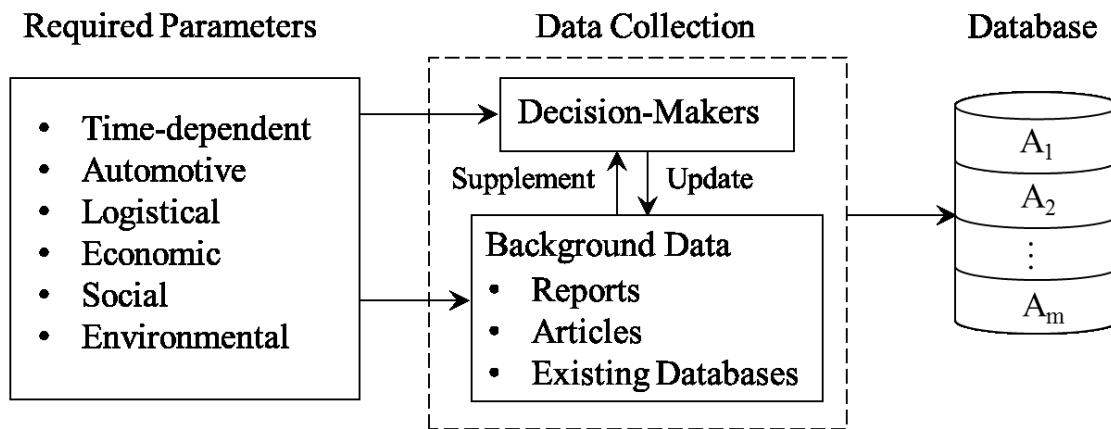


Figure 11: Connections between required parameters, data collection, and database

The required parameters are the basic elements of the procedure. According to the requirements summarized in Section 4.2, the parameters in this database should contain the time-dependent, the automotive, and the logistical parameters. Moreover, since the proposed concept intends to assess the ECV-UFT combinations with respect to the three dimensions, the economic, social, and environmental parameters are required for the assessment as well. To this effect, the required parameters in this database are a set of parameters, which can reveal the features of ECVs and UFT with the impact of time from the perspectives of three dimensions. The concrete required parameters are illustrated after formulating the assessment in the next section.

Subsequently, the values of these required parameters are collected from decision-makers or related publications. The decision-makers, who intend to assess the ECV-UFT combinations, should collect the corresponding values of parameters. However, since the ECV is an emerging product in UFT, the data collection seems difficult. In this context, a set of background data is organized by collecting the values from reports, articles, and existing databases. Decision-makers may fill the missing data by using the background data. Besides, as the values of related publications are partly trial data derived a few years ago, this set of background data can be updated by using the values collected from decision-makers.

The complete data for the chosen ECV-UFT combinations is generated depending on the extent of data collection. In other words, the complete data may be generated from the data of decision-makers, related publications, or the combination of both sources (Figure 12).

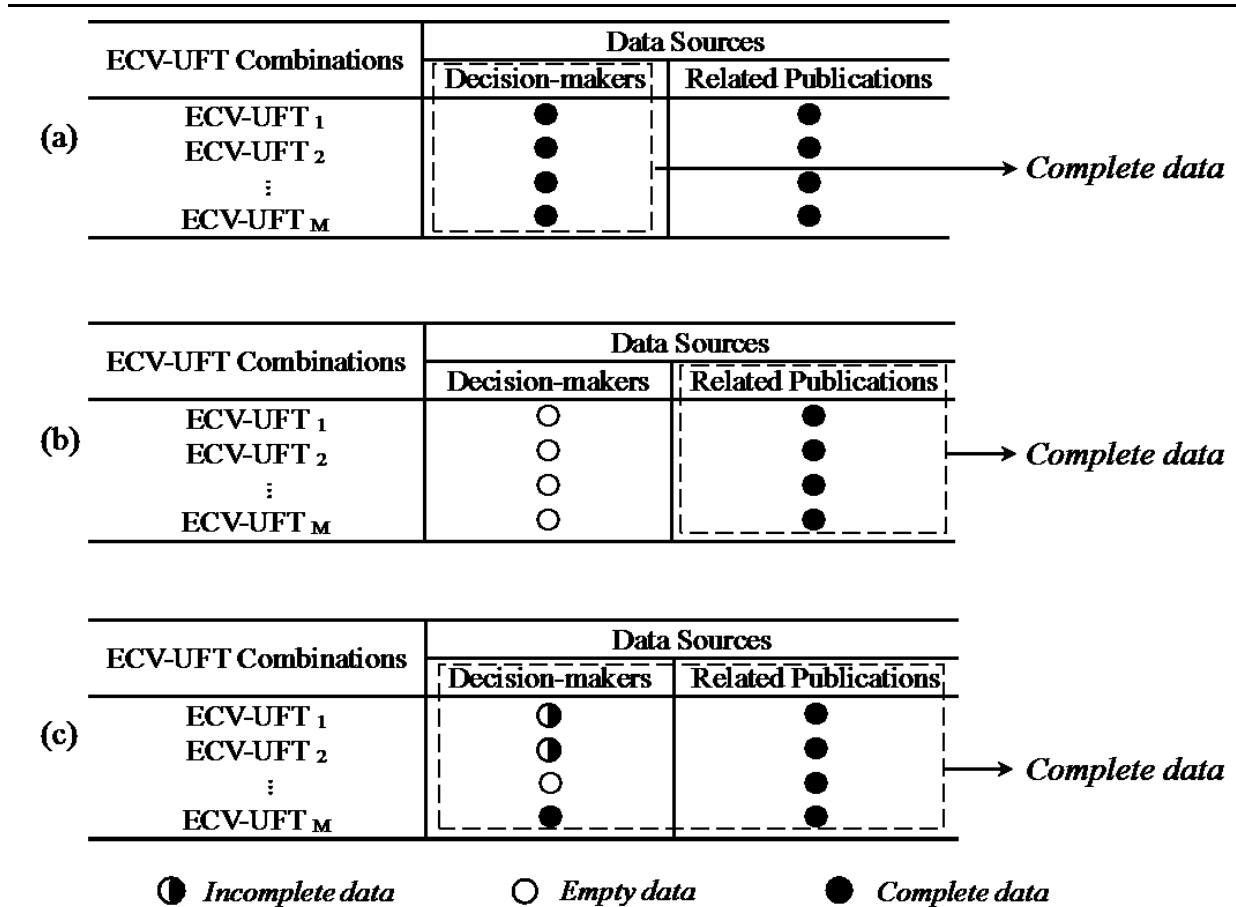


Figure 12: Three situations in generating complete data

The database separately stores the data from decision-makers and related publications. The required parameters and their values constitute this database. In this implementation, the background data, which is collected from the related publications, is essentially complete. It implies that the complete data generated in the database depends on the extent of data collection from the decision-makers. If the decision-makers provide complete data (Figure 12 (a)), the output then uses the complete data from decision-makers, since this data is specific to the conditions of users. If the decision-makers cannot provide any data (Figure 12 (b)), the background data is then the complete data. Finally, if the decision-makers provide partial data (Figure 12 (c)), the complete data is output by combining the data from both sources.

5.1.2 Assessment of ECV-UFT Combinations


In this subsection, the assessment of ECV-UFT combinations is concretely introduced. To implement this assessment, an adapted method, which can estimate the economic, social, and environmental performance of the diverse ECV-UFT combinations, is proposed. In addition, three mathematical expressions and a fuel economy simulation model are formulated to assist in quantifying this assessment. In the end, the method for validating the assessment results is presented.

5.1.2.1 Adapted Method


After reviewing the widely used MCDM methods in Section 3.4.2, there is no appropriate method to support the assessment of ECV-UFT combinations and satisfy the requirements specified in Section 4.2. This is deduced from following limitations of MCDM methods. First of all, since the assessment of the performance under the three dimensions is a multi-dimensional decision-making case, the WSM, which is suitable for single-dimensional decision cases, is excluded from this research. Furthermore, although the WPM and the AHP can numerically analyze the multi-dimensional decision-making cases, they cannot be applied directly because of a large number of ECV-UFT combinations and the subjective values of the three criteria. For instance, to rank 512 ECV-UFT combinations by using AHP may result in 392,448 pairwise comparisons to thoroughly assess all of the ECV-UFT combinations in terms of the three criteria. Additionally, the values of conducting these pairwise comparisons are subjective. To this effect, the existing MCDM methods have to be adapted to this research.

To adapt the methods and satisfy the requirements simultaneously, the mathematical expressions with respect to the three dimensions of sustainable UFT are suggested being introduced into this adaption (Figure 13). These three (economic, social, and environmental) mathematical expressions are formulated using time-dependent, automotive, and logistical parameters. The results of these mathematical expressions are calculated using the generated complete data.


ECV-UFT Combinations	Criteria		
	C_{eco}	C_{env}	C_{soc}
ECV-UFT ₁	a_{11}	a_{12}	a_{13}
ECV-UFT ₂	a_{21}	a_{22}	a_{23}
⋮	⋮	⋮	⋮
ECV-UFT _M	a_{M1}	a_{M2}	a_{M3}



a_{M1} = economic
mathematical
expression



a_{M2} = environmental
mathematical
expression



a_{M3} = social
mathematical
expression

Figure 13: Adaption of the AHP by synthesizing mathematical expressions

The principle of the AHP, namely the decision matrix (Table 5), is kept in this adaption. The results of the mathematical expressions replace the values, which are compared pairwise and derived from experts in Table 5. This replacement contributes to eliminating a large number of comparisons caused by the diverse ECV-FUT combinations. Moreover, to remove the impacts of units and normalize the actual values, the principle of WPM is considered in this adaption via

$$a_{ij} = \frac{b_{ij}}{\sum_{i=1}^M b_{ij}}, j = 1, 2, \dots, N \quad (6)$$

where a_{ij} is the relative values without units, b_{ij} is the actual values derived from mathematical expressions with units, M is the number of ECV-UFT combinations, and N is the number of criteria.

On the whole, the principles of the AHP and the WPM, as well as the three mathematical expressions, constitute the adapted method.

5.1.2.2 Mathematical Expressions⁴

The three mathematical expressions of this assessment are formulated in terms of the requirements specified in Section 4.2. It indicates that the formulated mathematical expressions in this research: a) have the capability of being adapted to calculating diverse ECV-UFT combinations; b) include the time-dependent, the automotive, and the logistical parameters, and; c) can assess the economic, social, and environmental performance. In addition to meeting the requirements, it is assumed that the number of each type of commercial vehicles employed in UFT is considered as one in these mathematical expressions.

Economic-Mathematical Expressions

To assess the economic performance of ECV-UFT combinations, an economic-mathematical expression is formulated. According to the factors outlined and discussed in Section 3.3, this economic-mathematical expression focuses on assessing a typical and measurable economic performance parameter, namely the Total Costs of Ownership (TCO). The role of this mathematical expression is to estimate the total expenditure of employing ECV-UFT combinations over the planned service years. Accordingly, the economic-mathematical expression, which is adapted from Davis and Figliozzi (2013) as well as Burnham (2016), is formulated as follows:

$$C_{tot,i,j}(N) = C_{dep,j}(N) - b \cdot c_s + b \cdot R(N) \cdot c_B \cdot (1 + r_{dis})^{-N} + \sum_{n=1}^N d(n) \cdot (1 + r_{dis})^{-n} \cdot (w(n) \cdot C_{i,j}(n) + C_{M,j}) \quad (7)$$

where

I = set of markets in UFT, $i \in \{Retail, Express/Post, HoReCa, Construction, Waste\}$

J = set of vehicle types, $j \in \{Diesel, BEVs, HEVs, PHEVs, FCEVs\}$

n = planned service years, $n \in [1, 2, \dots, N]$

$C_{tot,i,j}(N)$ = total cost of vehicle type j operating in market i N years

⁴ This section has been published in (Wang & Thoben, 2017a)

5 Implementation

$C_{dep,j}(N)$ = depreciation cost of vehicle type j in year N

b = whether the commercial vehicle is the BEV or the PHEV (0 or 1)

c_S = subsidies for purchasing a new vehicle

$R(N)$ = whether the battery is replaced in year N (0 or 1)

c_B = battery price

r_{dis} = discount rate

$d(n)$ = annual traveled distance in year n

$w(n)$ = annual transported weight in year n

$C_{i,j}(n)$ = fuel cost of vehicle type j per ton · km (tkm) in market i in year n

$C_{M,j}$ = maintenance cost of vehicle type j

In this mathematical expression, the TCO is calculated by taking into account the depreciation cost, the purchase subsidies, the battery replacement cost, the fuel cost, as well as the maintenance and repair cost. Exclusive of the purchase subsidies, the other costs are all relevant to the planned service years. On the basis of involving the planned service years, the result calculated from this mathematical expression is future value. To render this future value comparable to the present value, the discount rate is applied in this economic mathematical expression to convert the future value to the present value.

Furthermore, to precisely assess the total expenditure, the depreciation cost and the fuel cost are suggested to be calculated in line with the Eq. 8-11. The depreciation cost is illustrated in Eq. 8. The purchase price and the resale value of the vehicle type j are its main components. In this equation, it is assumed that the commercial vehicle is purchased before the first planned service year.

$$C_{dep,j}(N) = C_{P,j} \cdot \left[1 - (1 - r_{dep})^N \cdot (1 + r_{dis})^{-N} \right] \quad (8)$$

where

$C_{P,j}$ = purchase price of vehicle type j

r_{dep} = depreciation rate

Subsequently, the fuel cost is calculated by using the Eq. 9-11. The role of these three equations is to introduce a calculation method for assessing the expenditure of onboard fuel consumption by taking into consideration the drive cycles and the fuel price inflation over the planned service years. The three equations are expressed as follows:

$$c_j(n) = c_j(1) \cdot (1 + r_j)^{n-1} \quad (9)$$

$$P_{T,i,j} = \frac{P_{i,j}}{W_{p,j} \cdot \eta_c} \quad (10)$$

$$C_{i,j}(n) = P_{T,i,j} \cdot c_j(n) \quad (11)$$

where

$c_j(n)$ = fuel price of vehicle type j in year n

r_j = fuel price inflation rate of fuel type in vehicle type j

$P_{T,i,j}$ = fuel consumption per tkm of vehicle type j for market i

$P_{i,j}$ = fuel economy of vehicle type j for market i

$\overline{W_{p,j}}$ = payload capacity of vehicle type j

η_c = capacity utilization

Additionally, to synthesize the logistical parameters into the economic-mathematical expression, a parameter called fuel cost per ton kilometer ($C_{i,j}(n)$) with the unit €/tkm is introduced and applied in the calculation of fuel cost. This parameter is the product of the fuel price in year n ($c_j(n)$) and the fuel consumption per tkm ($P_{T,i,j}$). The value of the fuel price in year n is forecasted by applying the fuel price inflation rate (r_j) in Eq. 9. The value of the fuel consumption per tkm is calculated by using the fuel economy ($P_{i,j}$), the payload capacity ($\overline{W_{p,j}}$), and the capacity utilization (η_c). This fuel economy of vehicle type j operating in the market i is simulated by applying drive cycles (further discussed in Section 5.1.2.3). In short, the calculation of the fuel cost synthesizes the automotive parameters (fuel economy, payload capacity, etc.) and the logistical parameters (capacity utilization, fuel consumption per tkm, etc.) as well as the time-dependent parameters (planned service years and drive cycles).

The purchase subsidies, the battery replacement costs, as well as the maintenance and the repair cost in Eq. 7 are introduced as follows. According to the economic factors discussed in Section 3.3, the purchase subsidies are grants for users (freight carriers) to purchase ECVs. The vehicle-based and the battery energy-based subsidies are two categories of the purchase subsidies. This economic-mathematical expression is feasible for both categories. In addition, since the HEVs have small-sized and irremovable battery systems, the purchase subsidies and the battery replacement cost, which is the expenditure of replacing the onboard battery with a new one, are only valid for the BEVs and the PHEVs. The maintenance and repair cost is a constant parameter in Eq. 7. This cost represents the expenditure of maintaining and repairing the commercial vehicles per kilometer. Despite the fact that this cost may increase with the vehicle age, in this economic-mathematical expression, it is assumed to be a constant.

In the end, there are three costs excluded from this economic-mathematical expression. Since it is assumed that a new commercial vehicle is purchased without loans, therefore, the financing cost, which is calculated by vehicle interest payment in the event that there is a loan for purchasing a new vehicle, is excluded from this

mathematical expression. Moreover, the insurance cost as well as the license, and registration cost are excluded from this economic-mathematical expression, since there is no difference between conventional vehicles and electric vehicles in this regard (Lebeau et al., 2015).

Social-Mathematical Expressions

To assess the social performance of ECV-UFT combinations, a social-mathematical expression is formulated. A measurable parameter called actual transport capacity is proposed in this social-mathematical expression. The purpose of introducing this parameter is to provide a calculation method for quantifying the social dimension in the context of assessing ECV-UFT combinations.

The accessibility of using ECVs to deliver goods in UFT (Section 3.3) is the main focus of this social-mathematical expression. Commercial vehicles are the means to transport goods and have an influence on accessibility. In other words, the onboard energy capacity and the payload capacity of commercial vehicles are fixed. It implies that the number of goods transported per trip per vehicle and the total traveled distance per day are limited. In particular, these limitations are critical for the ECVs (see Section 3.1 & 3.3). In this case, the actual transport capacity, which is calculated by including the onboard energy capacity and the payload capacity, is significant to be estimated to illustrate the accessibility of each ECV-UFT combination. Accordingly, the social-mathematical expression is formulated by using the actual transport capacity in Eq. 12.

$$E_{T,i,j} = \frac{\bar{E}_j}{P_{T,i,j}} \quad (12)$$

where

$E_{T,i,j}$ = actual transport capacity of vehicle type j in market i

\bar{E}_j = on-board energy capacity of vehicle type j

The on-board energy capacity indicates the amount of energy stored in the vehicles, such as the amount of fossil fuel in Diesel Commercial Vehicles (DCVs) or the amount of battery capacity in ECVs. Moreover, as formulated in Eq. 10, the fuel consumption per tkm indicates the actual fuel consumption for transporting a specific weight in a specific travel distance with taking into account the payload capacity and the capacity utilization. In summary, the social-mathematical expression formulated in this research contributes to providing a feasible perspective to quantify the social dimension.

Environmental-Mathematical Expressions

To assess the environmental performance of ECV-UFT combinations, two environmental-mathematical expressions are formulated. In line with the

environmental factors discussed in Section 3.5, these environmental-mathematical expressions mainly focus on assessing the energy consumption and the GHG emissions respectively. Furthermore, since the values of energy consumption and GHG emissions may change from the life cycle's point of view, the assessment of the environmental performance involves a terminology called Well to Wheel (WTW). To this effect, the total energy consumption and the total GHG emissions from WTW are considered as the performance parameters under the environmental dimension to assess the diverse ECV-UFT combinations. The total energy consumption from WTW over the planned service years is formulated as:

$$E_{WTW,i,j}(N) = \sum_{n=1}^N w(n) \cdot d(n) \cdot P_{T,i,j} \cdot f_e \quad (13)$$

where

$E_{WTW,i,j}(N)$ = total energy consumption of vehicle type j for market i in N years

f_e = WTW energy conversion factor

This total energy consumption is a cumulative performance parameter. It is the sum of annual energy consumption. At the end of each year, annual energy consumption is calculated according to the annual transported weight, the annual traveled distance, and the fuel consumption per tkm. In addition, because of the diverse fuel types of ECVs and their different energy units, the energy conversion factor from WTW is considered to standardize the unit.

The total GHG emissions from WTW over the planned service years is formulated as:

$$G_{WTW,i,j}(N) = \sum_{n=1}^N w(n) \cdot d(n) \cdot P_{T,i,j} \cdot f_g \quad (14)$$

where

$G_{WTW,i,j}(N)$ = total GHG emissions of vehicle type j for market i in N years

f_g = WTW CO₂ equivalents conversion factor

The total GHG emissions are also a cumulative performance parameter. Eq. 14 is similar to the expression of Eq. 13. The difference between them is the conversion factor. The equation of calculating GHG emissions applies the factor for converting GHG emissions from WTW perspective. Since the CO₂ has the most extensive effects for the public in comparison to the other emissions, the GHG emissions, which commonly include carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) (Schmied et al., 2012; The Council of The European Union, 2015), are denoted as CO₂ equivalents in this conversion factor.

The required parameters, which are the component of the database for generating complete data, are identified from these mathematical expressions (Table 9).

Table 9: Required parameters in the three mathematical expressions

Parameters	Meaning
$C_{p,j}$	Purchase price of vehicle type j
c_S	Subsidies for purchasing a new vehicle
c_B	Battery price
$C_{M,j}$	Maintenance cost of vehicle type j
$c_j(1)$	Fuel price of vehicle type j in the first year
r_{dis}	Discount rate
r_{dep}	Depreciation rate
r_j	Fuel price inflation rate of fuel type in vehicle type j
$P_{i,j}$	Fuel economy of vehicle type j for market i
$\overline{W}_{p,j}$	Payload capacity of vehicle type j
\overline{E}_j	On-board energy capacity of vehicle type j
η_c	Capacity utilization
$d(n)$	Annual traveled distance in year n
$w(n)$	Annual transported weight in year n
f_e	WTW energy conversion factor
f_g	WTW CO ₂ equivalents conversion factor

On the whole, the mathematical expressions of the adapted method are formulated in this subsection to quantify the assessment and meet the specified requirements. Additionally, the required parameters for generating complete data are also identified from these formulated mathematical expressions. However, since there is very little data concerning the fuel economy of ECVs and this little data are averaged values collected from specifications of automobile manufacturers, the value of the fuel economy needs to be further studied to render this assessment close to the real conditions.

5.1.2.3 Simulation of Fuel Economy

A simulation model for estimating the fuel economy is formulated in this assessment of ECV-UFT combinations to obtain a value close to the real conditions in the context of lacking real-world data. The custom drive cycles and the Monte-Carlo method are applied in this simulation model. In particular, the custom drive cycle provides a set of original time-velocity data. The Monte-Carlo method is applied to create numerous sets of stochastic time-velocity data by using this drive cycle. Finally, the simulation model computes the expected values of the fuel economy by using stochastic data.

As specified in Section 4.2, this research is determined to use custom drive cycles for calculating the fuel economy. Normally, the fuel economy is tested by using standard drive cycles, such as the New European Driving Cycle (NEDC) in Europe, the Federal Test Procedure (FTP)-75 in the US, and the JC-08 in Japan. However, there is a significant difference between the fuel economy derived from the standard drive cycles and the real-world one. Additionally, the real-world data

of ECVs operating in UFT is scarce. Given these points, the custom drive cycles are applied in this simulation model for estimating the fuel economy.

The custom drive cycles are generated by processing and aggregating specific real-world data. This data is collected by operating vehicles in a specific market of UFT in several weeks or months. After deconstructing and reconstructing the collected drive cycles, the custom drive cycles are accordingly generated and present the typical characteristics of real operations in this specific UFT market. These typical characteristics, such as the velocity and the number of stops, support the simulation model to compute a representative fuel economy close to the real conditions.

However, the custom drive cycle can provide only one set of time-velocity data. This leads to a situation that the driver will transport goods precisely following the time-velocity curve in the duration of the custom drive cycle. Apparently, this situation is impractical. Therefore, the Monte-Carlo method is applied in this simulation model to generate numerous sets of stochastic time-velocity data for presenting different possibilities of a drive cycle.

The Monte-Carlo method is a statistical and numerical method. It generates a sequence of random numbers with given distribution probabilities (Jacoboni & Reggiani, 1983). Applying this method allows to estimate numerical quantities by repeating samplings and solve complicated optimization problems through randomized algorithms (Paltani, 2012). To perform the Monte-Carlo method, a random variable (X) is firstly calculated by applying the probability density function of the normal distribution as follows:

$$X = \sqrt{-2 \cdot \ln U_1} \cdot \cos(2 \cdot \pi \cdot U_2) \cdot \sigma + \mu \quad (15)$$

where

U_1, U_2 = uniform random numbers

σ = standard deviation of a normal distribution

μ = mean of a normal distribution

The uniform random numbers denoted by U_1, U_2 are essential random numbers, which are generated by software such as Matlab. The standard deviation and the mean are the main components of the normal distribution. The values of these two components are given to calculate the random variable. In order to generate a sequence of random numbers, the Wiener Process is subsequently applied in the Monte-Carlo method. A number of paths are generated via a random process. Each path includes a set of random numbers derived from the random variable. Finally, this sequence of random numbers times the initial values of time-velocity data are the set of stochastic values. This set of stochastic values is denoted as a matrix ($t \times p$). t is the size of the initial values, namely the length of time (seconds). p is the length of the paths. In other words, there are in total p sets of stochastic vehicle

speeds in t seconds generated by the Monte-Carlo method. A flow chart for generating this matrix is shown in Figure 14:

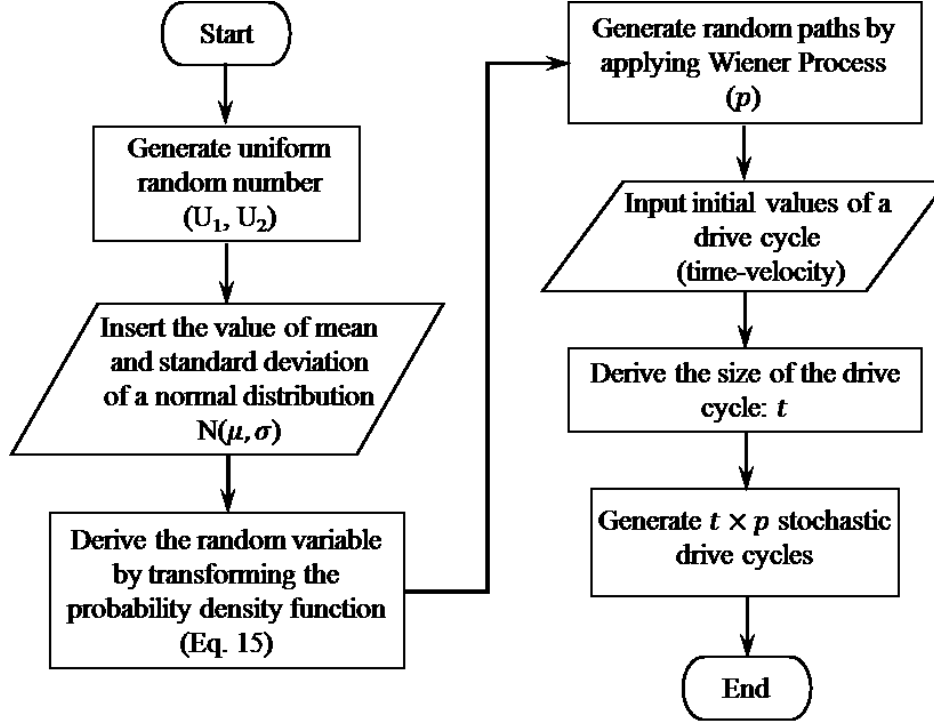


Figure 14: Flowchart for generating the stochastic values of drive cycles

After generating the stochastic values of the custom drive cycle, the simulation model computes the expected value of the fuel economy. Commonly, the fuel economy is estimated by the energy, which is required to propel vehicles over a roadway. This energy is required to overcome aerodynamic drag, rolling resistance, acceleration, and gravitational potential energy. Nevertheless, as the custom drive cycles used in this research are exclusive of road grade values, the gravitational potential energy is excluded from the estimation of the fuel economy. The equations for the estimation (Gao, Chu, & Ehsani, 2007; TA Engineering, 2014; Yu, 2009) are given by:

$$E_{aero,i,j}(K) = \sum_{k=2}^K \frac{\rho \cdot c_D \cdot A_j \cdot \bar{v}_i^3(k) \cdot \Delta t(k)}{2} \quad (16)$$

$$E_{res,i,j}(k) = \sum_{k=2}^K m_j \cdot g \cdot \bar{v}_i(k) \cdot c_{res} \cdot \Delta t(k) \quad (17)$$

$$E_{acc,i,j}(k) = \sum_{k=2}^K (1 + c_{acc}) \cdot m_j \cdot a_i \cdot \bar{v}_i(k) \cdot \Delta t(k) \quad (18)$$

where

k = scale of a driving cycle in market i , $k \in [1, 2, \dots, K]$

$E_{aero,i,j}(K)$ = energy required to overcome aerodynamic drag for vehicle type j running in market i

ρ = air density

c_D = coefficient of drag

A_j = frontal area of vehicle type j

$E_{res,i,j}(k)$ = energy required to overcome rolling resistance for vehicle type j running in market i

g = gravitational acceleration

c_{res} = rolling resistance coefficient

$E_{acc,i,j}(k)$ = energy required to accelerate vehicle type j running in market i

c_{acc} = rotational mass coefficient

a_i = acceleration at each time step running in market i

In these equations, $\bar{v}_i(k)$ is an average velocity at each time step calculated by two adjacent velocities:

$$\bar{v}_i(k) = v_i(k-1) + \frac{v_i(k) - v_i(k-1)}{2} \quad (19)$$

Furthermore, $\Delta t(k)$ is the duration of time between two adjacent time points in a drive cycle:

$$\Delta t(k) = t(k) - t(k-1) \quad (20)$$

To reflect the real conditions, the total mass of vehicle type j is considered as a variable, since the payload weight of this vehicle changes at each stop. In this context, it is assumed that the total mass of vehicle type j increases (loading) or decreases (unloading) a constant mass a at each stop. The stops are identified by the value of vehicle speeds. If the vehicle speed at the scale k equal to 0 and the prior speed is a constant, it is then identified as a stop at the scale k .

$$m_j(k) = \begin{cases} m_j(k-1), & \text{if } v_i(k) \neq 0 \\ m_j(k-1) \pm a, & \text{if } v_i(k) = 0 \text{ and } v_i(k-1) \neq 0 \end{cases} \quad (21)$$

The total energy consumption $E_{i,j}$ is calculated by taking into account the vehicle efficiency ($\eta_{v,j}$). In line with the different types of vehicles, the efficiency may include engine efficiency, generator/electric motor efficiency, battery charge/discharge efficiency, driveline efficiency, and regenerative braking efficiency (the details introduced in Chapter 5).

$$E_{i,j} = \frac{E_{aero,i,j}(k) + E_{res,i,j}(k) + E_{acc,i,j}(k)}{\eta_{v,j}} \quad (22)$$

The fuel economy is finally estimated by dividing the energy consumption by the total distance of a drive cycle ($d_{dc,i}$).

$$P_{i,j} = \frac{E_{i,j}}{d_{dc,i}} \quad (23)$$

5 Implementation

Synthesizing the stochastic values into this estimation, the expected value of fuel economy can be subsequently simulated. Each column of the matrix $t \times p$ is a set of time-velocity data. Accordingly, there are p values of fuel economy estimated by p sets of time-velocity data. At the end, the arithmetic mean is applied to calculate the expected value of fuel economy. This expected value of fuel economy is then input into the three mathematical expressions to calculate the expected values of the economic, social, and environmental performance.

In this research, since the value of fuel economy is simulated rather than collected from the specifications, some parameters are further required in the simulation. To this end, the values of these parameters are considered as a part of the required parameters for generating complete data (Table 10).

Table 10: Parameters required by the calculation of fuel economy

Parameters	Meaning
ρ	Air density
c_D	Coefficient of drag
A_j	Frontal area of vehicle type j
m_j	Total mass of vehicle type j running in market i
g	Gravitational acceleration
c_{res}	Rolling resistance coefficient
c_{acc}	Rotational mass coefficient
$\eta_{v,j}$	Efficiency of vehicle type j
d_{dc}	Total distance of the drive cycle in market i
v_i	Velocity of the drive cycle
t	Time of the drive cycle

In summary, there are three mathematical expressions and a fuel economy simulation model formulated to implement the methodology of assessment. However, the credibility of the performance derived from this assessment is uncertain. It implies that the assessment results need to be validated. Therefore, the next subsection focuses on introducing the methods for conducting the validation in this research.

5.1.2.4 Validation

This subsection introduces 10-fold cross validation as the method to validate the results obtained from the assessment. Cross validation is an accuracy estimation method and applied in the context of data that is difficultly or costly collected (Kohavi, 1995; Safaei, 2014). 10-fold cross validation is a widely used technique in cross validation. The role of the 10-fold cross validation in this research is to estimate the accuracy of the expected values and confirm a range, in which the expected values are credible to support making trustworthy decisions.

5.1 Implementation of the Methodology for Assessment

The procedure of 10-fold cross validation is illustrated in Figure 15. A series of random numbers is an essential component to carry out the 10-fold cross validation. In this research, this series of random numbers is the p sets of stochastic vehicle speeds of drive cycles generated from the Monte-Carlo method. These p sets are then randomly divided into 10 equal-sized sub samples. Nine of the ten sub samples are used as training data. The rest of one sub sample is test data. As illustrated in Figure 15, each of the sub samples is used exactly once as test data. To this end, there are 10 experiments created in this validation. In each of the experiments, there are p sets of expected values computed by using the test and training data.

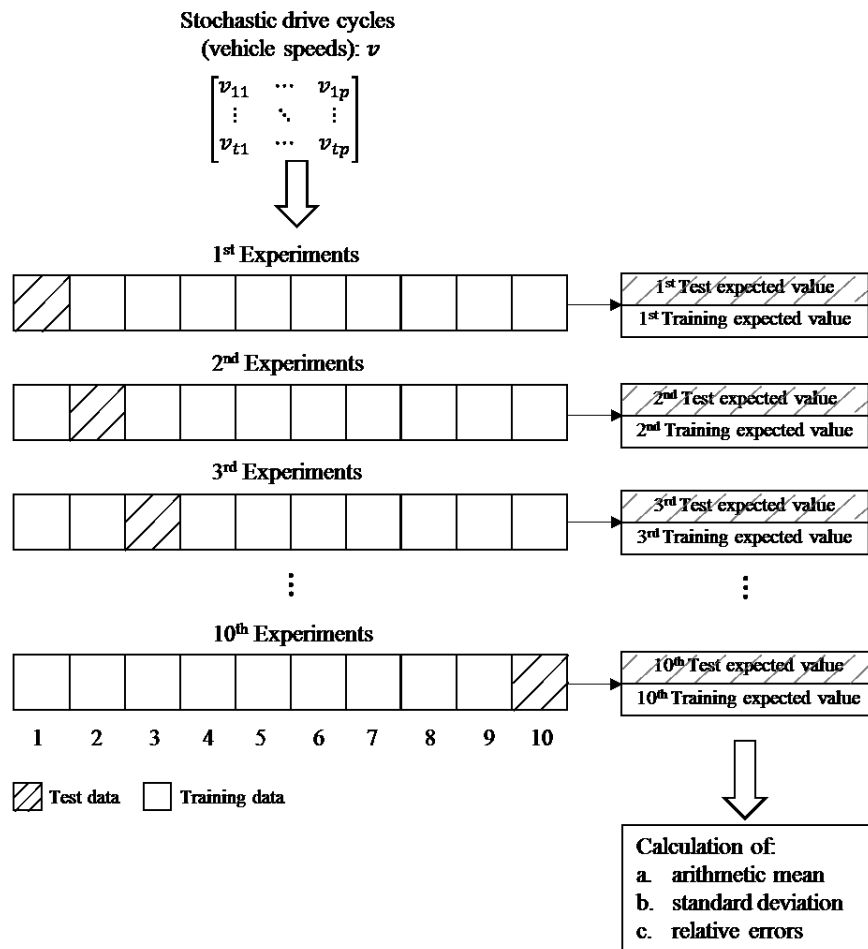


Figure 15: Procedure for conducting the 10-fold cross validation

To examine the accuracy of these expected values, their relative errors are calculated via:

$$re_h = \frac{\sum_{p=1}^P \frac{|exp-ex|}{ex}}{p} \quad (24)$$

$$re = \frac{\sum_{h=1}^{10} re_h}{10} \quad (25)$$

5 Implementation

where

p = the number of sets of stochastic values generated in one experiment;

h = the number of experiments;

ex = the expected values derived from the assessment before the validation;

ex_p = the expected value calculated by using the p^{th} set of stochastic values in the validation;

re_h = the h^{th} relative error;

re = the relative error of 10 experiments;

After examining the accuracy, the ten experiments finally yield ten test and ten training expected values. According to these results, their arithmetic mean values and the standard deviations are calculated by using:

$$\bar{ex} = \frac{1}{10} \sum_{h=1}^{10} ex_h \quad (26)$$

$$sd = \sqrt{\frac{1}{9} \sum_{h=1}^{10} (ex_h - \bar{ex})^2} \quad (27)$$

where

\bar{ex} = the arithmetic mean of expected values;

ex_h = the h^{th} expected value;

sd = the standard deviation of expected values;

The results of the arithmetic mean and the standard deviation are visualized as error bars (Figure 16) to show the dispersion of the expected values. The primary purpose is to use this dispersion for exploring the range, in which the expected values are credible to support making trustworthy decisions. These expected values refer to one of the economic, social, or environmental performance derived from different ECV-UFT combinations. For instance, in Figure 16, the expected values are the TCO of four ECV-UFT combinations. If there are non-overlapping error bars between two ECV-UFT combinations (see ECV-UFT₃ & ECV-UFT₄), it indicates that the minimum expected value of ECV-UFT₄ is greater than the maximum expected value of ECV-UFT₃ and this status remains constant. In this context, the expected values are validated as credible results. On the contrary, if there are overlapping error bars between ECV-UFT combinations (see ECV-UFT₁ & ECV-UFT₂), it implies that the expected values of ECV-UFT₁ may not always be greater than the ECV-UFT₂ in the overlapping area. In this context, the conclusion deduced from these expected values is validated as undecidable.

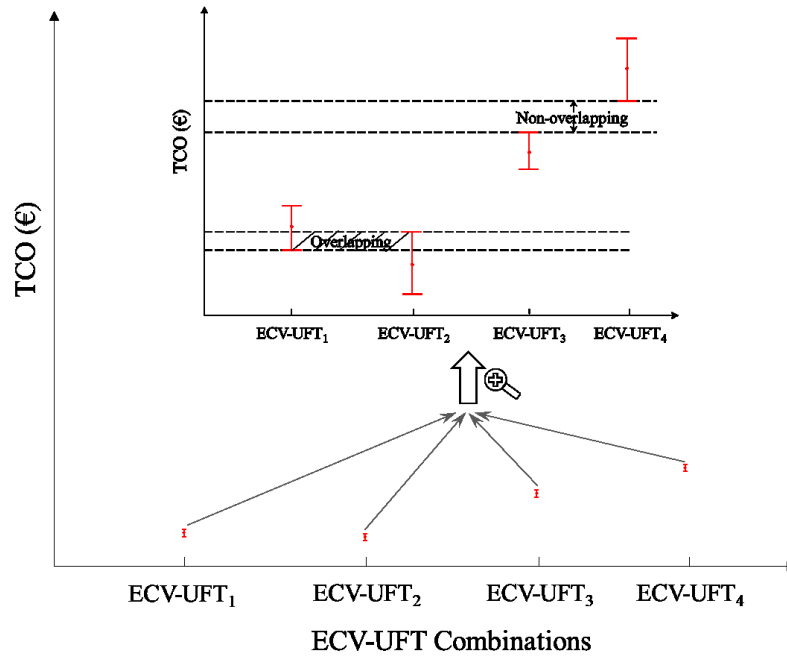


Figure 16: Relations between error bars

To avoid the undecidable status, a range, in which the error bars are constantly non-overlapping, is required to be identified. In this research, since the stochastic drive cycles are essentially generated by the normal distribution, this range is determined by the standard deviation of the normal distribution (σ). In other words, the value of the standard deviation of normal distribution impacts the dispersion of stochastic drive cycles and the expected values. Hence, the upper bound of σ is required to be identified so that the decisions deduced from the expected values are credible.

The procedure of identifying the upper bound of σ is given as follows. Firstly, it is assumed that only the value of the standard deviation of the normal distribution impacts on the upper bound. Next, the expected values and their standard deviations are calculated by assigning an initial value to σ . The error bars are then plotted accordingly. By observing the error bars, the dispersion of the expected values and the relation between error bars (non-overlapping or overlapping) are obtained. If the error bars are non-overlapping, σ is assigned a new value to repeat the procedure until the error bars are overlapping. The value of σ that causes the overlapping is identified as the upper bound.

In summary, after assessing the ECV-UFT combinations, the validation provides the methods for examining the accuracy of the assessment results and identifying the range of credible expected values. These validated results are considered as input for the methodology of determination.

5.2 Implementation of the Methodology for Determination

A procedure for analyzing the expected values is proposed to implement the methodology of determination. This procedure provides a sequence of methods to support decision-makers in understanding the expected values and determining the satisfactory match. Three methods, which are sensitivity analysis, ternary plot, as well as calculations of equivalent points, constitute this procedure (Figure 17).

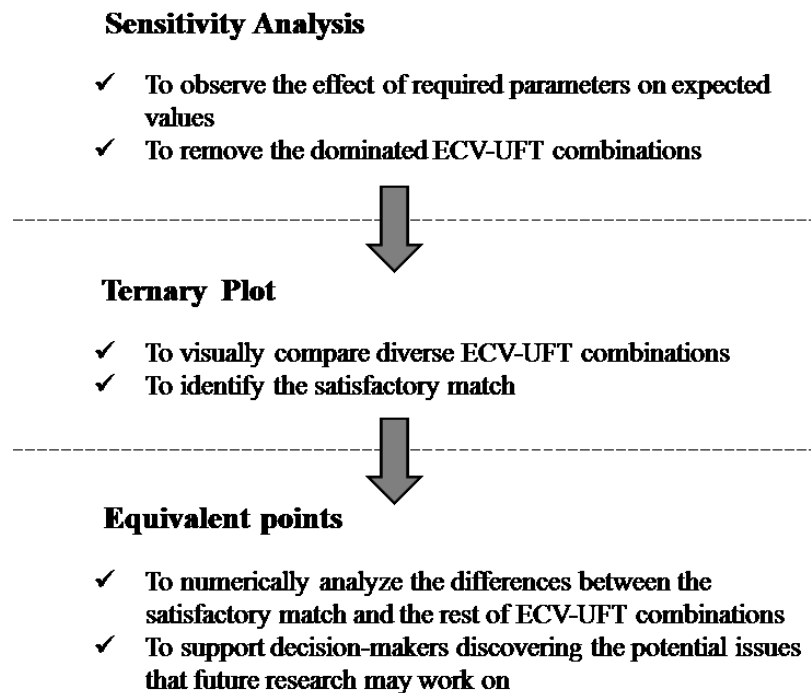


Figure 17: Procedure for analyzing the expected values

These three methods are conducted in three steps respectively to implement the methodology of determination. Firstly, the sensitivity analysis is applied to remove the dominated ECV-UFT combinations. Secondly, the ternary plot is drawn to compare the ECV-UFT combinations and identify the satisfactory match. Finally, the calculations of equivalent points provide numerical analysis for in-depth understanding the potential improvements of the satisfactory match.

5.2.1 Sensitivity Analysis

This subsection focuses on the sensitivity analysis to remove the dominated ECV-UFT combinations. As introduced in Section 4.3.2, the dominated ECV-UFT combinations are identified by the assessment results. Additionally, this identification also relies on whether these results can be improved and better than the other one in any of the three criteria by changing the values of the required parameters. In this context, the sensitivity analysis is applied to calculate the effect upon the expected values by changing the values of required parameters (Sargent, 2013) for supporting the identification of the dominated ECV-UFT combinations.

There are four steps to conduct the sensitivity analysis. The first step is to determine the required parameters, whose sensitivity will be analyzed. Secondly, it is essential to define a reasonable range, which provides a scope to change the values of the required parameters. For instance, the reasonable range of the payload weight per trip is from 0 (empty load) to the value of the payload capacity. After defining the range, a set of values of the same required parameter is obtained. Thirdly, to analyze the sensitivity of this parameter on the assessment results, a series of expected values are calculated by using the set of values in the formulated mathematical expressions. In this calculation, it is assumed that the set of values in a reasonable range is variable. The obtained series of expected values are finally plotted as a trend line to illustrate the possible changes of the expected values in terms of the values of the required parameters in the defined range (Figure 18).

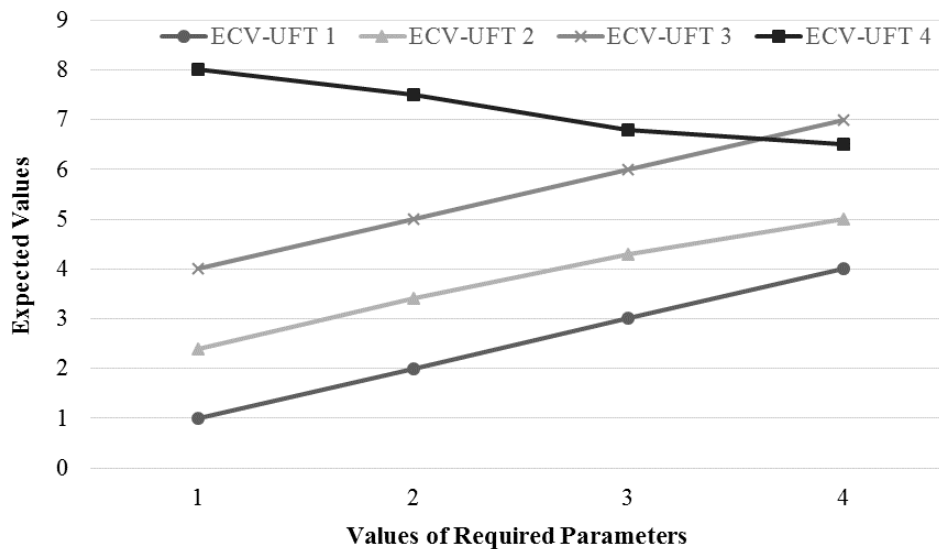


Figure 18: An example of figures in the sensitivity analysis

The sensitivity analysis allows decision-makers to compare the same performance of different ECV-UFT combinations visually and narrow the list of the available ECV-UFT combinations by plotting the trend lines (Figure 18). Decision-makers primarily observe the intersection points among trend lines of different ECV-UFT combinations. If there is an intersection point between two trend lines, it indicates that the expected value of one ECV-UFT combination may exceed the other ones in the context of changing values of required parameters in the defined range (see ECV-UFT₃ & ECV-UFT₄). If there is no intersection point between two trend lines, it implies that the expected value of one ECV-UFT combination remains greater or smaller than the other ECV-UFT combination's expected value (see ECV-UFT₁ & ECV-UFT₂). In this context, the dominated ECV-UFT combination can be identified and excluded from the list of the available ECV-UFT combinations. This exclusion in the sensitivity analysis allows to shrink the number of ECV-UFT combinations thereby simplifying the determination of a satisfactory match.

5.2.2 Ternary Plot

The method called ternary plot is applied in this subsection for supporting decision-makers in determining their satisfactory match. This method can illustrate the decision problem in an easy-to-understand graphical representation (Hofstetter, 1998). In other words, the ternary plot allows to synthesize and visualize the expected values, which are calculated under the economic, social, and environmental criteria, in a triangle.

The synthesized expected values are visualized as points in a two-dimensional graph (Figure 19). An equilateral triangle constitutes this 2D graph. The three sides of this triangle are the three axes, which respectively denote the economic, social, and environmental criteria. There are 11 numbers from 0 to 1 with an interval of 0.1 on each axis. The number 0 stands for the bad performance in each criterion, while the number 1 represents the good performance. For instance, the number 0 on the economic axis may refer to the high TCO, and the number 1 on the environmental axis may refer to the low energy consumption and GHG emissions. Additionally, these numbers are read in a clockwise direction.

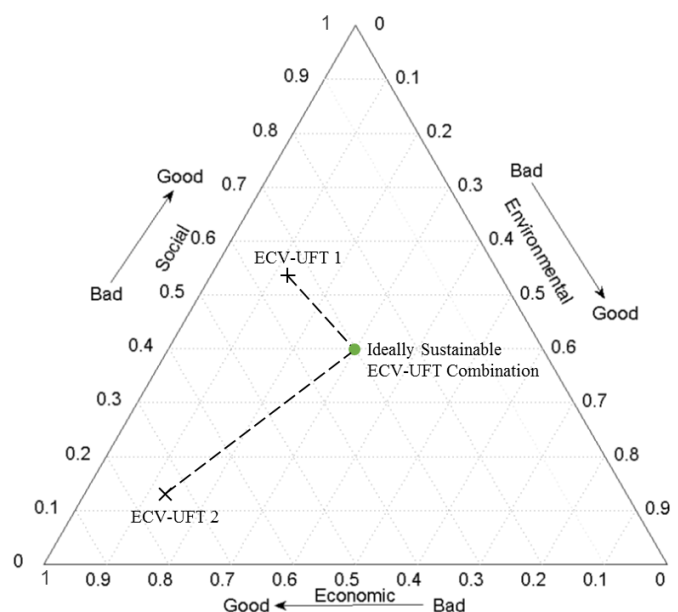


Figure 19: An example of a ternary plot

As introduced in Section 4.3.2, this triangle presents the extent of harmonization of the three criteria in each of ECV-UFT combinations. The sustainable ECV-UFT combination is identified not only regarding the performance but also the extent of harmonization. In other words, a very good performance in one criterion, which is achieved by sacrificing the performance in the other two criteria, is regarded as unsustainable. In this triangle, the extent of harmonization refers to the distance between the point of synthesized expected values and the middle point. Since the middle point is mapped onto each of the axes in the same distance, it is considered

as the ideally sustainable ECV-UFT combination, which performs identically good in each criterion. The closer the point of synthesized expected values is to the middle point, the more sustainable the ECV-UFT combination will be (for instance, the ECV-UFT₁ is more sustainable than the ECV-UFT₂).

Furthermore, it is crucial to normalize the expected values, which are calculated under the three criteria before plotting the triangle. The role of this normalization is to remove the units of expected values in the ternary plot. The normalization in this research uses the equations in Table 11 to plot the expected values in the triangle consistent with the meaning on each axis. This meaning of each axis refers to a rule that the higher the number is, the better the performance will be. Nevertheless, the greater the expected values in economic and environmental criteria are, the worse the performance will be. The expected value of TCO calculated in economic criteria is an example. Since freight carriers intend to achieve low TCO, the high TCO then implies bad economic performance. In this context, to plot the expected values of economic and environmental criteria consistent with the rule of axes, the difference between each expected value and their maximum expected value is calculated in this normalization. On the contrary, a higher expected value is better for social criteria. Hence, the difference between each expected value and their minimum expected value is calculated in this case. After normalizing the expected values from column two to four in Table 11, the proportions of normalized values in three criteria for the same ECV-UFT combination are calculated for the ternary plot. These proportions are finally visualized as points plotted in the triangle.

Table 11: Normalization of expected values for the ternary plot

ECV-UFT	Criteria			Ternary Plot
	C_{eco}	C_{env}	C_{soc}	
ECV-UFT ₁	a_{m1}	a_{m2}	a_{m3}	$tp(A_m)$
ECV-UFT ₂	$\frac{b_{max1} - b_{m1}}{\sum_{i=1}^m (b_{max1} - b_{m1})}$	$\frac{b_{max2} - b_{m2}}{\sum_{i=1}^m (b_{max2} - b_{m2})}$	$\frac{b_{m3} - b_{min3}}{\sum_{i=1}^m (b_{m3} - b_{min3})}$	$\frac{a_{mj}}{\sum_{j=1}^3 a_{mj}}$
⋮				
ECV-UFT _m				

Where, a_{ij} is the normalized values without units, b_{ij} is the actual expected values calculated by mathematical expressions with units, b_{maxj} is the maximum actual expected value under the j^{th} criterion, b_{minj} is the minimum actual expected value under the j^{th} criterion, m is the number of ECV-UFT combinations after removing the dominated ECV-UFT combinations in the sensitivity analysis.

On the whole, the ternary plot provides a method for decision-makers to identify their satisfactory match. This means that the synthesized expected values in the triangle can distinctly illustrate the performance of each ECV-UFT combinations and their extent of harmonization. Decision-makers then determine the satisfactory match, which satisfies their conditions, by observing these points in the triangle.

5.2.3 Calculation of Equivalent points

In this subsection, the calculation of equivalent points is introduced to in-depth understand the identified satisfactory match. The differences between the satisfactory match and the ECV-UFT combinations, which have the best performance in a specific criterion, are calculated. For instance, Eq.28 shows the calculation of the equivalent point in environmental criteria. It is assumed that a required parameter, whose difference the decision-makers intend to quantify between two ECV-UFT combinations, is denoted as x . ECV-UFT₁ in Eq.28 is assumed as the combination, which has the best environmental performance. ECV-UFT₂ is assumed as the obtained satisfactory match. In this example, the equivalent point (annual transport weight) is solved by using the data of ECV-UFT₂ equal to the energy consumption of ECV-UFT₁. As a result, this equivalent point may help decision-makers to discover the potential improvements regarding the satisfactory match that future research may work on.

$$E_{WTW,ECV-UFT_1}(N) = \sum_{n=1}^N x \cdot d(n) \cdot P_{T,ECV-UFT_2} \cdot f_e \quad (28)$$

In summary, this section provides a sequence of methods for decision-makers to implement the methodology of determination. On top of this, the next section focuses on combining the implementations of these two methodologies to establish connections between all the methods.

5.3 Simulation Platform

This section introduces a simulation platform to implement the Sustainable ECV-UFT Matching Concept holistically. This platform consists of six modules, which transform the methodology of assessment and the methodology of determination into the computer (Figure 20). Since MATLAB provides an easy-to-use matrix-based programming environment for performing calculations (Markel et al., 2002), these modules are implemented in the MATLAB environment. In this simulation platform, a set of complete data is firstly generated in the input module. This set of data is then read by the second module to simulate fuel economy. Subsequently, the simulated results of fuel economy are input into the economic-, social-, and environmental- mathematical expressions to calculate expected values. To confirm the accuracy and the credibility of these expected values, a validation is conducted in the fourth module. These validated expected values are then summarized in a table as an output. In addition, these expected values are further analyzed in the fifth module to support decision-makers to determine their satisfactory match. A triangle, which visualizes and synthesizes these expected values derived from the ternary plot in the fifth module, is considered as another output of this simulation platform. Besides, the potential improvements of the satisfactory match, which are deduced from the calculation of equivalent points, are the third output of this simulation platform. The details of each module are elaborated as follows.

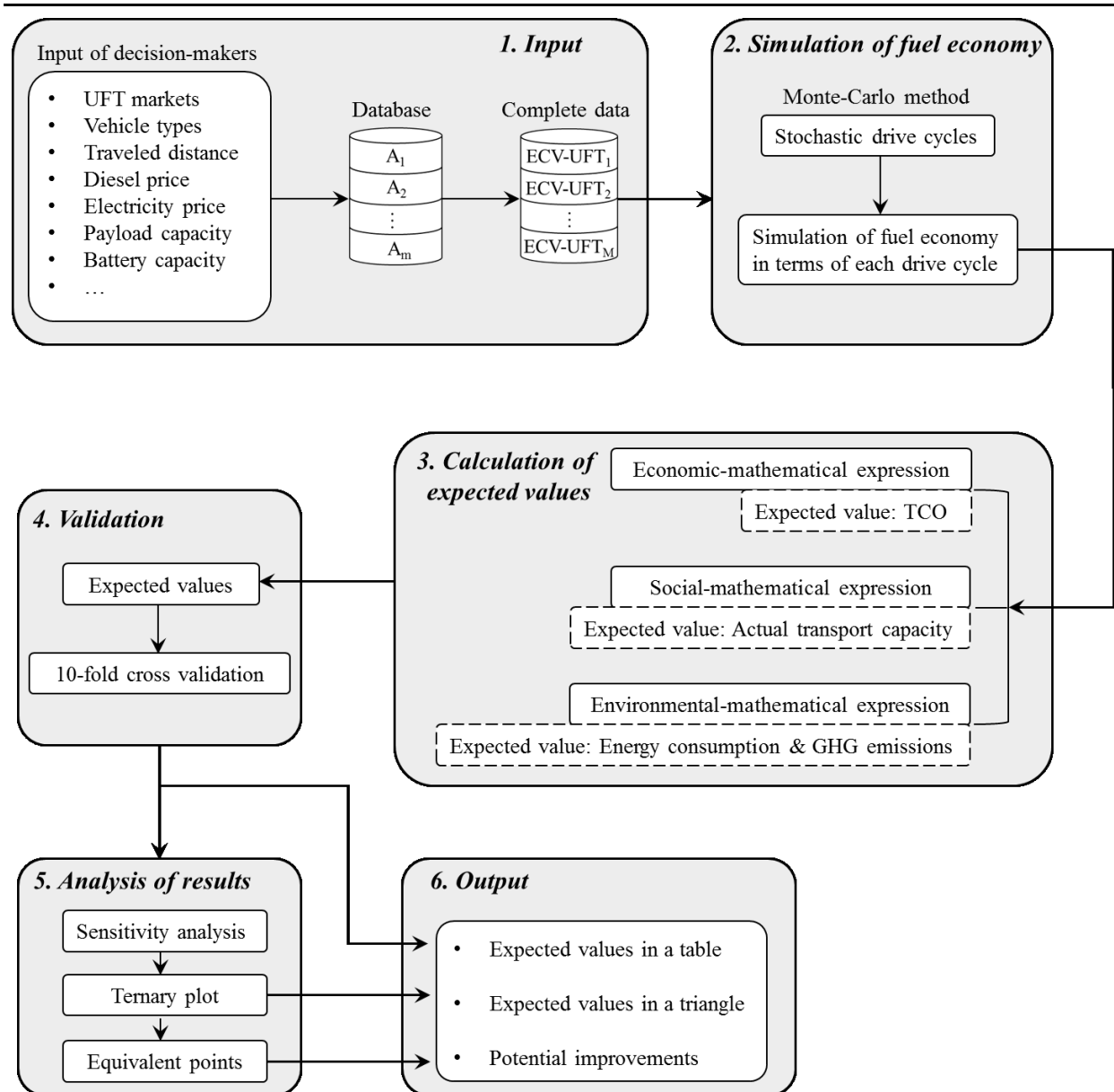
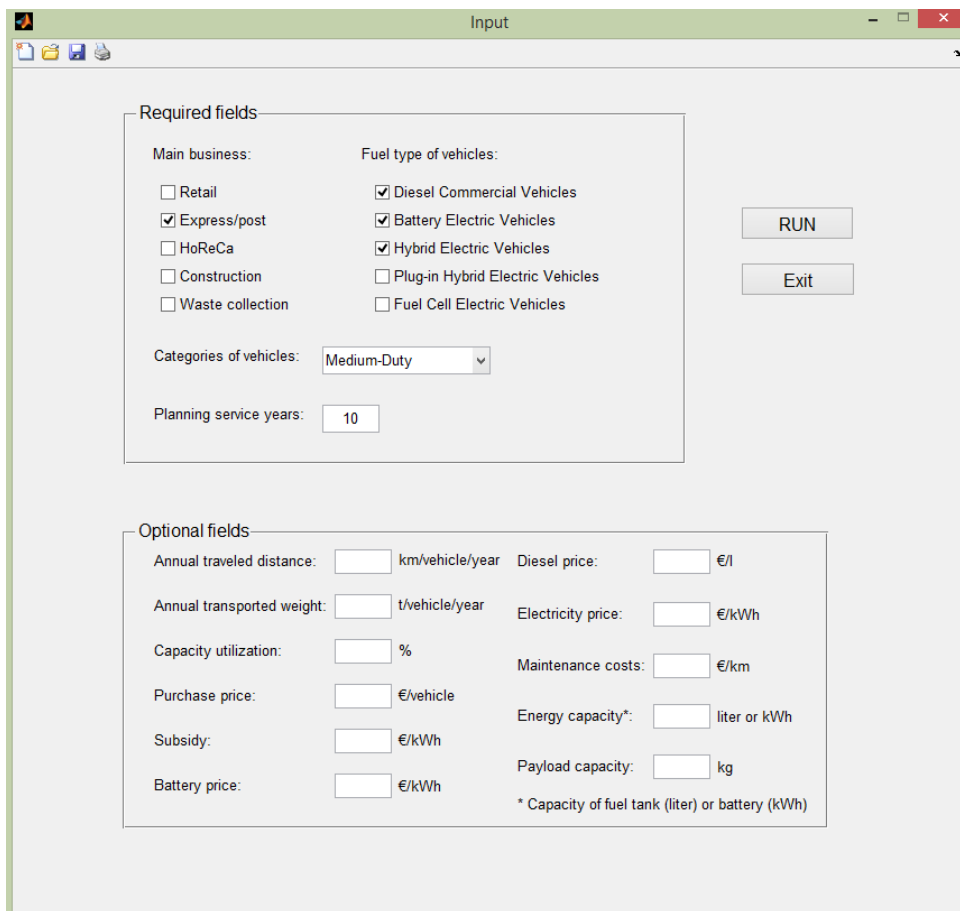


Figure 20: Simulation platform for implementing the methodological concept

The input module implements the generation of complete data in the methodology of assessment. As stated in Section 5.1.1, there are mainly two sources for collecting data. One source of the data collection is related publications. In this implementation, the values of required parameters that are collected from the related publications are stored as the background data in the database. Furthermore, users (decision-makers) are required to enter their data in the user interface designed in this simulation platform (Figure 21). The main business and the fuel type of vehicles in this interface determine which ECV-UFT combinations will be assessed in this simulation platform. Since the ECV is an emerging technology in UFT, three situations may happen after users input data. The first situation is that the users only fill the required fields. It indicates that the decision-makers lack corresponding data, although they intend to understand this emerging technology in UFT better. In this context, a set of complete data is generated from the

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background data according to the information filled in the required fields. The second situation is that the users entirely fill the required fields and partly fill the optional fields. In this context, the set of complete data is generated by merging the data from the users and the background data. It means that the missing data of users is filled by the background data in the database. Moreover, the third situation is that the users fill all of the fields in the interface. In this context, the set of complete data is constituted by the input of users. In the end, the complete data generated in this module is considered as the input for the subsequent simulation, calculation, and validation.



The screenshot shows a software window titled "Input" with a standard Windows-style title bar. The window is divided into two main sections: "Required fields" and "Optional fields".

Required fields:

- Main business:** A group of checkboxes with "Express/post" selected.
- Fuel type of vehicles:** A group of checkboxes with "Diesel Commercial Vehicles", "Battery Electric Vehicles", and "Hybrid Electric Vehicles" selected.
- Categories of vehicles:** A dropdown menu currently showing "Medium-Duty".
- Planning service years:** A text input field containing the number "10".

Two buttons, "RUN" and "Exit", are located to the right of the required fields section.

Optional fields:

This section contains several input fields for various parameters:

- Annual traveled distance: [] km/vehicle/year
- Annual transported weight: [] t/vehicle/year
- Capacity utilization: [] %
- Purchase price: [] €/vehicle
- Subsidy: [] €/kWh
- Battery price: [] €/kWh
- Diesel price: [] €/l
- Electricity price: [] €/kWh
- Maintenance costs: [] €/km
- Energy capacity*: [] liter or kWh
- Payload capacity: [] kg

* Capacity of fuel tank (liter) or battery (kWh)

Figure 21: User interface for inputting data

The assessment of ECV-UFT combinations is implemented in the next three modules, namely the simulation of fuel economy, the calculation of expected values, and the validation. In the module – simulation of fuel economy, a simulation model for computing the fuel economy is formulated by applying the Monte-Carlo method. The drive cycle determined by the main business in the last module is input as a part of the complete data in this module. According to this drive cycle, the Monte-Carlo method stochastically creates a number of similar drive cycles. The number of these drive cycles is decided by the sample size. This sample size is possible to be changed by the users. Since one fuel economy is computed by using one drive cycle, therefore, there are a number of fuel economy

derived from this simulation in terms of the sample size. This fuel economy is then inputted into the next module – calculation of expected values. Three mathematical expressions formulated in Section 5.1.2.2 constitute this module. TCO, actual transport capacity, energy consumption, and GHG emissions are the corresponding performance computed in this module. Each of the fuel economy derived from the last module is used once for computing the performance. To this effect, the number of times for computing the performance is equal to the sample size. In the end, the expected value of each performance is calculated by the arithmetic mean.

Next, the fourth module implements the validation of expected values. The method 10-fold cross validation is computerized to confirm the credibility of the expected values. As stated in Section 5.1.2.4, the stochastic drive cycles created in the Monte-Carlo method are randomly divided into ten equal-sized subsamples to calculate the expected values. The relative errors, the arithmetic mean, and the standard deviation of these expected values are computed as the results in this module. The relative errors show the extent of the accuracy of the expected values computed in this simulation platform. Additionally, the error bars plotted by using the arithmetic mean and the standard deviation illustrate the credibility of the expected values. The accuracy and the credibility of expected values determine the next step in this simulation platform. If the expected values are validated as accurate and credible values, these expected values will then summarized into a table as output and simultaneously input into the module – analysis of results. On the contrary, if the expected values are validated as low accuracy and credibility, this simulation platform will move back to the module – simulation of fuel economy to recalculate the expected values.

The methodology of determination is implemented in the fifth module. It indicates that the sensitivity analysis, the ternary plot, and the calculation of equivalent points introduced in Section 5.2 are transformed into a computerized module. The triangle, which synthesizes the computed performance of each criterion by applying the ternary plot, is considered as a significant output in the final module. Combining this triangle and the potential improvements derived from the calculation of equivalent points, the output module in this simulation platform may ultimately present and provide constructive results for supporting decision-makers to determine their satisfactory match and explore the future research.

5.4 Summary

In this chapter, a simulation platform was designed to implement the proposed methodological concept. In particular, a simple database was established to support the quantitative assessment. Moreover, an adapted MCDM method was proposed and three mathematical expressions were accordingly formulated to implement the methodology of assessment. To analyze the results derived from the assessment, a sequence of methods was proposed (sensitivity analysis, ternary plot, and

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calculation of equivalent points) for implementing the methodology of determination. In the end, the simulation platform was designed to integrate the methods, the database, and the mathematical expressions to convert the methodological concept from the theoretical to the practical guidance.

To evaluate the proposed methodological concept, three scenarios are introduced as examples and assessed by applying the designed simulation platform in the next chapter.

6 Evaluation

This chapter focuses on evaluating the proposed methodological concept by applying the proposed simulation platform. The objective is to confirm that this concept is feasible to assess the diverse ECV-UFT combinations and support decision-makers to determine their satisfactory match by addressing the identified challenges and meeting the specified requirements. There are three scenarios introduced in Section 6.1 to conduct this evaluation. The assumptions of this evaluation are defined in Section 6.2. In Section 6.3, the results, such as the expected values, the sensitivity analysis, and the equivalent points, are shown after carrying out the evaluation in the three scenarios. These results are then discussed in Section 6.4 to establish the feasibility of this methodological concept. Finally, the limitations of the methodological concept and a summary of this chapter are elaborated in Section 6.5 and 6.6.

6.1 Scenarios in the Evaluation

In this section, three scenarios, namely the Diesel Commercial Vehicle (DCV) - Express/post, the Battery Electric Vehicle (BEV) - Express/post, and the Hybrid Electric Vehicle (HEV) - Express/post, are introduced for the evaluation of the Sustainable ECV-UFT Matching Concept. The purpose of selecting these scenarios is to confirm the feasibility of the proposed methodological concept in the common and the emerging situations respectively. In particular, these three scenarios are constituted by the combinations of single vehicle type and single UFT market. In other words, the three scenarios were selected from the ECV-UFT combinations (Section 3.4).

There are three reasons driven the selection of the express/post as the UFT market to constitute the scenarios for the evaluation. Firstly, on account of the rapid development of e-commerce over the recent decade, the express/post has become one of the markets, which appears frequently in the daily life of the citizens. It indicates that replacing conventional vehicles with ECVs in this express/post market may effectively demonstrate the applicability of ECVs to the citizens. Furthermore, on the basis of the stop-and-go feature in the express/post market, the ECVs, which have the on-board regenerative braking systems, benefit of this feature in this market. On top of these two reasons, the third reason is that the data of the express/post market is available to be extracted from the literature and the demonstration projects. Given these points, the express/post market was determined as the UFT market to constitute the three scenarios in this evaluation.

Combining the express/post market with the three vehicle types (DCV, BEV, and HEV) respectively composes the three scenarios. Specifically, the role of using the DCV-Express/post is to represent a typical situation existing in the current urban freight transport for evaluating the proposed concept. Additionally, this scenario is

considered as a benchmark in this evaluation to distinctly compare the difference between the conventional vehicles (DCV) and the electric vehicles operating in an identical UFT market. Furthermore, the BEV- and the HEV-Express/post scenarios symbolize an emerging situation in the UFT for conducting the evaluation. According to the literature review in Section 3.4, the BEV and the HEV were observed as the main vehicle types studied frequently in the literature. This implies that the data of these two vehicle types is available to be collected for the evaluation. Moreover, since the powertrain of the BEV and the HEV are representative and differ from the DCV, these two vehicle types are considered in the scenarios of the evaluation to provide more options for examining the methodological concept.

Following subsections focus on specifying the three scenarios respectively. Since the main difference between the scenarios is the powertrain of the vehicles, the characteristics of these powertrains are specified to adapt the corresponding equations in the simulation platform to the three scenarios. Additionally, the available data of each scenario for the evaluation is presented at the end of this section.

6.1.1 Scenario I : DCV – Express/Post

Since the DCV consists of the conventional powertrain, the scenario I DCV-Express/post is considered as a benchmark firstly specified in this subsection. This specification mainly focuses on illustrating the characteristics of the powertrain in the DCV by applying an energy flow chart. Regarding the specified characteristics, the equations in the simulation platform are accordingly adapted to this scenario.

To visualize the characteristics of the powertrains distinctly, Figure 22 shows the main components of the powertrain in the DCV and the energy flow between the components. In this figure, the energy provided by the fuel tank ($E_{fuel\ tank}$) is the total energy consumption, which is used for simulating the fuel economy. To derive this total energy consumption, a backward simulation is required to be conducted in terms of this energy flow chart. The estimation of the energy to accelerate vehicles and to overcome the aerodynamic drag as well as the rolling resistance at wheels (E_{wheels}) is the first step in this backward simulation. Subsequently, since there is energy loss in the driveline (E_{dloss}) and the diesel engine ($E_{engloss}$), the total energy consumption from the fuel tank is required not only to power the wheels but also to undertake the energy loss of the main components. To this end, the total energy consumption is backward computed to include the energy loss by using the engine (η_{eng}) and the driveline efficiency (η_{dl}). Finally, the fuel economy is simulated by dividing the total energy consumption by the total distance of the drive cycle in the express/post market.

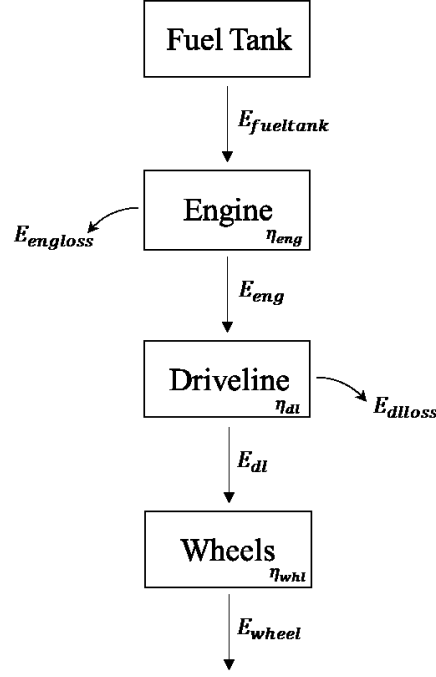


Figure 22: Energy flows in diesel commercial vehicles

The Eq. 22 and 23 in Section 5.1.2.3, which is required to be adapted to the powertrain of the DCV, are shown as:

$$E_{fueltank} = E_{ex/po,diesel} = \frac{E_{aero,ex/po,diesel} + E_{res,ex/po,diesel} + E_{acc,ex/po,diesel}}{\eta_{dl,diesel} \eta_{eng,diesel}} \quad (29)$$

$$P_{ex/po,diesel} = \frac{E_{ex/po,diesel} \cdot 10^{-6}}{35.9 \cdot d_{ac,ex/po}} \quad (30)$$

where

$E_{ex/po,diesel}$ = total energy consumption simulated in the DCV-Express/post combination

$E_{aero,ex/po,diesel}$ = energy required to overcome aerodynamic drag in the DCV-Express/post combination

$E_{res,ex/po,diesel}$ = energy required to overcome rolling resistance in the DCV-Express/post combination

$E_{acc,ex/po,diesel}$ = energy required to accelerate the DCV running in express/post market

$\eta_{dl,diesel}$ = driveline efficiency of the DCV

$\eta_{eng,diesel}$ = engine efficiency of the DCV

$P_{ex/po,diesel}$ = fuel economy simulated in the DCV-Express/post combination

$d_{ac,ex/po}$ = total distance of the drive cycle in the express/post market

Since drive cycles commonly use seconds as the unit to denote the period of driving time, the total energy consumption in Eq.29 is therefore simulated with the unit watt-seconds (Ws). To obtain the fuel economy in the unit liter per kilometer (l/km), the total energy consumption is required to be converted from the unit Ws

to the unit megajoule (MJ) by multiplying by 10^{-6} (see Appendix 2). Besides, since the energy of one-liter diesel is equal to 35.9 MJ (see Appendix 2), the fuel economy in the unit l/km is then obtained by using this value in Eq.30. In short, this subsection specified the characteristics of the powertrain in the DCV by applying an energy flow chart. In addition, two equations formulated in the simulation of fuel economy were adapted to this scenario.

6.1.2 Scenario II : BEV – Express/Post

This subsection focuses on specifying the powertrain of the BEV in scenario II BEV-express/post. The purpose of specifying this powertrain is to adapt the equations in the simulation of fuel economy to this scenario. Similar to the last subsection, the powertrain of the BEV is specified by applying the energy flow chart. Figure 23 shows the energy flow chart in the powertrain of the BEV. In comparison with the energy flow chart of the DCV, the main components in the powertrain of the BEV are changed. In this powertrain, the battery pack and the electric motor replace the fuel tank and the diesel engine respectively. Moreover, since the electric motor has the capability of being used as a generator, the energy lost during braking at wheels can be captured by using the generator. This captured energy is called regenerative braking energy. After capturing this energy at wheels, it is finally stored in the battery pack. In this context, there are two energy flows formed in this powertrain of the BEV. As illustrated in Figure 23, one energy flow discharges the battery pack to propel the vehicles, whereas another energy flow captures the regenerative braking energy at wheels to recharge the battery pack by using the generator. To this effect, the simulation of fuel economy is required to be adapted by involving these two energy flows.

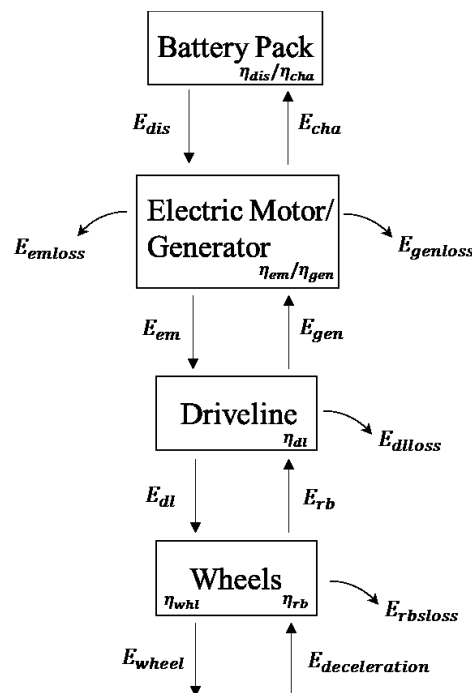


Figure 23: Energy flows in battery electric commercial vehicles

The equations formulated in the simulation of fuel economy (Section 5.1.2.3) is accordingly adapted as:

$$E_{rb,ex/po,BEV} = \min\left(\frac{E_{dec,ex/po,BEV} \cdot \eta_{rb,BEV}}{t_{dc}}, \frac{P_{gen,BEV}}{\eta_{dl,BEV}}\right) \cdot t_{dc} \quad (31)$$

where

$E_{rb,ex/po,BEV}$ = regenerative braking energy on the driveline in the BEV-Express/post

$E_{dec,ex/po,BEV}$ = energy required to decelerate the BEV running in express/post market

$\eta_{rb,BEV}$ = efficiency of regenerative braking energy captured at wheels

$P_{gen,BEV}$ = generator peak power in the BEV

t_{dc} = total driving time of the drive cycle in the express/post market

On the basis of the restriction of the generator peak power, Eq. 31 limits and formulates the maximum regenerative braking energy on the driveline. The energy required to decelerate the BEV is computed by using the Eq.18 in the context of the acceleration less than 0. After deriving the available regenerative braking energy, the actual energy to recharge the battery pack ($E_{cha,ex/po,BEV}$) by taking into account the driveline ($\eta_{dl,BEV}$) and the generator efficiency ($\eta_{gen,BEV}$) is shown as:

$$E_{cha,ex/po,BEV} = E_{rb,ex/po,BEV} \cdot \eta_{dl,BEV} \cdot \eta_{gen,BEV} \quad (32)$$

Similar to Eq.29, the discharged energy from the battery pack ($E_{dis,ex/po,BEV}$) is required to overcome the aerodynamic drag ($E_{aero,ex/po,BEV}$) and the rolling resistance ($E_{res,ex/po,BEV}$) as well as to accelerate the vehicles ($E_{acc,ex/po,BEV}$) in the BEV. Additionally, the energy loss in the electric motor ($\eta_{em,BEV}$) and the driveline ($\eta_{dl,BEV}$) is taken into consideration as well.

$$E_{dis,ex/po,BEV} = \frac{E_{aero,ex/po,BEV} + E_{res,ex/po,BEV} + E_{acc,ex/po,BEV}}{\eta_{dl,BEV} \cdot \eta_{em,BEV}} \quad (33)$$

Eq.34 shows the total energy consumption in the BEV-Express/post in terms of the discharged and recharged energy in the battery pack. $\eta_{dis,BEV}$ and $\eta_{cha,BEV}$ refer to the discharge and charge efficiency respectively.

$$E_{ex/po,BEV} = \frac{E_{dis,ex/po,BEV}}{\eta_{dis,BEV}} - E_{cha,ex/po,BEV} \cdot \eta_{cha,BEV} \quad (34)$$

Based on the total energy consumption, the fuel economy of the BEV is computed with the unit kWh/km and the unit l/km, which are:

$$P_{ex/po,BEV} = \frac{E_{ex/po,BEV} \cdot 10^{-6}}{3.6 \cdot d_{dc,ex/po}} \quad (35)$$

$$P_{liter,ex/po,BEV} = \frac{E_{ex/po,BEV} \cdot 10^{-6}}{35.9 \cdot d_{dc,ex/po}} \quad (36)$$

Given these points, this section specified the powertrain of the BEV in the express/post market and adapted the equations for computing the fuel economy of the BEV-Express/post combination appropriately.

6.1.3 Scenario III: HEV – Express/Post

The HEV employed in the express/post market as scenario III is specified in this subsection. Figure 24 illustrates the energy flow in the powertrain of the HEV. In this powertrain, two propulsion systems, namely the diesel engine and the electric motor, are involved in the HEV. As stated in Section 2.3, the configuration of this powertrain is the parallel HEV. In this context, the propulsion power may be supplied by the diesel engine, by the electric motor, or by both (Chan, 2007). To simulate the fuel economy of this HEV, the total energy consumption in this scenario is simply considered as the difference subtracting the total energy recharged in the battery pack from the total energy provided by the fuel tank. This difference indicates that the recharged energy captured from the regenerative braking energy is used to assist the diesel engine to propel the HEV. To this end, the discharged energy is assumed to be equal to the recharged energy. Accordingly, the equations in the simulation of the fuel economy (Section 5.1.2.3) are required to be adapted to this powertrain of the HEV.

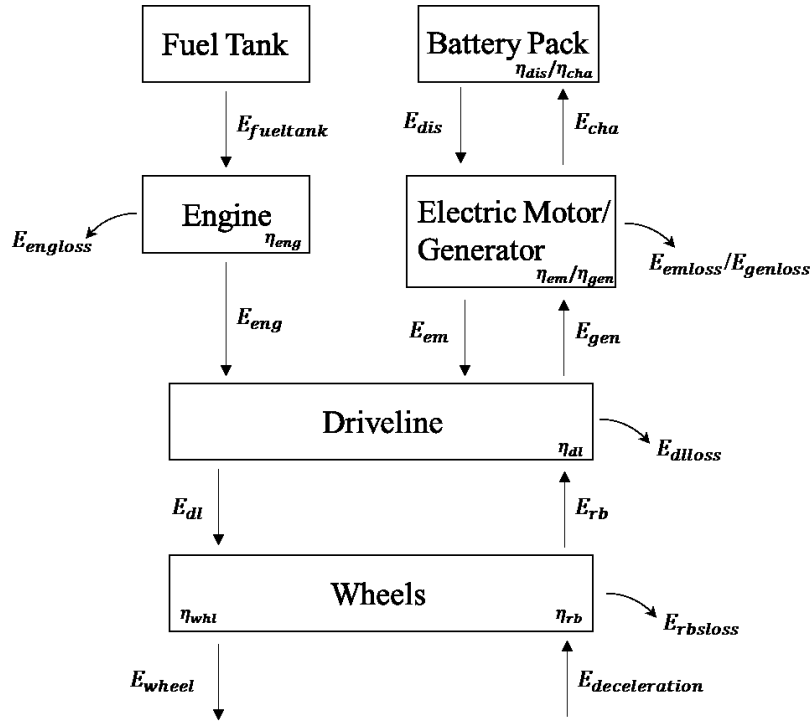


Figure 24: Energy flows in hybrid electric commercial vehicles

The adaption of the equations is shown as follows:

$$E_{rb,ex/po,HEV} = \min\left(\frac{E_{dec,ex/po,HEV} \cdot \eta_{rb,HEV}}{t_{dc}}, \frac{P_{gen,HEV}}{\eta_{dl,HEV}}\right) \cdot t_{dc} \quad (37)$$

Similar to the Eq.31, the regenerative braking energy in the HEV ($E_{rb,ex/po,HEV}$) is formulated in terms of the generator peak power ($P_{gen,HEV}$). Afterwards, this regenerative braking energy is stored in the battery pack ($E_{cha,ex/po,HEV}$) by taking

into account the efficiency of the driveline ($\eta_{dl,HEV}$), the generator ($\eta_{gen,HEV}$), and the recharging ($\eta_{cha,HEV}$), which is expressed as:

$$E_{cha,ex/po,HEV} = E_{rb,ex/po,HEV} \cdot \eta_{dl,HEV} \cdot \eta_{gen,HEV} \cdot \eta_{cha,HEV} \quad (38)$$

Furthermore, the energy required to overcome the aerodynamic drag ($E_{aero,ex/po,HEV}$) and the rolling resistance ($E_{res,ex/po,HEV}$) as well as to accelerate the HEV ($E_{acc,ex/po,HEV}$) is formulated as:

$$E_{fueltank,ex/po,HEV} = \frac{E_{aero,ex/po,HEV} + E_{res,ex/po,HEV} + E_{acc,ex/po,HEV}}{\eta_{dl,HEV} \cdot \eta_{eng,HEV}} \quad (39)$$

To compute the total energy consumption in the fuel tank, the efficiency of the driveline and the diesel engine ($\eta_{eng,HEV}$) are involved in Eq.39 as well.

In the end, the total energy consumption and the fuel economy are shown as:

$$E_{ex/po,HEV} = E_{fueltank,ex/po,HEV} - E_{cha,ex/po,HEV} \quad (40)$$

$$P_{ex/po,HEV} = \frac{E_{ex/po,HEV} \cdot 10^{-6}}{35.9 \cdot d_{dc,ex/po}} \quad (41)$$

The specification of these three scenarios has been completed so far. According to these specified scenarios, the data required by the adapted equations and the mathematical expressions in Section 5.1.2.2 is enumerated in Table 12.

Table 12: Available data of three scenarios

Parameters (Units)	DCV- express/post	BEV- express/post	HEV- express/post
Specification of Vehicles			
Gross vehicle weight (kg) ^a	10433	9992	10433
Payload capacity (kg) ^a	5384	4423	4840
Onboard energy capacity (l, kWh)	113.562 ^a	80 ^b	113.562
Electric motor peak power (kW)	-	150 ^b	44 ^c
Drag coefficient ^d	0.7	0.7	0.7
Rolling resistance coefficient ^e	0.0094	0.0094	0.0094
Rotational mass factor ^d	0.1	0.1	0.1
Frontal area (m ²) ^f	7.07	7.07	7.07
Energy conversion factor TTW (MJ/l) ^g	35.9	35.9	35.9
Air density (kg/m ³) ^e	1.23	1.23	1.23
Engine efficiency (%) ^d	46	-	46
Driveline efficiency (%) ^d	98	98	98
Electric motor efficiency (%) ^d	-	95	95
Generator efficiency (%) ^d	-	85	85
Battery charge efficiency (%) ^h	-	80	80
Battery discharge efficiency (%) ^h	-	80	80
Regenerative braking efficiency (%) ^d	-	75	75
Costs			

6 Evaluation

Parameters (Units)	DCV- express/post	BEV- express/post	HEV- express/post
Purchase price (€) ⁱ	61100	141000	98700
Fuel price (€/l, €/kWh) ^j	1.13	0.119	1.13
Subsidy (€/kWh) ⁱ	-	392	-
Battery price (€/kWh) ^k	-	376	-
Depreciation rate in the first year (%) ⁱ	23	23	23
Depreciation rate in the rest of years (%) ⁱ	15	15	15
Discount rate (%) ^l	6	6	6
Fuel price escalation (%) ⁱ	2.6	2.7	2.6
Maintenance cost (€/km) ⁱ	0.3041	0.2103	0.239
Logistics			
Annual traveled distance (km) ⁱ	26554	26554	26554
Empty trip factor ^m	0.1	0.1	0.1
Daily transported weight (kg) ⁿ	1814	1814	1814
Drive Cycle^o	Baltimore Parcel Delivery	Baltimore Parcel Delivery	Baltimore Parcel Delivery
Conversion Factor (WTW)^g			
Energy conversion factor (MJ/l)	42.7	-	42.7
CO ₂ equivalents conversion factor (kg/l)	3.24	-	3.24

^aLammert et al., 2012, the on-board energy capacity is converted from 30 gallons.

^bProhaska et al., 2016

^cEnergy Efficiency & Renewable Energy, 2011

^dTA Engineering, 2014

^eMarkel et al., 2002

^fUPS, 2018

^gSchmied and Knörr, 2012

^hDavis and Figliozzi, 2012

ⁱBurnham, 2016, the price in euro is converted by 1 USD = 0.94 € (March 06, 2017).

^jEurostat Statistics Explained, 2017, the diesel price is at-the-pump price, the electricity price is the industry price (500 MWh < annual consumption < 2000 MWh; excluding VAT).

^kElectrification Coalition, 2010

^lHou et al., 2014

^mifeu Heidelberg et al., 2016, empty trip factor for volume goods

ⁿLammert, Burton, Sindler, & Duran, 2014

^oKelly et al., 2016

Owing to the fact that the BEV and the HEV are still emerging technology in the UFT, the data for the three scenarios is therefore obtained chiefly from demonstration projects. The United Parcel Service (UPS) project conducted by the National Renewable Energy Laboratory (NREL) in the U.S. is considered as one data source. This project tracked and evaluated the in-service performance of the parallel HEV and the DCV (Lammert et al., 2012), which is consistent with the DCV- and the HEV- express/post scenario in this evaluation. The data appeared in this project, such as the specification of the DCV and the HEV as well as the daily transported weight in the parcel delivery, are available data for the scenarios.

Furthermore, the medium-duty vehicle is the category of vehicles demonstrated in this project. To compare the three scenarios fairly, the category of the BEV is required to be the medium-duty as well. In this context, the Ftiro-Lay project, which evaluated the performance of the medium-duty BEV conducted by the NREL, is involved as another data source. Since this project operated the BEV in a retail market, therefore, only the data regarding the specification of the BEV is extracted from this project.

Furthermore, to be consistent with the three scenarios specified in this section, a custom drive cycle of the express/post market (Figure 25) is incorporated in each scenario. This drive cycle is created by the Drive Cycle Analysis Tool (DriveCAT) of the NREL (Kelly, Prohaska, Ragatz, & Konan, 2016).

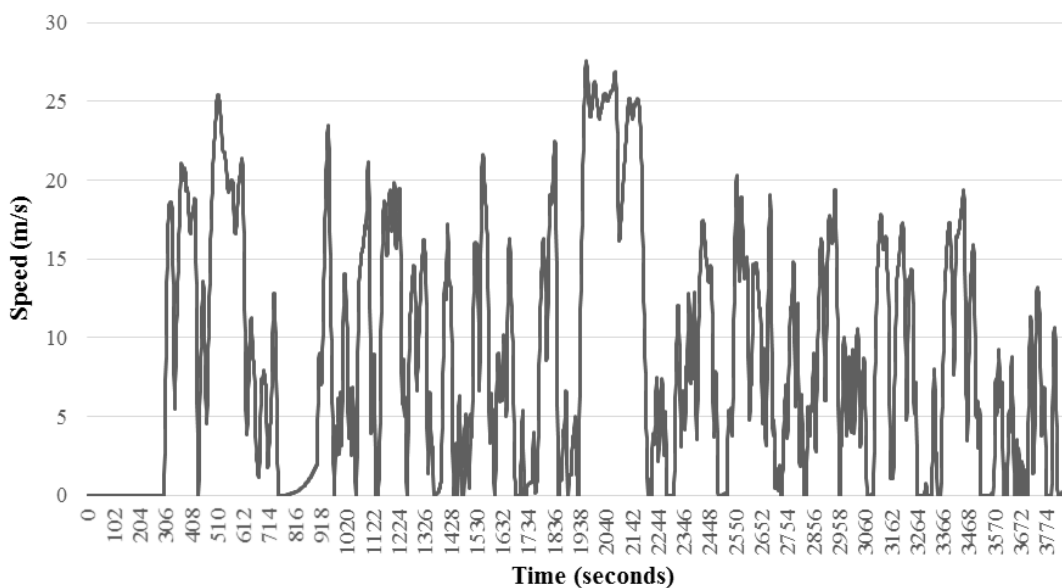


Figure 25: The custom drive cycle in the express/post market

In addition to the UPS and the Ftiro-Lay projects, the data sources also include some tools (such as ADVISOR, AFLEET) and publications (such as Davis & Figliozzi, 2013; Hou et al., 2014). In the end, the available data for each scenario in Table 12 is stored in the simulation platform as the background data.

6.2 Assumptions and Alternatives

In this section, a group of assumptions is made before carrying out the evaluation of the Sustainable ECV-UFT Matching Concept. Since the available data is relatively little in these emerging scenarios, it is first assumed that the data used in this evaluation is the background data presented in Table 12. This assumption implies that only the panel of required fields in the user interface (Figure 21) is entirely filled, whereas the panel of optional fields remains empty in this evaluation. Additionally, this assumption also indicates that the category of commercial vehicles considered in this evaluation is the medium-duty vehicles.

6 Evaluation

Although the background data is assumed as the data source in this evaluation, the values of three required parameters are still missing in the background data. These three required parameters are annual transported weight, capacity utilization, and the initial total mass of vehicles. To obtain the values of these required parameters, three equations are formulated as follows by using the values stored in the background data.

The annual transported weight is derived by involving the daily transported weight and the total operational days per year, which is formulated as:

$$w(n) = W_{p,j} \cdot od(n) \cdot 10^{-3} \quad (42)$$

where

$w(n)$ = annual transported weight in year n

$W_{p,j}$ = daily transported weight using vehicle type j

$od(n)$ = operational days in year n

In this evaluation, the value of the daily transported weight is derived from the background data. Additionally, 260 days is considered as the operational days per year in this evaluation. Since the unit of the annual transported weight in Eq.7 is required to be tons, the unit of the Eq.42 is therefore converted from kilogram to tons to be consistent with the order of magnitudes in Eq.7.

Next, to estimate the capacity utilization, the EcoTransIT (2016) suggests:

$$\eta_c = \frac{W_{p,j}}{(1+f_{et}) \cdot \overline{W_{p,j}}} \quad (43)$$

where

η_c = capacity utilization

$\overline{W_{p,j}}$ = payload capacity of vehicle type j

f_{et} = empty trip factor

The values of the daily transported weight, the empty trip factor, and the payload capacity are given by the background data. Among these values, since this evaluation focuses on the express/post market, the value of the empty trip factor is the value for volume goods.

The initial total mass of vehicles is shown as:

$$m_j(1) = W_{GVW,j} - \overline{W_{p,j}} + W_{p,j} \quad (44)$$

where

$m_j(1)$ = the initial total mass of vehicle type j

$W_{GVW,j}$ = gross vehicle weight of vehicle type j

The value of this total mass is determined by the gross vehicle weight, the payload capacity, and the daily transported weight. In this evaluation, it is assumed that the goods are transported once per day. To this effect, the daily transported weight is also the initial loading weight for the goods delivery. This initial total mass is a supplementary information for Eq.21.

In addition to the aforementioned assumptions, in this evaluation, the planned service years is assumed as ten years (Davis & Figliozzi, 2013; Lebeau, Macharis, Van Mierlo, et al., 2015). Moreover, the battery life of the BEV is assumed as six years in terms of the cycle life of the lithium-ion batteries (Electrification Coalition, 2010; Lebeau, Macharis, Van Mierlo, et al., 2015). These two assumptions in this context convey that the on-board battery of the BEV is required to be replaced after six years in this evaluation. Moreover, the BEV is assumed to be recharged once a day at depots. Besides, it is also assumed that the BEV is fully charged at the start of the goods delivery per day. Finally, to conduct the Monte-Carlo method, the standard deviation of the normal distribution is assumed to be equal to 0.01 and the mean of the normal distribution is assumed as 1. Under these assumptions, the evaluation of the methodological concept is then carried out by using the three scenarios in the simulation platform.

Furthermore, to evaluate the methodological concept extensively, six alternatives are created in terms of the three scenarios specified in Section 6.1. The role of the alternatives is to compare not only the difference between scenarios but also the difference in the same scenario. Since the propulsion system is the main difference between the three scenarios, the alternatives are created accordingly by changing the efficiency of the engines or the electric motors (Table 13) based on the background data in the same scenario. For example, in scenario I, two engine efficiency of the DCV constitute two alternatives, which represent two possibilities in the same scenario. Similarly, two alternatives in scenario II are created by changing the electric motor efficiency of the BEV. To this end, six alternatives are created in the three scenarios and are applied to support the evaluation.

Table 13: Alternatives for the evaluation

Scenarios	Alternatives	Type of Vehicles	UFT Markets
Scenario I	A_1	DCVs (46% engine efficiency)	Express/post
	A_2	DCVs (41% engine efficiency)	Express/post
Scenario II	A_3	BEVs (95% electric motor efficiency)	Express/post
	A_4	BEVs (90% electric motor efficiency)	Express/post
Scenario III	A_5	HEVs (46% engine efficiency)	Express/post
	A_6	HEVs (41% engine efficiency)	Express/post

On the whole, a group of assumptions and six alternatives were clarified in this section before evaluating the Sustainable ECV-UFT Matching Concept. In the next section, these assumptions and alternatives are entered into the simulation platform to conduct the evaluation and compute the results.

6.3 Evaluation Results

This subsection presents the results of evaluating the methodological concept. The expected values of the six alternatives, the accuracy of the results, the sensitivity analysis, the determination of the satisfactory match, and the exploration of the potential improvements constitute this subsection.

6.3.1 Expected Values

In this subsection, the expected values of the economic, the social, and the two environmental performance for the six alternatives are presented respectively. In each of the performance, the expected values of the six alternatives were compared to show the difference between scenarios and the difference in the same scenario. In particular, since all of the mathematical expressions contain the parameter – fuel economy, the expected values of the fuel economy for each alternative are also illustrated in this subsection.

The scenario that combines the BEV with the express/post market consumed the least fuel according to the expected values of the fuel economy (Table 14). To render the fuel economy of the BEV comparable with the fuel economy of the DCV and the HEV, the unit of the fuel economy in the BEV was converted from kWh/km to the diesel equivalent l/km. As shown in Table 14, the HEV consumed more fuel than the BEV to deliver goods in the express/post market. On the contrary, the HEV consumed less fuel in comparison to the expected values of the fuel economy in the DCV. To this effect, the BEV had an advantage over the HEV and the DCV in the perspective of the fuel economy. This conclusion derived from the fuel economy in different scenarios is consistent with the results demonstrated in the UPS and Ftiro-Lay projects (Lammert et al., 2012; Prohaska, Ragatz, Simpson, & Kelly, 2016).

Table 14: Expected values of fuel economy

Alternatives	Fuel economy (l/km)	Fuel economy (kWh/km)
A ₁ (DCVs 46% - Express/post)	0.2076	-
A ₂ (DCVs 41% - Express/post)	0.2329	-
A ₃ (BEVs 95% - Express/post)	0.1046	1.0432
A ₄ (BEVs 90% - Express/post)	0.1120	1.1166
A ₅ (HEVs 46% - Express/post)	0.1919	-
A ₆ (HEVs 41% - Express/post)	0.2187	-

Furthermore, in terms of observing the expected values of the fuel economy in the same scenario, the alternatives with higher efficiency consumed less fuel. For example, since the engine efficiency of A_1 and A_5 are 5% higher than A_2 and A_6 , the expected values of the fuel economy in A_1 and A_5 improved 11% - 12%. Likewise, the fuel economy of the BEV in A_3 is 6.6% better than A_4 on the basis of the higher electric motor efficiency. Given these points, a conclusion from the fuel economy in the same scenario is drawn that an economical commercial vehicle may benefit of the high engine or electric motor efficiency.

The expected values of the four performance in the three criteria are illustrated in Table 15. In this table, the best alternative in each performance can be observed. Exclusive of the first column, the rest of columns refer to the TCO computed from the economic-mathematical expression, the total energy consumption and the total GHG emissions computed from the environmental-mathematical expression, as well as the actual transport capacity computed from the social-mathematical expression.

Table 15: Expected values of the four performance

Alternatives	Criteria			
	C_{eco} (€)	$C_{env,e}$ (MJ)	$C_{env,g}$ (t)	C_{soc} (tkm)
A_1 (DCVs 46% - Express/post)	1.7050×10^5	2.5886×10^6	196.4219	902.3221
A_2 (DCVs 41% - Express/post)	1.7734×10^5	2.9044×10^6	220.3790	804.2313
A_3 (BEVs 95% - Express/post)	2.0759×10^5	1.3044×10^6	98.9768	126.4972
A_4 (BEVs 90% - Express/post)	2.0970×10^5	1.3966×10^6	105.9716	118.1476
A_5 (HEVs 46% - Express/post)	1.8738×10^5	2.3922×10^6	181.5185	976.4040
A_6 (HEVs 41% - Express/post)	1.9464×10^5	2.7274×10^6	206.9502	856.4153

In the economic perspective, the scenario that combines the DCV with the express/post market expended the lowest total costs followed by the scenario HEV-Express/post and the BEV-Express/post. This result indicates that the DCV remains the best performer and the HEV has an advantage over the BEV in this evaluation from the economic point of view. Furthermore, to compare the other alternatives in the same scenario, the alternative that has higher efficiency expended the lower total costs. To in-depth explore this economic performance, the expected values of the TCO were divided to illustrate the details.

As formulated in the economic-mathematical expression, five elements (depreciation cost, subsidy, battery cost, fuel cost, and maintenance cost) constitute the TCO. The expected values of each element are illustrated in Table 16. Obviously, the main difference between these three scenarios is the depreciation cost. This cost in the scenario of the BEV is approximately an order of magnitude greater than the scenarios of the DCV. Moreover, since the battery life is shorter than the planned service years in this evaluation, there is an additional cost to replace the battery in the BEV. To this effect, although the BEV is incentivized by

purchase subsidies and has lower fuel cost as well as maintenance cost, these saved costs are insufficient to fill the gap of the TCO between the scenario of the BEV and the DCV. Furthermore, the main difference between the two alternatives in the same scenario is the fuel cost. As shown in Table 14, the alternative with the lower engine or electric motor efficiency consumed more fuel. In this context, more fuel consumption resulted in higher fuel cost.

Table 16: Expected values of five elements in the TCO

Alternatives	Depreciation	Subsidy	Battery cost	Fuel cost	Maintenance
A_1 (DCVs 46% - Express/post)	5.5015×10^4	0	0	5.6053×10^4	5.9433×10^4
A_2 (DCVs 41% - Express/post)	5.5015×10^4	0	0	6.2891×10^4	5.9433×10^4
A_3 (BEVs 95% - Express/post)	1.2696×10^5	7050	1.6797×10^4	2.9785×10^4	4.1101×10^4
A_4 (BEVs 90% - Express/post)	1.2696×10^5	7050	1.6797×10^4	3.1891×10^4	4.1101×10^4
A_5 (HEVs 46% - Express/post)	8.8871×10^4	0	0	5.1800×10^4	4.6710×10^4
A_6 (HEVs 41% - Express/post)	8.8871×10^4	0	0	5.9059×10^4	4.6710×10^4

In the environmental perspective, the scenario employing the BEV in the express/post market consumed the least amount of total energy consumption and emitted the least amount of total GHG emissions during the planned service years (Table 15). On the contrary, the total energy consumption and GHG emissions in the scenario of the DCV were the highest among the three scenarios. To explore the difference between these expected values in the three scenarios, the environmental-mathematical expressions (Eq.13 & 14) were analyzed. In this analysis, since the three scenarios operated in the same UFT market, the main difference leading to the expected values then presented in the fuel economy. Same as the expected values of the fuel economy shown in Table 14, the scenario of the BEV performed the best in the environmental perspective followed by the HEV and the DCV. In addition, on the basis of the fuel economy, the alternative with higher efficiency saved energy and reduced GHG emissions in comparison with the alternative with lower efficiency in the same scenario.

Finally, in the social perspective, the scenario combining the HEV and the express/post market had the largest actual transport capacity (tkm), whereas the scenario of the BEV performed the worst in this perspective. According to the Eq.12, this difference between the three scenarios is mainly determined by the onboard energy capacity and the fuel economy. In this context, since the HEV consumed less fuel than the DCV and has the same size of the fuel tank as the DCV, the actual transport capacity in the scenario of the HEV was therefore better than the DCV. Similarly, although the BEV consumed the least fuel among the three scenarios, the energy provided by the battery capacity was much smaller than the fuel tank in the HEV and the DCV. Accordingly, the scenario of the BEV had the smallest actual transport capacity. Besides the comparisons in the scenarios, since the alternative with higher efficiency consumed less fuel, the actual transport capacity of this alternative was greater than the other one in the same scenario.

6.3.2 Validation

The expected values derived from the evaluation are validated in this subsection. The accuracy of these expected values and the range, in which the expected values are credible to support making trustworthy decisions, are illustrated by using the 10-fold cross validation (Section 5.1.2.4).

The accuracy of the expected values was derived from the calculation of the relative errors (Table 17). The range of the accuracy for the six alternatives was between 98.33% and 99.80%. This range indicates that the expected values computed in the validation are 98.33%-99.80% accurate relative to the expected values in Table 15. Decision-makers may determine whether the validated accuracy satisfies their requirements for the accuracy of the expected values. In this evaluation, since there were minor changes of the expected values in the validation, the accuracy was considered as acceptable.

Table 17: Accuracy of the expected values

Alternatives	TCO	Energy consumption	GHG emissions	Accessibility
A ₁ (DCVs 46% - Express/post)	99.45%	98.33%	98.33%	98.33%
A ₂ (DCVs 41% - Express/post)	99.45%	98.45%	98.45%	98.45%
A ₃ (BEVs 95% - Express/post)	99.80%	98.64%	98.64%	98.64%
A ₄ (BEVs 90% - Express/post)	99.80%	98.71%	98.71%	98.71%
A ₅ (HEVs 46% - Express/post)	99.58%	98.48%	98.48%	98.48%
A ₆ (HEVs 41% - Express/post)	99.57%	98.57%	98.57%	98.57%

Furthermore, the upper bound of the standard deviation of the normal distribution was identified. In this identification, three decimal places were considered for the upper bound. Following the procedure of identifying the upper bound portrayed in Section 5.1.2.4, the result shows that the upper bound of the normal distribution is 0.047 (Figure 26) in this evaluation. Figure 26 (a) presents the expected values of the TCO in the six alternatives. Figure 26 (b) is the enlarged diagram of Figure 26 (a) to illustrate the relation between the minimum TCO of A₄ and the maximum TCO of A₆. Apparently, the error bars of A₄ and A₆ are non-overlapping and the TCO of A₄ is greater than A₆.

6 Evaluation

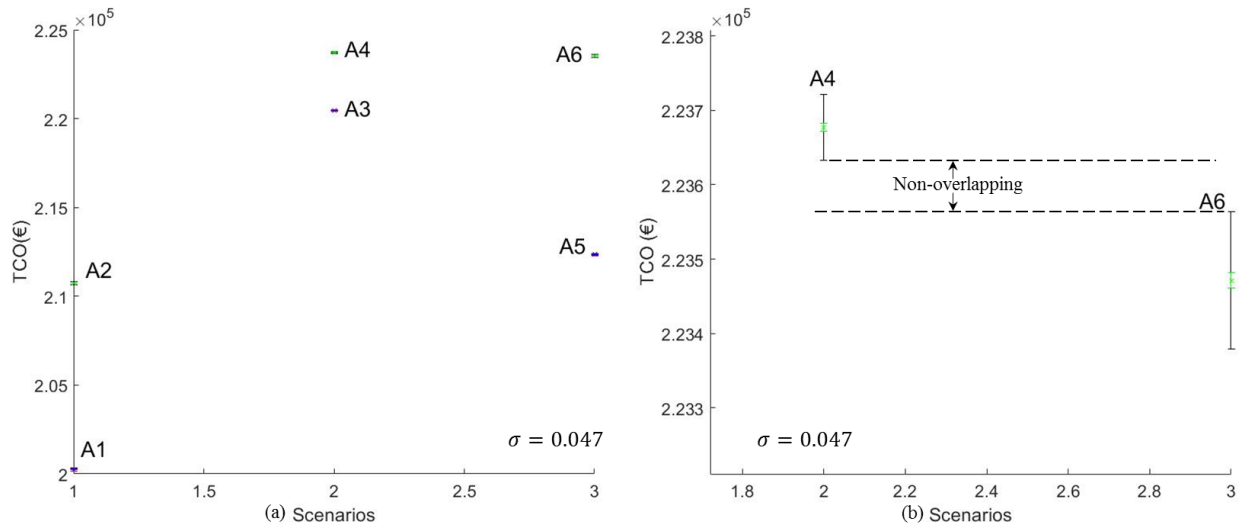


Figure 26: Upper bound of standard deviation

This upper bound was further confirmed by observing the changes of the TCO in the condition that the standard deviation exceeds 0.047 (Figure 27). Since the identification of the upper bound involved three decimal places, the standard deviation equal to 0.048 was subsequently validated. Figure 27 (c) shows that although there are non-overlapping error bars between A_4 and A_6 , the TCO of A_4 is smaller than A_6 . This change implies that an overlapping error bar between A_4 and A_6 has appeared between 0.047 and 0.048. In this perspective, the standard deviations from 0.0471 to 0.0479 were further validated. Figure 27 (b) illustrates that the first overlapping expected values appeared in the condition of the standard deviation equal to 0.0472. This result reveals that the relation between the TCO of A_4 and A_6 is not absolute and the conclusion deduced from the TCO is undecidable. Since this validation only considered three decimal places, the upper bound of the standard deviation was finally identified as 0.047. This identified upper bound indicates that the range of standard deviation, in which the assessed expected values are credible to support making trustworthy decisions, is between 0 and 0.047 in this evaluation.

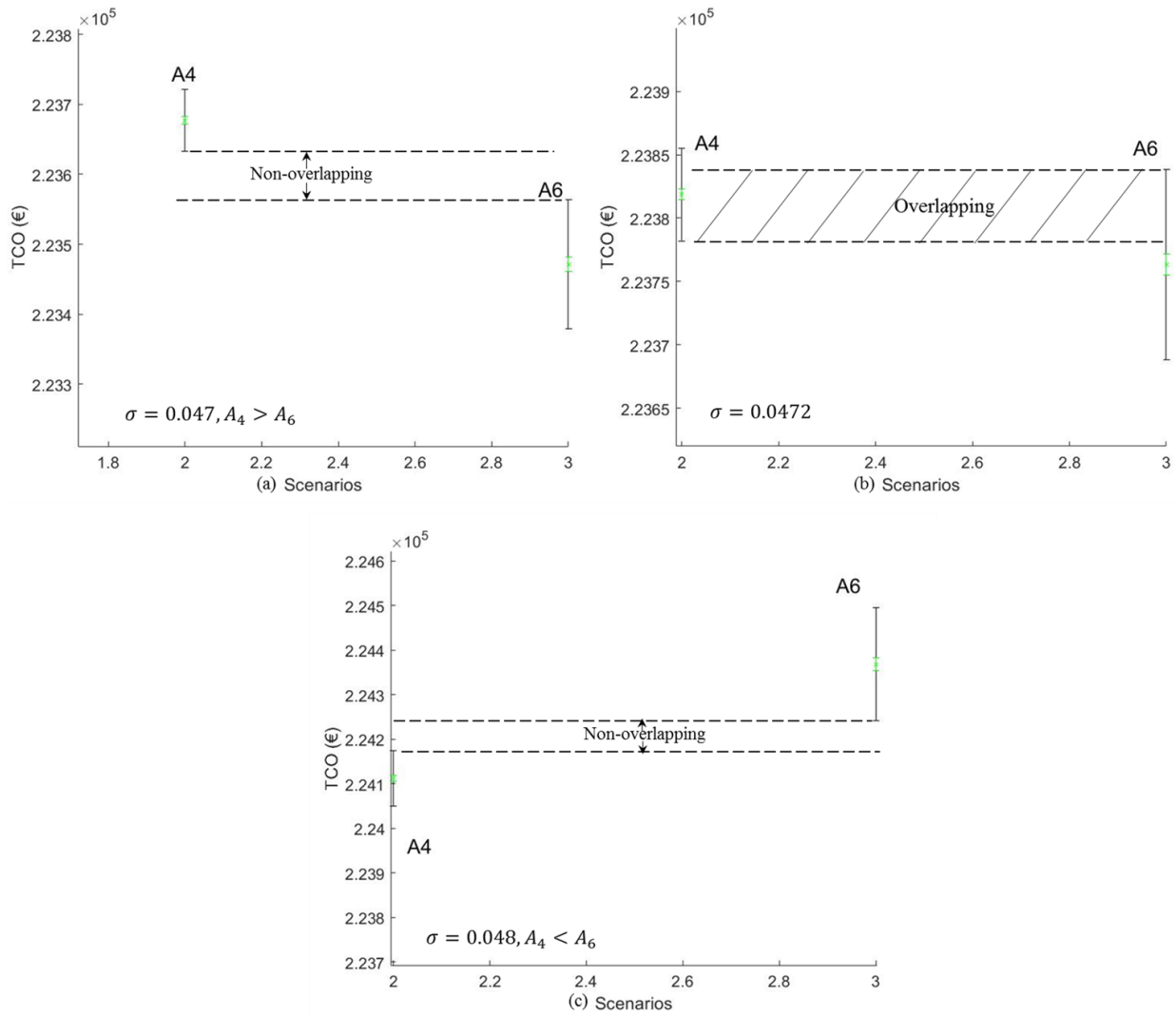


Figure 27: Changes of TCO exceeding the upper bound

Overall, the expected values of this evaluation were accurate and credible in the range of standard deviation between 0 and 0.047. In subsequent subsections, these validated expected values are in-depth analyzed to evaluate the methodology of determination.

6.3.3 Sensitivity Analysis

The validated expected values are considered as input for evaluating the methodology of determination. This subsection focuses on the sensitivity analysis to observe the effect of changing the required parameters on the expected values. In addition, the dominated alternatives are identified and removed by using the observations derived from the sensitivity analysis.

The sensitivity analysis of three required parameters is illustrated in this subsection. As formulated in Section 5.1.2.2, the fuel consumption per tkm is the only required parameter, which appears in all mathematical expressions. Moreover,

the fuel consumption per tkm is determined by the payload weight per trip, the empty trip factor, and the fuel economy by synthesizing the Eq. 10 and Eq.43. In other words, changing the values of these three required parameters in the sensitivity analysis affects all expected values under the three criteria. Hence, the following subsections mainly illustrate the sensitivity analysis of these three required parameters to provide examples for supporting decision-makers to analyze their results. Besides, the available alternatives are identified by removing the dominated alternatives deduced from the sensitivity analysis.

6.3.3.1 Sensitivity Analysis: Payload Weight per Trip

This subsection presents the sensitivity of the expected values under the changes of the payload weight per trip. The range of its value was defined depending on the payload capacity. This means that if the trip is a full load trip, the maximum payload weight per trip is equal to the value of the payload capacity. If the trip is an empty trip, the minimum payload weight per trip is then equal to 0 kg. Thus, the range of the payload weight per trip was defined between 0 kg and the payload capacity.

The effect of changing the payload weight per trip on the four expected values is shown in Figure 28. The expected values of the TCO in the six alternatives are illustrated in Figure 28 (a). In comparison with the alternatives A_1 , A_3 , and A_5 , if the value of payload weight per trip is more than 907 kg, the expected values of TCO in operating BEVs in the express/post (A_3) will be higher than the rest of two alternatives in 10 planned service years. Nonetheless, if the commercial vehicles transport goods between 362.8 to 907 kg per trip, the TCO of operating HEVs in the express/post (A_5) will be the highest expenditure. In addition, if the value of payload weight per trip is less than 181.4 kg or empty trip, the DCV-Express/post (A_1) will expend the most TCO. In this context, the sensitivity analysis of the payload weight per trip unveils that the alternative of using BEVs in the express/post market (A_3) will not expend the most TCO in the condition of the payload weight per trip less than 907 kg. Furthermore, in comparison with the alternatives A_2 , A_4 , and A_6 , the results present that the BEVs (A_4) will cost the most if the payload weight per trip equal and more than 1088.4 kg. On the contrary, the HEVs (A_6) will expend the most TCO. Finally, this sensitivity analysis also illustrated that the alternatives A_1 , A_3 , and A_5 expended lower TCO than A_2 , A_4 , and A_6 .

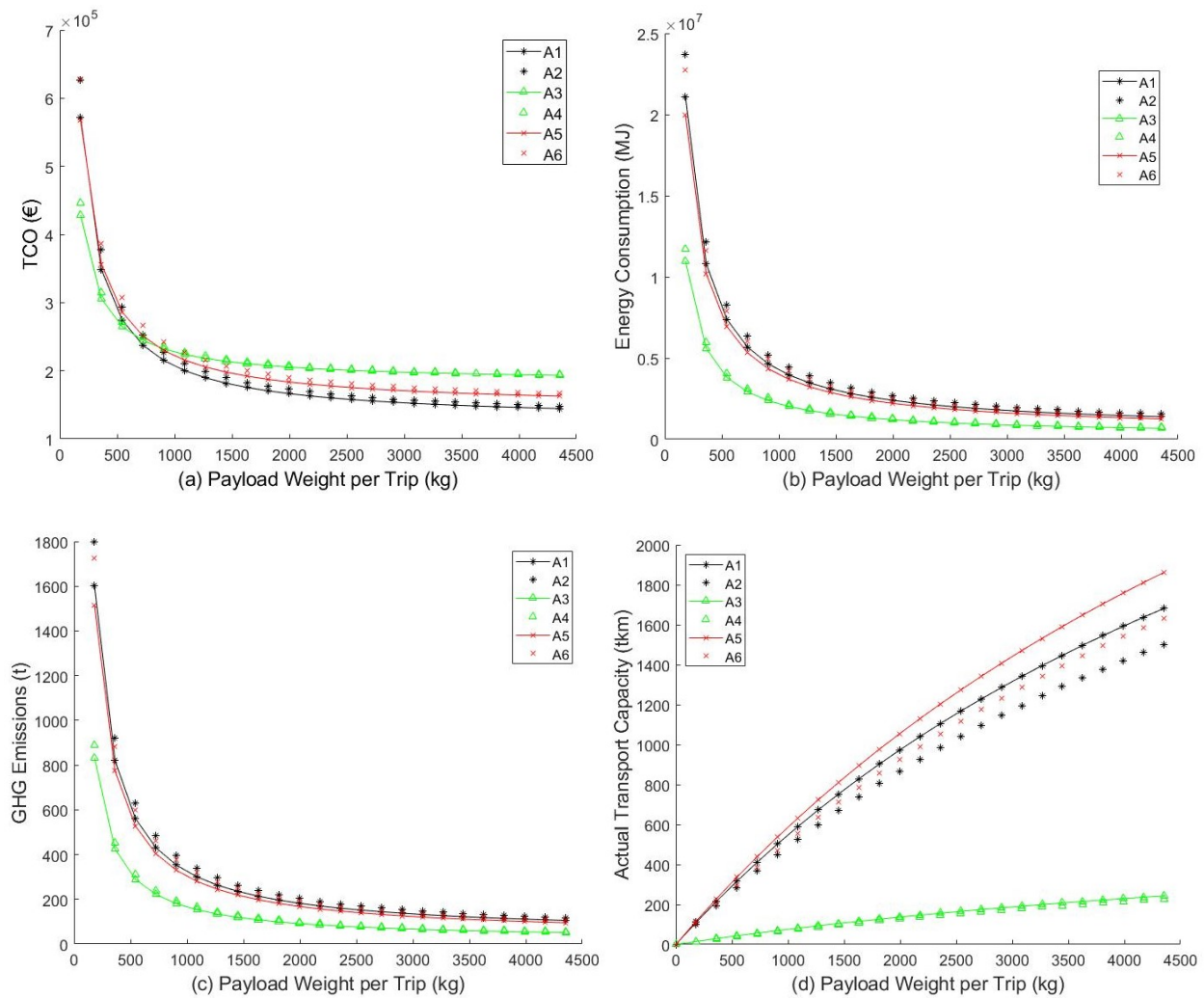


Figure 28: Sensitivity analysis in changing the payload weight per trip

The effect of changing the payload weight per trip on energy consumption and GHG emissions is shown in Figure 28 (b) and (c). The results present that the low payload weight per trip induced a dramatic increase of energy consumption and GHG emissions. These changes indicate that increasing the payload weight per trip can reduce the amount of energy consumption and GHG emissions. Furthermore, it is worth pointing out that there are no intersection points in these two figures. It implies that the relations between the six alternatives regarding the environmental performance are constant. In other words, the environmental performance of BEVs-Express/post (scenario II) remained the best in comparison with the other scenarios in the condition of changing the payload weight per trip. Besides, the alternatives with higher efficiency (A₁, A₃, and A₅) were more environmentally friendly than the other alternatives (A₂, A₄, and A₆) in the same scenario.

The effect of changing the payload weight per trip on the actual transport capacity differs from the other three figures (Figure 28 (d)). This difference results from the mathematical expressions formulated in Section 5.1.2.2. This means that the actual transport capacity is directly proportional to the payload weight per trip, whereas

the TCO, energy consumption, and GHG emissions are inversely proportional to payload weight per trip. By observing Figure 28 (d), the slopes of the HEV scenario and the DCV scenario are greater than the BEV scenario. This result shows that the social performance in the HEV scenario was the best followed by the DCV scenario and the BEV scenarios. In addition, this result also reveals that the on-board energy capacity limits the social performance in the BEV scenario. Finally, in comparison with the two alternatives in the same scenario, the actual transport capacity performed better in the alternative with the higher efficiency.

In conclusion, the higher the payload weight per trip is, the better the expected values in the three criteria can be derived. Besides this conclusion, it is also worth pointing out that the alternative with the relatively high efficiency performs better than the alternative with the low efficiency in the same scenario.

6.3.3.2 Sensitivity Analysis: Empty Trip Factor

The empty trip factor is one of the parameters influence on all expected values. The definition of the empty trip factor can be described as the division of the empty traveled distance by the loaded traveled distance (ifeu Heidelberg et al., 2016). Since the data regarding the empty and the loaded traveled distance is scarce, the data of the empty trip factor is mainly collected from the existing tool, namely EcoTransIT, which summarized the data from transport statistics. The range of the empty trip factor in this sensitivity analysis was defined between 0 and 1.

The effect of changing the empty trip factor on the economic, social, and environmental performance is shown in Figure 29. In general, the greater the empty trip factor is, the worse the performance will be. In particular, the BEV scenario expended the most TCO in comparison with the other scenarios in the condition of the empty trip factor less than 0.6. This condition was deduced from the slopes of each scenario in Figure 29 (a). Additionally, this figure shows that the changes of the empty trip factor have less influence on the BEV scenario than the other scenarios. In this context, the result of this sensitivity analysis illustrates that if the empty trip factor is greater than 0.7, the TCO of the alternative A_6 will replace the BEV scenario as the alternative with the highest costs. Besides, in the same scenario, the alternative with high efficiency can save costs.

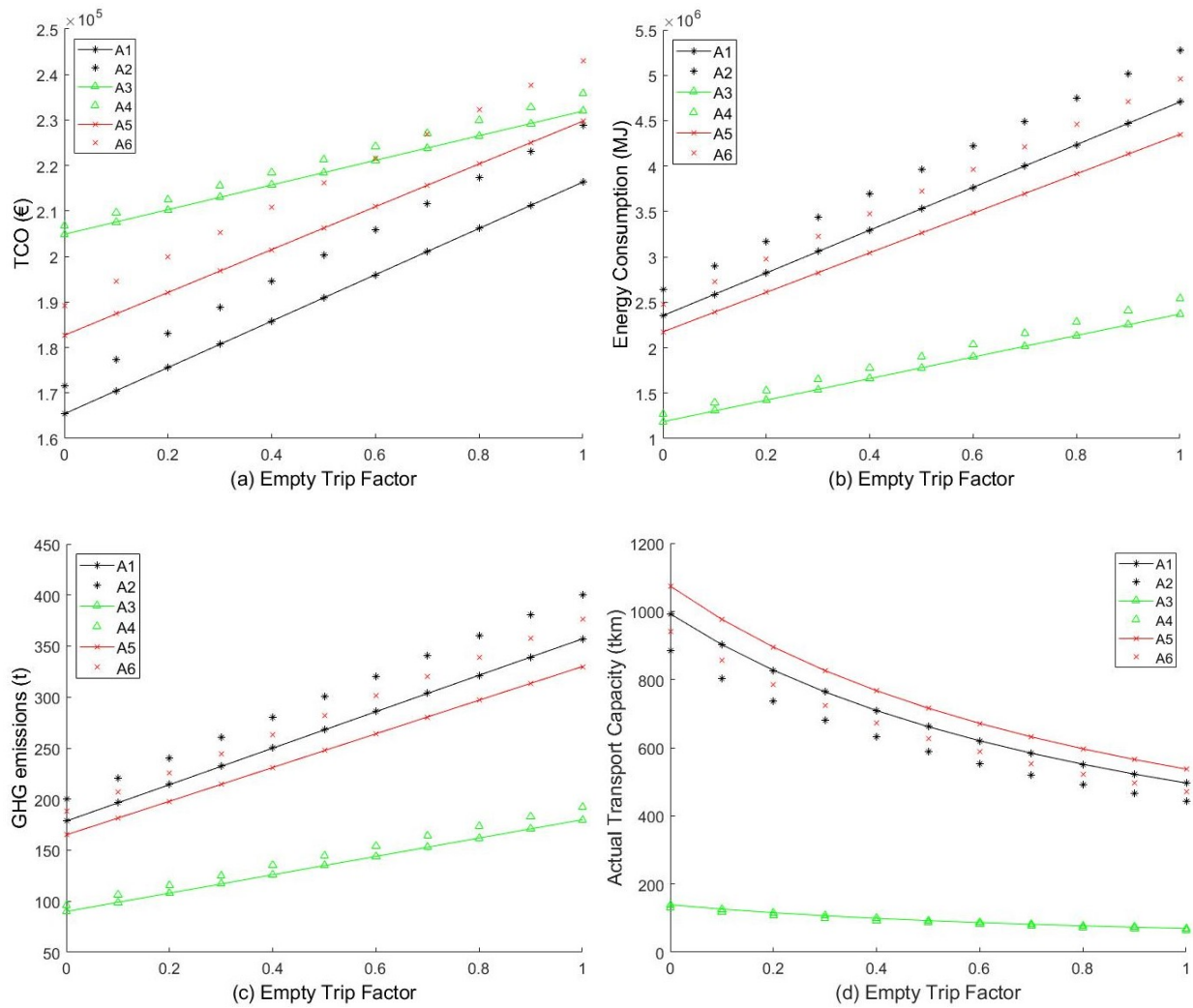


Figure 29: Sensitivity analysis in changing the empty trip factor

Furthermore, the effect of changing the empty trip factor on energy consumption and GHG emissions is shown in Figure (b) and (c). In general, the BEV scenario consumed the least amount of energy and emitted the least amount of GHG. In addition, since there are no intersection points between the expected values of the six alternatives in these two figures, the BEV scenario remained the best environmental performance in changing the empty trip factor. Moreover, the figures illustrate that the alternatives with low efficiency perform worse than the alternatives with the high efficiency in the environmental perspective. In particular, the alternative A_6 (HEV scenario) consumed more energy and emitted more GHG emissions than the alternative A_1 (DCV scenario).

Finally, the actual transport capacity decreased with rising the empty trip factor for all alternatives (Figure 29 (d)). The alternative A_5 (HEV scenario) had the maximum actual transport capacity. On the contrary, since the BEV scenario is limited by the on-board energy capacity, the alternative A_4 (BEV scenario) had the minimum actual transport capacity. To observe this sensitivity analysis in the same

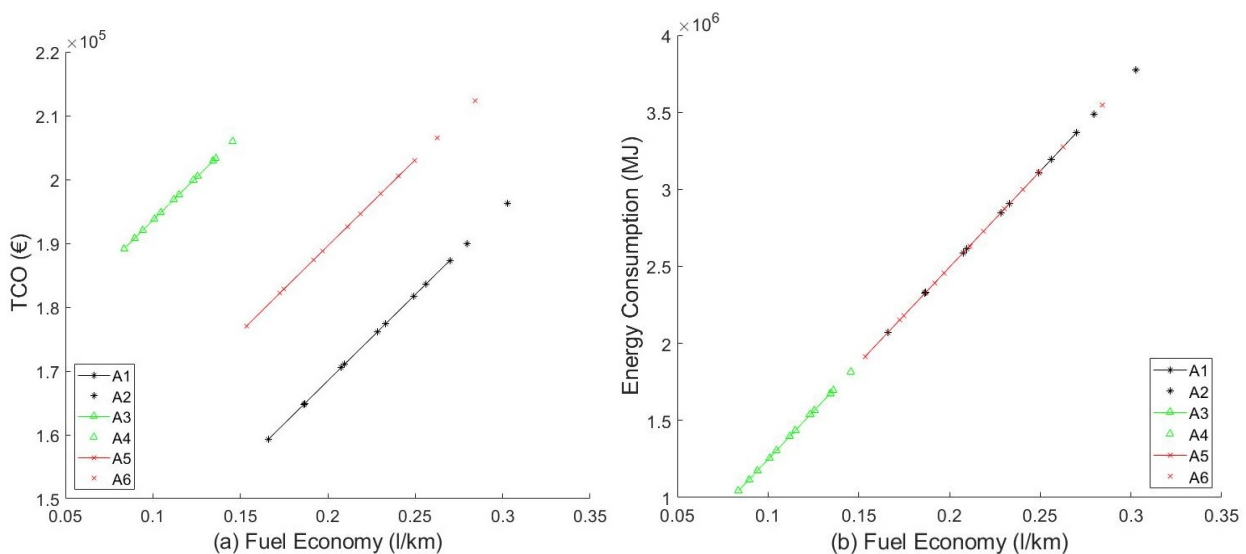
scenario, the alternatives with high efficiency contributed more actual transport capacity than the others.

In conclusion, the smaller the empty trip factor is, the better the expected values can be derived. Additionally, the alternatives with high efficiency present better expected values than the alternatives with low efficiency. Besides these two observations, there is the least effect of changing the empty trip factor on the BEV scenarios in all three perspectives.

6.3.3.3 Sensitivity Analysis: Fuel Economy

The fuel economy is the main focus of the sensitivity analysis in this subsection. The range of the fuel economy in this sensitivity analysis was defined as $\pm 10\%$ of the fuel economy assessed in the simulation platform (Table 14). In addition, the units of the fuel economy in the three scenarios were unified to liter per km (l/km) by using the unit conversion table in Appendix 2.

The effect of changing the fuel economy on the four performance in the three criteria is shown in Figure 30. In general, the four performance decreased with raising the fuel economy. In the economic perspective, the BEV scenario consumed the least amount of energy (liter) per km than the other scenarios in the condition of expending the same TCO (Figure 30 (a)). On the contrary, if the three scenarios consume the same amount of energy per km, the DCV scenario will expend the lowest TCO, whereas the BEV scenario will expend the highest. Furthermore, if the fuel economy of the BEV scenario is less than 0.09 l/km, the DCV scenario is greater than 0.27 l/km, or the HEV scenario is greater than 0.2 l/km, the TCO of the BEV scenario will be less than the other two scenarios. In the same scenario, since the alternatives with the low efficiency consumed more energy, the TCO of these alternatives was higher than the alternatives with the high efficiency.



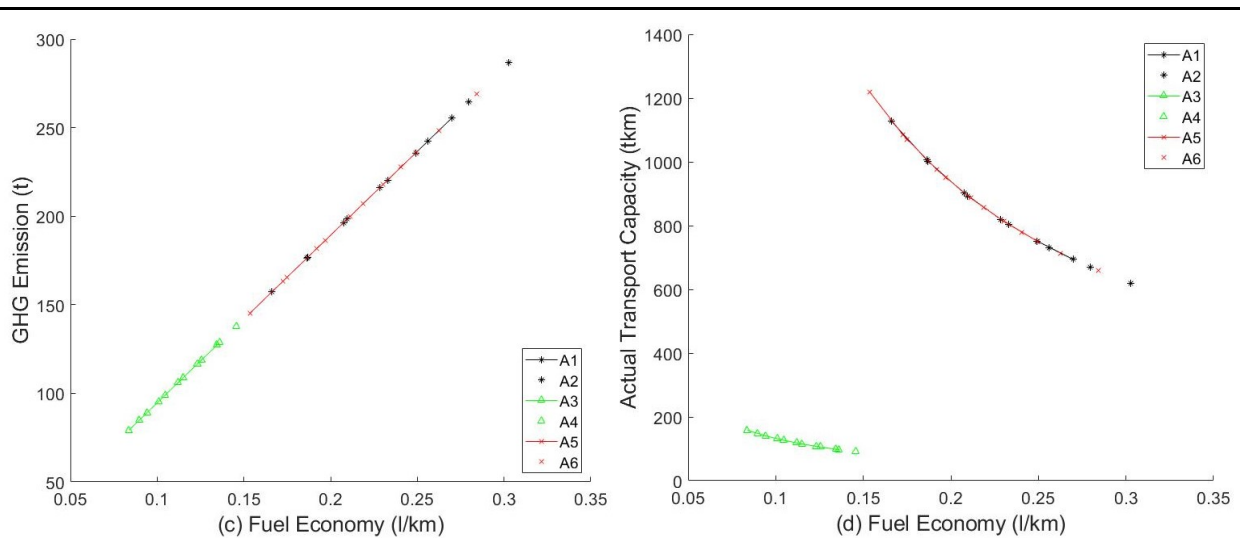


Figure 30: Sensitivity analysis in changing the fuel economy

The effect of changing the fuel economy on environmental performance is illustrated in Figure 30 (b) and (c). Apparently, the BEV scenario has advantages over the rest of two scenarios in the environmental perspective. The low fuel economy in the BEV scenario resulted in this observation directly. Moreover, the slopes of the expected values in the three scenarios are the same. This observation implies that the DCV and the HEV scenarios may also be environmentally friendly, if their fuel economy is low enough. In addition, the alternatives with high efficiency may save more energy and emit less GHG than the alternatives with low efficiency.

The effect of changing the fuel economy on social performance is shown in Figure 30 (d). The actual transport capacity of the HEV scenario is in general the best than the others. In addition, there is a significant difference between the BEV scenario and the rest of two scenarios on account of the limited on-board energy capacity in BEVs. Moreover, similar to the results derived from the environmental perspective, the actual transport capacity of the DCV scenario may be better than the HEV scenario, if the fuel economy in the DCV scenario is low enough. Finally, since the alternatives with the low efficiency consumed more energy per km, the actual transport capacity of these alternatives is smaller than the alternatives with the high efficiency. In conclusion, the lower the fuel economy is, the better the expected values can be derived.

In addition to the sensitivity analysis of these three parameters on the economic, social, and environmental performance, the rest of the required parameters in the mathematical expressions were also analyzed. The figures of the sensitivity analysis are presented in Appendix 3-7.

6.3.3.4 Available Alternatives

This subsection provides a discussion of the results of the sensitivity analysis to deduce the available alternatives. According to the extent of the effect on the economic, social, and environmental performance, this discussion is divided into three groups. These three groups refer to the three sets of required parameters, in which the sensitivity analysis affects the performance in three dimensions, two dimensions, or one dimension respectively.

The first group in this discussion focuses on the required parameters, which affect the performance in economic, social, and environmental dimensions. These required parameters are the payload weight per trip, the empty trip factor, and the fuel economy, which are illustrated in the last three subsections. In general, the results of the sensitivity analysis showed that the expected values in the three criteria can be improved by increasing the payload weight per trip and reducing the empty trip factor as well as the fuel economy. This unveils that reasonably planning the payload weight per trip, avoiding the empty trip, and decreasing the energy consumption per km may improve the economic, social, and environmental performance.

The second group in this discussion presents the effect of changing the annual traveled distance, annual transported weight, and the planned service years on both economic and environmental performance (Appendix 3-5). The results illustrated that the smaller the three required parameters are, the better the expected values can be derived. Nevertheless, the short annual traveled distance, the low amount of annual transported weight, and the short planned service years are unavailable in practice. In this context, the slopes of each expected value were further analyzed to show the trends of these expected values by increasing the values of the required parameters. Obviously, since the slopes of the expected values in the BEV scenario are gentler than the other scenarios by increasing the annual traveled distance and the annual transported weight, the BEV scenario may have advantages over the DCV and the HEV scenarios, if the freight carriers transport goods in long distance and large amount of weight per year. On the contrary, since the battery life is shorter than the planned service years in this evaluation, the BEV scenario may expend more TCO in the long service years on account of the battery replacement costs.

The third group concentrates on a set of required parameters (subsidies, battery price, purchase price, fuel price, and energy capacity), which affect only the performance in one dimension. The results of changing these parameters showed that reducing the battery price and purchase price as well as increasing the subsidies and the fuel price of fossil fuels may save the TCO. Besides, since the on-board energy capacity of BEVs is much smaller than the DCVs and HEVs, it is

difficult for the BEV scenario to improve the actual transport capacity in the social perspective.

Furthermore, the dominated alternatives are identified by observing the trends in the sensitivity analysis. As explained in Section 4.3.2, the dominated alternatives commonly remain the worse performance in comparison with the other alternatives in the sensitivity analysis. The observations derived from the trends of expected values in the six alternatives reveal that the expected values of the alternatives with the low efficiency perform worse than the alternatives with the high efficiency in the same scenario. Therefore, A_2 , A_4 , and A_6 are identified as the dominated alternatives in this evaluation. In other words, the alternatives A_1 , A_3 , and A_5 are the available alternatives derived from this sensitivity analysis.

6.3.4 Results in Ternary Plot

This subsection shows the synthesized expected values of the available alternatives by applying the ternary plot for supporting decision-makers to determine their satisfactory match (Figure 31).

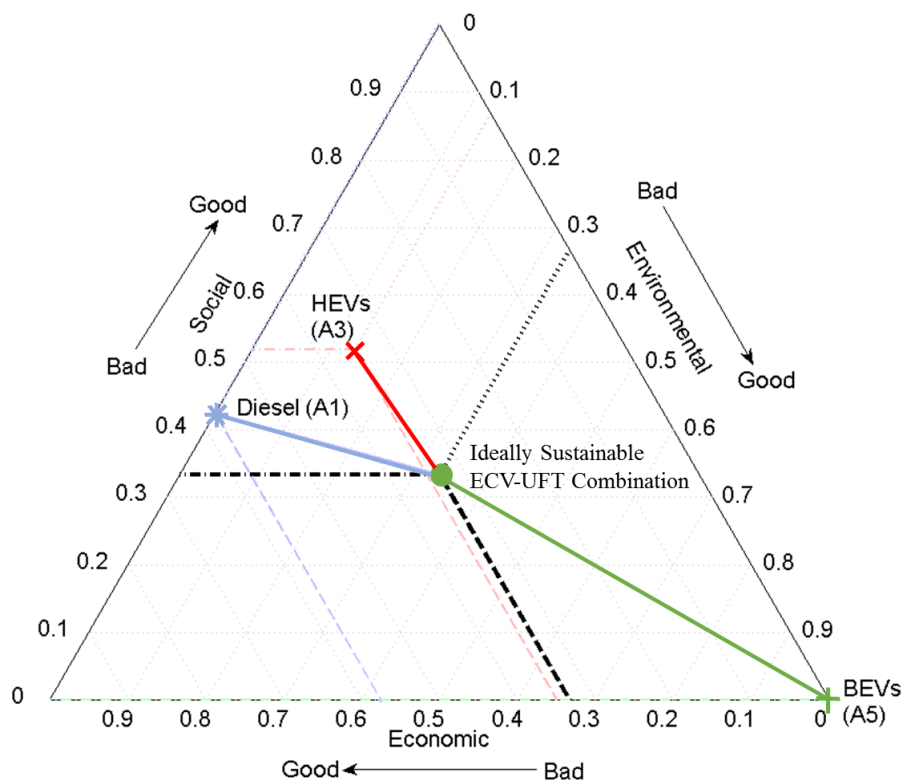


Figure 31: Synthesized expected values of the available alternatives in a triangle

The three sides of this triangle represent the economic, social, and environmental dimensions respectively. In particular, the economic axis refers to the TCO, the social axis stands for the actual transport capacity, and the environmental axis represents the energy consumption as well as GHG emissions in this evaluation.

To plot the assessed results in the triangle, the expected values of the available alternatives in Table 15 are firstly normalized by using the equations in Table 11. The normalized results are shown in Table 18. Since the expected values are subtracted from the maximum expected values in the same dimension, these normalized values are relative results rather than absolute results. For instance, the number 0 in the economic column means that the BEV scenario has the relatively highest total costs in comparison with the other two scenarios.

Table 18: Normalization of the assessment results

Alternatives	C_{eco}	C_{env}	C_{soc}
A_1 (DCVs 46% - Express/post)	0.58	0	0.42
A_3 (BEVs 95% - Express/post)	0	1	0
A_5 (HEVs 46% - Express/post)	0.35	0.13	0.52

Three points are plotted by synthesizing the normalized values in the triangle. Mapping these points onto each axis can distinctly demonstrate the performance of each available alternative in three criteria. As defined in Section 5.2.2, since the middle point in the triangle is mapped onto each of axes in the same distance, this point is considered as the ideally sustainable ECV-UFT combination on account of the identically good performance under each criterion. In Figure 31, the solid lines refer to the distance between the points of alternatives (synthesized expected values) and the middle point. The shorter the solid line is, the more sustainable the alternatives will be. Overall, the ternary plot provides a direct and distinct picture for decision-makers to determine their satisfactory match.

In Figure 31, the alternative of operating DCVs with 46% engine efficiency in express/post market presents the worst environmental performance, the best economic performance, and the medium social performance in comparison with the rest of two alternatives. This observation is consistent with the practical condition. In other words, the worst environmental performance is the motivation of developing the electric vehicles, whereas the best economic performance is one of the reasons that the DCVs are still dominant in UFT. In addition, since the DCVs show the sufficient actual transport capacity (medium social performance), little attention has been paid to the replacement of DCVs with ECVs in the UFT.

The alternative of operating BEVs with 95% electric motor efficiency in express/post market shows the best environmental performance as well as the worst economic and social performance comparing with the rest of the alternatives. Similarly, this result reflects the practical condition and presents the advantages as well as the challenges of employing BEVs in UFT. In particular, the best environmental performance is the advantage of BEVs for decision-makers to consider replacing DCVs. Nonetheless, the worst economic performance prevents decision-makers from purchasing BEVs and using them in real life. Besides, since

the actual transport capacity of BEVs is much smaller than the benchmark of this evaluation (the DCV scenario), the worst social performance has become an obstacle to replace DCVs with BEVs.

Finally, the alternative of operating HEVs with 46% engine efficiency in express/post market illustrates the best social performance as well as the medium economic and environmental performance in comparison to the alternatives of DCVs (A_1) and BEVs (A_5). The best social performance refers to the largest actual transport capacity in the alternative regarding the HEVs (A_3). This best performance results from the additional battery systems in the HEVs. Furthermore, as a consequence of keeping engines and battery systems in the same configuration, HEVs expended lower TCO than BEVs and were more environmentally friendly than DCVs. In this context, the economic and environmental performance of HEVs is regarded as medium performance.

In comparison with the distance between the synthesized expected values (the three points in Figure 31) and the middle point, the alternative regarding HEVs (A_3) has advantages over the other alternatives. In other words, the length between the point of HEVs and the middle point is the shortest among the three alternatives. This result indicates that the HEV-Express/post is the combination closest to the ideally sustainable ECV-UFT combination in this evaluation. Depending on the performance and the distance, decision-makers can determine their satisfactory match. If the satisfactory match of decision-makers refers to the sustainable ECV-UFT combination, the HEV-Express/post with the 46% engine efficiency can be identified as the satisfactory match derived from this evaluation. If decision-makers demand an environmentally friendly combination without considering the TCO, the BEV-Express/post with the 95% electric motor efficiency can be the satisfactory match. On the whole, the satisfactory match is determined by the demands of decision-makers by using the ternary plot.

A global triangle was extracted from this evaluation (Figure 32). This extracted triangle plays a role of supporting decision-makers to identify the features of the alternatives quickly. Three trapezoids constitute this global triangle by mapping the middle point onto each axis. In this dissertation, the trapezoids of the global triangle are defined as the weakly environmental (mapping with dotted line), economic (mapping with dashed line), and social zone (mapping with the dot-dash line). These three zones mean that the synthesized expected values plotted in these trapezoids perform badly under the corresponding economic, environmental, or social criteria.

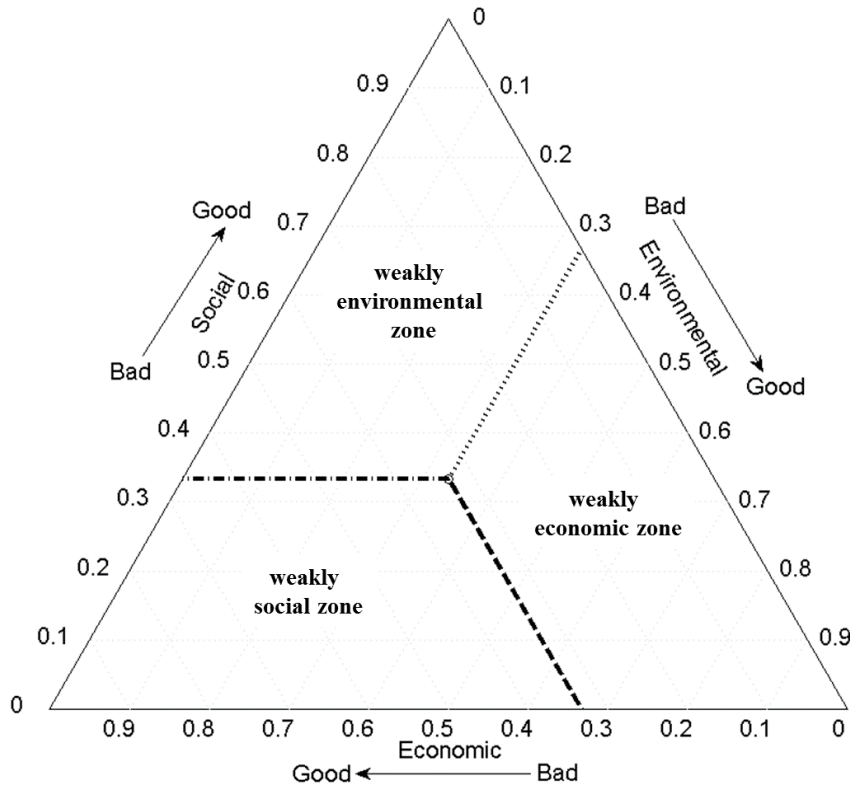


Figure 32: Global triangle

Taking the examples of the three points (A_1 , A_3 , and A_5) in Figure 31, the alternatives regarding the DCVs and the HEVs appeared in the weakly environmental zone, while the alternative regarding the BEVs appeared in the weakly economic zone. These results indicated that the environmental performance of the points A_1 and A_3 , as well as the economic performance of the point A_5 , were bad in the weakly environmental and economic zone. In this context, decision-makers can accelerate the determination of the satisfactory match by using this global triangle.

In short, this subsection shows the synthesized expected values of the available alternatives in a triangle for supporting decision-makers to determine their satisfactory match. Additionally, a global triangle is proposed to speed up and simplify the determination.

6.3.5 Calculation of Equivalent Points

This subsection focuses on calculating equivalent points to support decision-makers to discover the potential improvements in the satisfactory match for future research. As formulated in Section 5.2.3, the equivalent points are calculated between the satisfactory match and the assessed ECV-UFT combination, which has the best performance in the specific criteria. In this evaluation, since the HEV-Express/post (A_3) is the alternative closest to the middle point in the triangle (Figure 31), the A_3 is taken as an example to be the satisfactory match for the

calculation of equivalent points. In addition, since the DCV-Express/post (A_1) expends the lowest TCO and the BEV-Express/post (A_5) is the most environmentally friendly alternative in this evaluation, the potential improvements in the satisfactory match is in-depth analyzed by calculating the equivalent points between A_1 and A_3 in the economic perspective as well as between A_3 and A_5 in the environmental perspective.

The equivalent points between the DCV-Express/post and the HEV-Express/post in the economic perspective are illustrated in Table 19. This table includes the original data of the main required parameters in the economic-mathematical expressions for assessing the HEV-Express/post and the difference between the original data and the equivalent points. According to the differences and the values of the equivalent points, the potential improvements may focus on reducing the purchase price, the maintenance costs, or the fuel economy to cut the TCO of the HEV-Express/post to the TCO of the DCV-Express/post. This conclusion implies that sacrificing the annual traveled distance, the annual transported weight, or the planned service years to cut the TCO may not be the potential improvements in consideration of the practical condition. Besides, although reducing the fossil fuel price can cut the TCO, since the fossil fuel is non-renewable energy, this reduction is uncertain in the future. Given these points, the purchase price, the maintenance costs, and the fuel economy of HEVs may be the main focus for future research to improve the TCO.

Table 19: Equivalent points of A_3 in the economic perspective

Required parameters	Unit	Original data	Equivalent points	Differences
Purchase price	€	98700	79955.17491	-18.99%
Annual distance	Km	26554	22003.91547	-17.14%
Maintenance cost	€/km	0.239	0.1526	-36.13%
Fuel price	€/l	1.13	0.7619	-32.58%
Fuel economy	l/km	0.1918	0.1293	-32.58%
Annual weight	t	471.64	317.9873	-32.58%
Planned service years	Year	10	8.4221	-15.78%

Furthermore, the equivalent points between the HEV-Express/post and the BEV-Express/post in the environmental perspective are shown in Table 20. The results illustrate that increasing the payload capacity or the capacity utilization, or decreasing the fuel economy may improve the energy consumption and the GHG emissions of the HEV-Express/post to the same values of the environmental performance in the BEV-Express/post. Although the differences between the original data and the equivalent points are significant, these results unveil the potential improvements in the required parameters for future research.

Table 20: Equivalent points of A_3 in the environmental perspective

Required parameters	Unit	Original data	Equivalent points	Differences
Payload capacity	kg	4840	8876.4298	+83.40%
Capacity utilization	%	34.07	62.49	+83.41%
Fuel economy	l/km	0.1918	0.1046	-45.47%

On the whole, this subsection gives an example to analyze the equivalent points regarding the results of this evaluation. Decision-makers may explore the potential improvements in their satisfactory match by using the calculation of the equivalent points provided in this subsection.

6.4 Discussion

This section focuses on discussing three questions proposed in Section 1.3 to interpret how the proposed methodological concept has answered the research question (*How can decision-makers obtain a satisfactory match to increase the market penetration of ECVs for achieving sustainable UFT?*) based on the evaluation results. This discussion constitutes three subsections to conduct the interpretation step by step.

Question (Q) 1

What are the challenges and requirements of obtaining the satisfactory match between the characteristics of ECVs and the preferences of UFT?

The answers to this question (challenges in Section 4.1 & requirements in Section 4.2) constitute the foundation of the methodological concept. The identification of challenges provides a specific research gap for supporting in answering the main research question. The specification of the requirements enumerates the significant items to fill the research gap.

The methodological concept was inspired by addressing the challenges identified in Section 4.1. In particular, after reviewing the state of the art regarding the employment of ECVs in UFT, a limitation was outlined that there is a need for a systematic solution to guide and support decision-makers in obtaining their satisfactory match. Accordingly, how can decision-makers obtain their satisfactory match was reified by identifying the challenges. A specific research gap (*there is no appropriate methodology to assess the diverse ECV-UFT combinations and determine the satisfactory match by taking into consideration: a. the time-dependent parameters; b. the automotive and logistical parameters, and; c. the economic, social, as well as environmental dimensions*) was summarized as the

challenges by analyzing the limitations of the literature and existing tools. The methodological concept was accordingly initiated by the identified challenges.

Furthermore, the methodological concept was formulated based on meeting the requirements specified in Section 4.2. There are five requirements specified by extending the identified challenges. Among these requirements, the consideration of the three dimensions and the time-dependent, the automotive as well as logistical parameters were enumerated to cover the challenges. In addition, the requirements, such as involving diverse ECV-UFT combinations, providing a database, and synthesizing the results assessed under the three dimensions, were specified to support in proposing an explicit methodological concept.

In summary, the discussion regarding the Q1 focuses on demonstrating the relation between the answers of the Q1 and the methodological concept. On top of this relation, the details regarding how the methodological concept has addressed these challenges and satisfied the requirements to obtain a satisfactory match are discussed in Q2 based on the evaluation results.

Question (Q) 2

How can decision-makers assess and determine the satisfactory match by addressing the challenges and satisfying the requirements?

The methodological concept (Sustainable ECV-UFT Matching Concept) proposed in this dissertation is the answer of Q2. In general, the evaluation results confirmed that the proposed methodological concept can address the challenges and meet the requirements to support decision-makers to assess and determine the satisfactory match. In particular, how these challenges and requirements have been covered by the methodological concept is discussed respectively as follows.

The expected values and the sensitivity analysis of the planned services years confirmed that the methodological concept can address the challenge regarding the time-dependent parameters. Additionally, these evaluation results established that it is critical to involve the time-dependent parameters to assess the ECV-UFT combinations. Concretely, the expected values of the economic and environmental criteria are the sum of the TCO, energy consumption, and GHG emissions in each year. This summation presents the future performance, which may support decision-makers to determine the satisfactory match suitable for not only the current but also the future scenarios. Furthermore, the expected values of the fuel economy stated that it is feasible to simulate the fuel economy by applying the custom drive cycles in this methodological concept. It indicates that the simulation of the fuel economy provides the available values close to the practical conditions for assessing the ECV-UFT combinations (Lammert et al., 2012; Prohaska et al., 2016). Besides, the sensitivity analysis of the planned service years illustrates the

changes of the economic and environmental performance in 10 years (Appendix 5). Since the battery life is shorter than the planned service years in this evaluation, the battery replacement costs render the TCO of the BEV scenario much higher than the other scenarios after the sixth year. On the contrary, the BEV scenario presents the advantages over the other scenarios in the environmental performance on the basis of its gentler slopes in the sensitivity analysis. Given these points, these changes demonstrate that it is significant to consider the time-dependent parameters to support decision-makers to determine the satisfactory match in a plain and comprehensive view.

Next, the evaluation results confirmed that the methodological concept can meet the requirement of considering the automotive and the logistical parameters as well as their connections. The fuel consumption per tkm is a key parameter to connect the automotive and the logistical parameters in the formulation of the three mathematical expressions. The sensitivity analysis and the expected values calculated by using this key parameter are the evidence that this requirement has been satisfied. Moreover, since the fuel consumption per tkm is determined by payload weight per trip, the empty trip factor, and the fuel economy, the effect of changing these parameters on the economic, environmental, and social performance (Section 6.3.3) also demonstrated the significance of meeting this requirement. For instance, according to the sensitivity analysis of the empty trip factor, it is possible to observe that the BEV scenario may expend lower TCO than the HEV scenario in the condition of the empty trip factor greater than 0.7. This observation shows that the methodological concept has not only satisfied the requirement regarding the automotive and logistical parameters, but also provided potential improvements of these parameters for future research.

Furthermore, the expected values of the three criteria (Table 15) and the points shown in the triangle (Figure 31) demonstrated that the methodological concept can assess the ECV-UFT combinations in the three dimensions of sustainable UFT and synthesize the expected values in the triangle. Among these evaluation results, the social performance confirmed that it is possible to quantify the social dimension. Moreover, the ternary plot presented that it is feasible to synthesize and visualize the expected values derived from the three criteria without using subjective data. This indicates that although the decision-makers determine the satisfactory match depending on their demands, the determination is made based on the facts (synthesized results in the triangle). On the whole, the methodological concept can meet the requirement regarding the three dimensions by discussing the evaluation results.

Finally, the evaluation results established that the methodological concept can meet the requirements of assessing the diverse ECV-UFT combinations and providing the database. The assessment of the six alternatives in this evaluation is the evidence that the methodological concept can assess diverse ECV-UFT

combinations by adapting the corresponding equations in the simulation platform (Section 6.1). Besides, the database generated in this methodological concept, which stores a set of complete data of different alternatives, supports the assessment of the diverse ECV-UFT combinations.

Synthesizing the discussion in this subsection, the methodological concept is confirmed as the answer of the Q2 to address the challenges and meet the requirements for supporting decision-makers to determine the satisfactory match.

Question (Q) 3

To what extent does the methodological concept support the decision-makers?

The proposed methodological concept mainly plays an assistant role in the determination of a satisfactory match. In other words, this methodological concept provides assessment results of different ECV-UFT combinations and the guidance of analyzing the results. Decision-makers use these analyzed results to determine the satisfactory match depending on their demands. In particular, two perspectives (theoretical and practical) and three groups of decision-makers (freight carriers, automobile manufacturers, and regional/national governments) are considered to answer the Q3 concretely by discussing the evaluation results.

In the theoretical perspective, the methodological concept contributes two methodologies to quantify the process of determining a satisfactory match. These methodologies outline the essential components including the corresponding methods and mathematical expressions. The academic researchers and the decision-makers (freight carriers, automobile manufacturers, and regional/national governments) may adapt, optimize, or extend these methodologies in terms of their conditions. For instance, the researchers may optimize the fuel economy by considering the vehicle routing problem with recharging stations. The freight carriers may add the insurance costs as well as the license and registration costs in the economic-mathematical expression. The automobile manufacturers may adapt the equations in the simulation of fuel economy to the other ECV-UFT combinations, such as PHEV-Express/post or FCEV-Express/post. Besides, the regional/national governments may extend the range of the social performance, such as including the number of accidents or human health impacts. In short, the methodological concept may fill the gap of lacking appropriate methodologies to assess diverse ECV-UFT combinations and determine the satisfactory match in the theoretical perspective.

In the practical perspective, the simulation platform transformed from the methodological concept provides assessment results and analysis results for decision-makers to determine the satisfactory match. Decision-makers can optionally assess the ECV-UFT combinations by applying the simulation platform

in their practical conditions. The expected values, the sensitivity analysis, the synthesized points in the triangle, and the equivalent points are the bases for the determination. Taking these bases derived from this evaluation as an example, the discussion regarding to what extent the methodological concept support the decision-makers in the practical perspective is conducted as follows.

The freight carriers in the express/post market can compare the DCV, the BEV, and the HEV by observing the synthesized results in the triangle. The observations include the positions of the synthesized points as well as the length between the synthesized points and the middle points. These observations can help the freight carriers to determine their satisfactory type of ECVs. Moreover, combining the sensitivity analysis and the equivalent points can suggest the areas of focus for improving the performance of the satisfactory match. For instance, according to combining the results of sensitivity analysis and equivalent points regarding the annual traveled distance, the increase of the annual traveled distance is suggested to cut the TCO of BEVs and HEVs. Similarly, the payload weight per trip, the maintenance costs, and the fuel consumption per tkm may also be the areas of focus for improving the performance of the satisfactory match deduced from this evaluation.

Furthermore, the automobile manufacturers can benefit from this methodological concept to improve their products to adapt to the express/post market. For example, increasing the on-board energy capacity of BEVs may be a solution to improve the social performance and mitigate the “range anxiety” of users (Appendix 9). Additionally, the battery price, the maintenance costs, the gross vehicle weight, the payload capacity, and the fuel economy have also influence on the performance. To this effect, the methodological concept plays a role in suggesting the possible areas of focus for the automobile manufactures to adapt to the UFT markets by improving their products.

In the end, the regional/national governments can make relevant policies based on the evaluation results. For instance, on account of the high TCO in the BEV scenario, the governments may consider providing appropriate financial subsidies for supporting the development of BEVs. Moreover, since the HEV scenario is the synthesized points closest to the middle point in the triangle, the governments may consider making the policy, which encourages the practitioners, such as freight carriers and automobile manufacturers, to focus on commercializing the HEVs in the express/post market. In short, the methodological concept provides the bases for the governments to make appropriate policies.

On the whole, the methodological concept proposed in this dissertation is an assistant to help decision-makers to obtain a satisfactory match so that the market penetration of ECVs in UFT can be facilitated.

6.5 Limitations

Four limitations of the methodological concept are elaborated in this section. The first limitation is relevant to the scenarios in the evaluation. There are three scenarios: DCV-Express/post, BEV-Express/post, and HEV-Express/post considered in the evaluation. These scenarios are determined mainly depending on the available data. The shortage of available and complete data regarding the PHEV, the FCEV, the retail, the HoReCa, the construction, and the waste collection market result in these three scenarios involved in the evaluation. To this effect, future research may focus on complementing the database in the methodological concept to overcome this limitation.

The second limitation relates to the data used in the evaluation. As stated in Section 6.2, this data is the background data collected from related publications. This means that the data for evaluating the methodological concept is the theoretical or historical data, which can support the evaluation results close to the practical conditions. However, the practical data collected from the decision-makers is lacking in the database and the evaluation. To this end, it is crucial to consider the practical data in the assessment of the ECV-UFT combinations to determine the satisfactory match closer to the practical conditions.

The third limitation concerns the validation in the methodological concept. The expected values, which are validated as inaccurate results or excluded from the credible range, are required to be further considered in the validation. This means that there is a need for a closed loop in the methodological concept to deal with the unsatisfied validated results. Besides, it is significant to refine the definitions of the unsatisfied results for supporting decision-makers to obtain a more trustworthy satisfactory match.

The fourth limitation focuses on the simulation of the fuel economy. As introduced in Section 6.1, there are adaptations of the equations to the different configurations of ECVs in the simulation. Since the DCV, the BEV, and the parallel HEV are considered in the evaluation, the adaptations are accordingly formulated in the simulation. Nevertheless, the equations adapting to the series HEV, the series-parallel HEV, the PHEV, and the FCEV are missing in the simulation of the fuel economy. In this perspective, the methodological concept may need further update by including these adaptations.

6.6 Summary

This chapter has presented an evaluation of the methodological concept by using three scenarios. In addition, this chapter has discussed and confirmed that the proposed methodological concept can answer the research question. In other

words, the proposed methodological concept provides decision-makers with the guidance of obtaining their satisfactory match.

Six alternatives were introduced into this evaluation. The corresponding adaptations and assumptions were made for conducting the evaluation. The results of these six alternatives have been analyzed and finally illustrated in a triangle. These results established that the methodological concept can address the challenges and meet the requirements of assessing the diverse ECV-UFT combinations. Besides, the conclusion of the discussion shows that the methodological concept plays an assistant role in the determination of the satisfactory match from not only the theoretical but also the practical point of view.

7 Conclusion and Outlook

This chapter focuses on concluding the dissertation and proposing the outlook for future research. Section 7.1 recaps the challenges and the methodological concept as well as highlights the contributions of this dissertation. Section 7.2 provides four future topics as the outlook to end this chapter.

7.1 Conclusion

The environmental challenges of ICE vehicles motivate the development of electric vehicles. In this development, much attention has been paid to the electric passenger cars, whereas little attention has been paid to the electrification of commercial vehicles (ECVs) for addressing the environmental challenges in UFT. This little attention is reflected in the extent of the commercialization of ECVs. Although policies are supporting the employment of ECVs in UFT and the UFT provides suitable conditions for the employment, the extent of commercialization is still low. In other words, there is a low market penetration of ECVs in UFT. To this effect, four areas of focus (feasibility of ECVs, adaptations of logistics concepts, adaptations of vehicle concepts, and support of stakeholders) in the literature have been studied regarding the employment of ECVs in UFT to figure out the limitations leading to the low market penetration. Besides these areas, the related existing tools have been reviewed as well.

According to the state of the art in the literature and existing tools, a feature of employing ECVs in UFT – diversity was extracted in this dissertation. Moreover, obtaining a satisfactory match between the characteristics of ECVs and the requirements of UFT has been noticed in this dissertation as a solution to increase market penetration. However, many possibilities resulted from the diversity (512 ECV-UFT combinations) has become a limitation for decision-makers to select their satisfactory match. Additionally, since little attention has been paid on the diversity and the satisfactory match, decision-makers cannot derive appropriate and systematic solutions from academic studies to support themselves in better understanding the diversity and obtaining a satisfactory match.

In particular, the challenges of obtaining a satisfactory match were refined from the literature and existing tools. Generally, there is no appropriate methodology, which can support decision-makers to assess the diverse ECV-UFT combinations and determine the satisfactory match. Concretely, in the assessment, some parameters, such as the time-dependent, the automotive, and the logistical parameters, as well as the connection between the parameters are missing. In the determination, the three dimensions of sustainable UFT are incompletely considered. Additionally, the available data or database of the diverse ECV-UFT combinations are scarce in the academic studies, the demonstration projects, and the related tools. Overall, the challenges can be outlined that there is a need for appropriate methodologies to

guide and support decision-makers in assessing the diverse ECV-UFT quantitatively and determining their satisfactory match.

A methodological concept called Sustainable ECV-UFT Matching Concept was developed in this dissertation to address the outlined challenges. In particular, this concept is constituted by two methodologies (methodology of assessment and methodology of determination). The methodology of assessment helps decision-makers to quantitatively assess the diverse ECV-UFT combinations including the time-dependent, the automotive, and the logistical parameters from the economic, social, and environmental dimensions. The methodology of determination provides a system of methods to analyze the assessment results and support decision-makers to determine their satisfactory match. A simulation platform, which contains an available database, three mathematical expressions, a simulation model of fuel economy, and three methods for analyzing the results, was designed to implement the methodological concept.

Six alternatives in three scenarios (DCV-, BEV-, and HEV-Express/post) were entered into the simulation platform to evaluate the proposed methodological concept. The evaluation results confirmed that the Sustainable ECV-UFT Matching Concept provides decision-makers with the guidance of obtaining a satisfactory match. This guidance can address the outlined challenges to assess the diverse ECV-UFT combinations and plays an assistant role in the determination of the satisfactory match. In addition, this methodological concept also provides a possible solution for similar decision-making problems in UFT and support decision-makers to explore the potential improvements. In a practical perspective, the designed simulation platform in this dissertation was evaluated as a feasible approach to support in obtaining a satisfactory match.

On the whole, this dissertation contributes to the commercialization of ECVs for achieving sustainable UFT by proposing the methodological concept. Decision-makers can better understand the economic, social, and environmental performance of different ECV-UFT combinations by applying this concept. The synthesized results of the performance can support decision-makers to determine the satisfactory match in terms of their conditions. The benefits of employing this satisfactory match may inspire decision-makers to consider the corresponding ECVs using in their UFT markets. This consideration may facilitate the market penetration of ECVs for achieving sustainable UFT.

7.2 Outlook

Some topics, which are inspired by this dissertation, constitute the outlook. In other words, these topics are the extension of the limitations outlined in Section 6.5. Two perspectives, namely the theoretical and the practical perspectives, are applied to structure this outlook.

The extension of the ECV-UFT combinations in the methodological concept is considered as a topic for future research from the theoretical point of view. This extension refers to take into account more types of ECVs and UFT markets. Since the proposed methodological concept involves three scenarios (the DCV-, BEV-, and HEV-Express/post), the future research may widen the range of the scenarios to combine the PHEV and the FCEV with the retail, the HoReCa, the construction, as well as the waste collection markets. In this extension, the challenges of each scenario are required to be taken into account. For instance, the scenarios constituted by employing FCEVs may need to consider the challenges, such as high fuel cell costs, difficult to store and transport hydrogen, as well as insufficient hydrogen filling stations, into the methodological concept. In addition, it is crucial to complete the background data regarding the new scenarios. This indicates that there is a need to extend the database of the methodological concept in future research. This extended database may provide practitioners with a holistic view in the field of employing ECVs in UFT.

The adaption of the simulation model of fuel economy is the second topic in the theoretical perspective. This adaption is attributed to the extension of ECV-UFT combinations. Since the equations in the simulation of the fuel economy are formulated depending on the configurations of ECVs, the adaption of the equations in the extended ECV-UFT combinations, which contain the PHEV and the FCEV, is considered as the topic for the future research. Besides the adaption of equations to the extended ECV-UFT combinations, the future research may also concern the improvement of the regenerative braking systems and the battery systems in this methodological concept. Additionally, the electric vehicle routing problem may also constitute the adaption of the simulation.

The third topic in the theoretical perspective relates the validation. In particular, future research may focus on improving the validation of this methodological concept to support decision-makers to deal with the unsatisfied validated results. This means that there is a need for refining the definitions of the unsatisfied results to establish a closed loop in the methodological concept. To this end, decision-makers may obtain more trustworthy results for determining the satisfactory match.

Finally, from a practical perspective, the development of applicable tools is considered as a future topic. In this development, the future work may collect and use the practical data from users to customize the tools. Concretely, the tools may contain a function of creating the custom drive cycles for the users. The original data of the custom drive cycles is the practical data collected from users. In this context, some new concepts, such as Internet of Things and Industry 4.0, are suggested to be integrated into the methodological concept to help practitioners to achieve the data collection.

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Appendix

Appendix 1: 82 possible ECV-UFT combinations in the literature

ECV – UFT combinations	ECV – UFT combinations
BEVs - Unspecified	PHEVs - HoReCa
BEVs - Retail	PHEVs - (Retail, Express/post)
BEVs - Express/post	PHEVs - (Retail, HoReCa)
BEVs - HoReCa	FCEVs - Unspecified
BEVs - Construction	Unspecified - Unspecified
BEVs - Waste	Unspecified - Retail
BEVs - (Retail, Express/post)	Unspecified - Express/post
BEVs - (Retail, HoReCa)	Unspecified - HoReCa
BEVs - (Retail, Construction)	Unspecified - (Retail, Express/post)
BEVs - (Retail, Waste)	Unspecified - (Retail, HoReCa)
BEVs - (Express/post, HoReCa)	(BEVs, HEVs) - Unspecified
BEVs - (Express/post, Construction)	(BEVs, HEVs) - Retail
BEVs - (Express/post, Waste)	(BEVs, HEVs) - Express/post
BEVs - (HoReCa, Construction)	(BEVs, HEVs) - HoReCa
BEVs - (HoReCa, Waste)	(BEVs, HEVs) - (Retail, Express/post)
BEVs - (Construction, Waste)	(BEVs, HEVs) - (Retail, HoReCa)
BEVs - (Retail, Express/post, HoReCa)	(BEVs, PHEVs) - Unspecified
BEVs - (Retail, Express/post, Construction)	(BEVs, PHEVs) - Retail
BEVs - (Retail, Express/post, Waste)	(BEVs, PHEVs) - Express/post
BEVs - (Retail, HoReCa, Construction)	(BEVs, PHEVs) - HoReCa
BEVs - (Retail, HoReCa, Waste)	(BEVs, PHEVs) - (Retail, Express/post)
BEVs - (Retail, Construction, Waste)	(BEVs, PHEVs) - (Retail, HoReCa)
BEVs - (Express/post, HoReCa, Construction)	(BEVs, FCEVs) - Unspecified
BEVs - (Express/post, HoReCa, Waste)	(HEVs, PHEVs) - Unspecified
BEVs - (Express/post, Construction, Waste)	(HEVs, PHEVs) - Retail
BEVs - (HoReCa, Construction, Waste)	(HEVs, PHEVs) - Express/post
BEVs - (Retail, Express/post, HoReCa, Construction)	(HEVs, PHEVs) - HoReCa
BEVs - (Retail, Express/post, HoReCa, Waste)	(HEVs, PHEVs) - (Retail, Express/post)
BEVs - (Retail, Express/post, Construction, Waste)	(HEVs, PHEVs) - (Retail, HoReCa)
BEVs - (Retail, HoReCa, Construction, Waste)	(HEVs, FCEVs) - Unspecified
BEVs - (Express/post, HoReCa, Construction, Waste)	(PHEVs, FCEVs) - Unspecified
BEVs - (Retail, Express/post, HoReCa, Construction, Waste)	(BEVs, HEVs, PHEVs) - Retail
HEVs - Unspecified	(BEVs, HEVs, PHEVs) - Express/post
HEVs - Express/post	(BEVs, HEVs, PHEVs) - HoReCa
HEVs - Retail	(BEVs, HEVs, PHEVs) - (Retail, Express/post)
HEVs - HoReCa	(BEVs, HEVs, PHEVs) - (Retail, HoReCa)
HEVs - (Retail, Express/post)	(BEVs, HEVs, PHEVs) - Unspecified

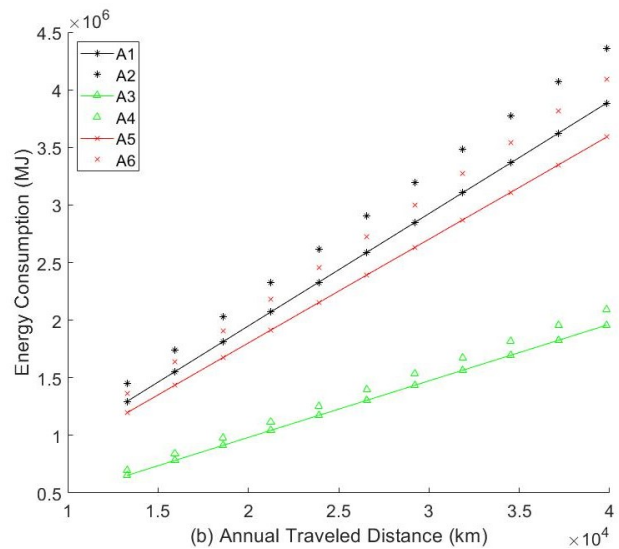
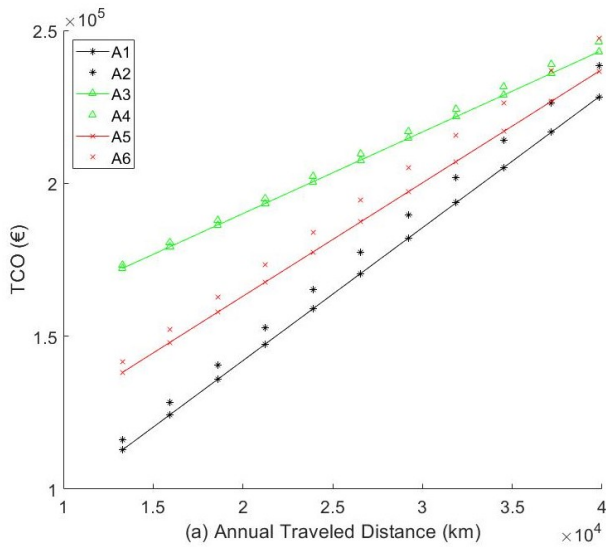
Appendix

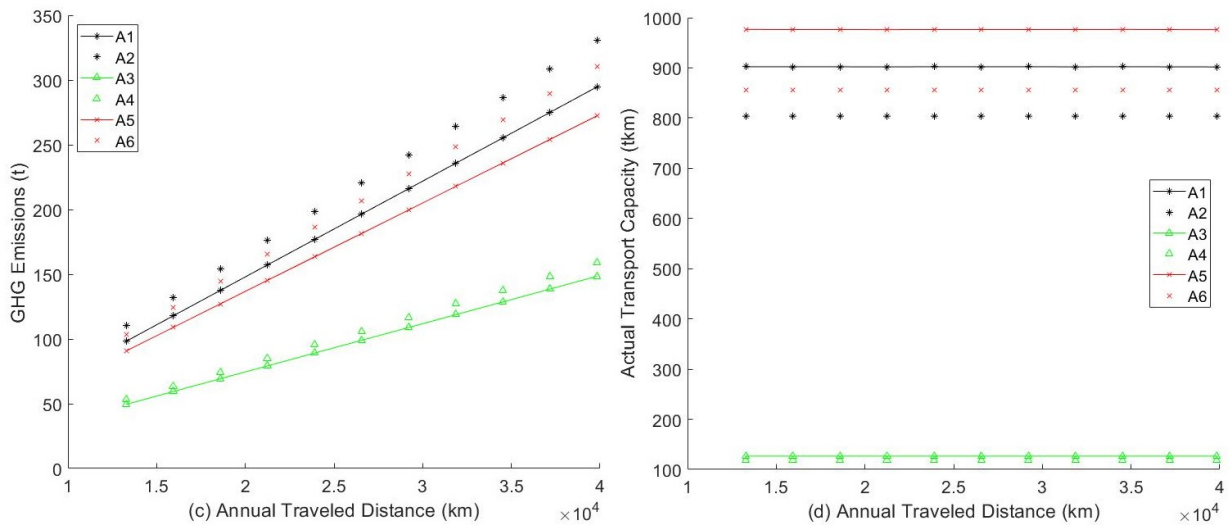
ECV – UFT combinations	ECV – UFT combinations
HEVs - (Retail, HoReCa)	(BEVs, HEVs, FCEVs) - Unspecified
PHEVs - Unspecified	(BEVs, PHEVs, FCEVs) - Unspecified
PHEVs - Retail	(HEVs, PHEVs, FCEVs) - Unspecified
PHEVs - Express/post	(BEVs, HEVs, PHEVs, FCEVs) - Unspecified

Appendix 2: Unit conversion table

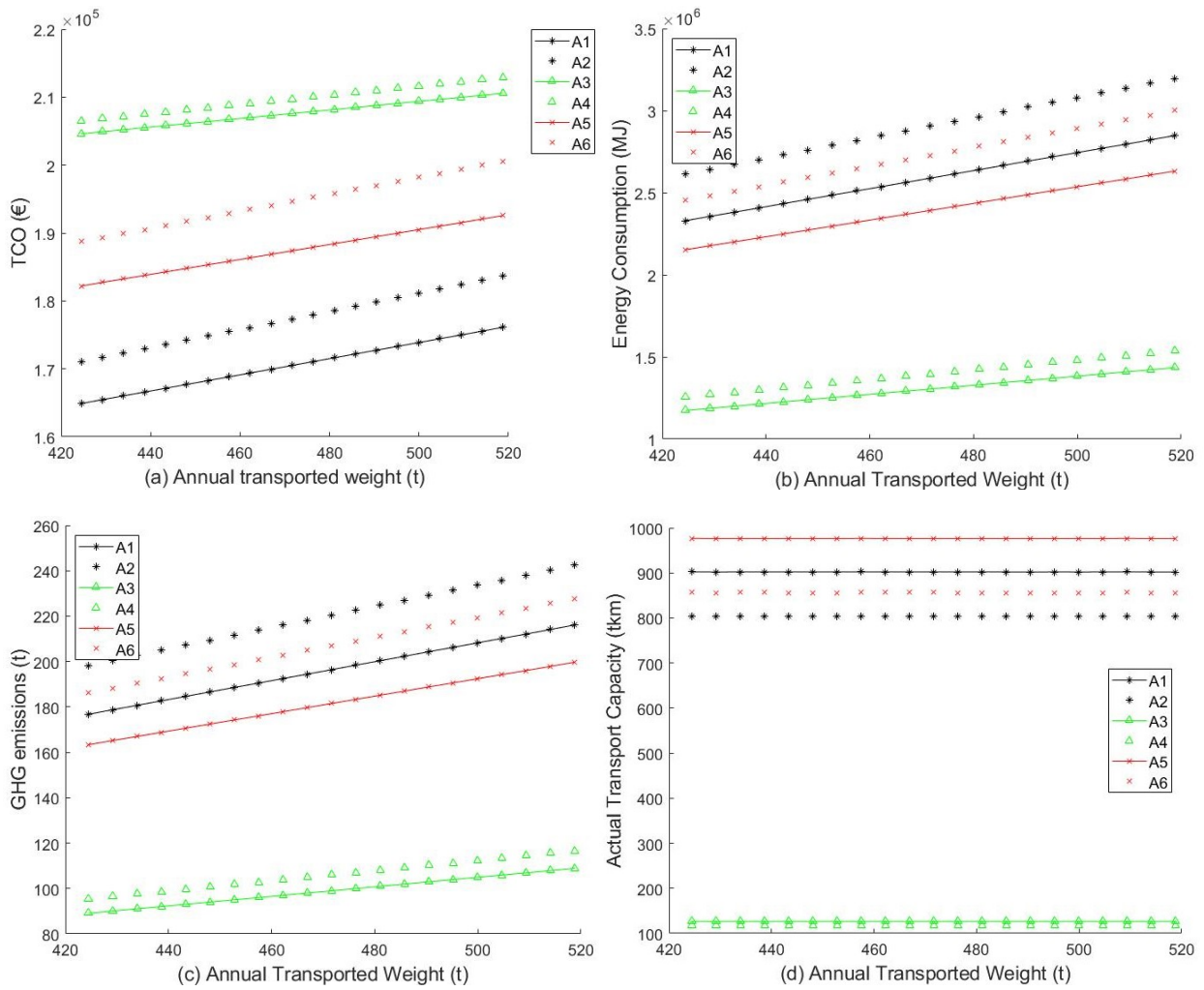
1 MJ	0.2778 kWh
1 MJ	0.0279 liter diesel
1 kWh	3.6 MJ
1 kWh	0.1004 liters diesel
1 liter diesel (TTW)	35.9 MJ
1 liter diesel (WTW)	42.7 MJ
1 liter diesel (TTW)	2.67 kg CO _{2eq}
1 liter diesel (WTW)	3.24 kg CO _{2eq}
1 liter diesel	10 kWh
1 mile	1.6093 km
1 gallon	3.7854 liter

Appendix 3: Sensitivity analysis in changing the annual traveled distance

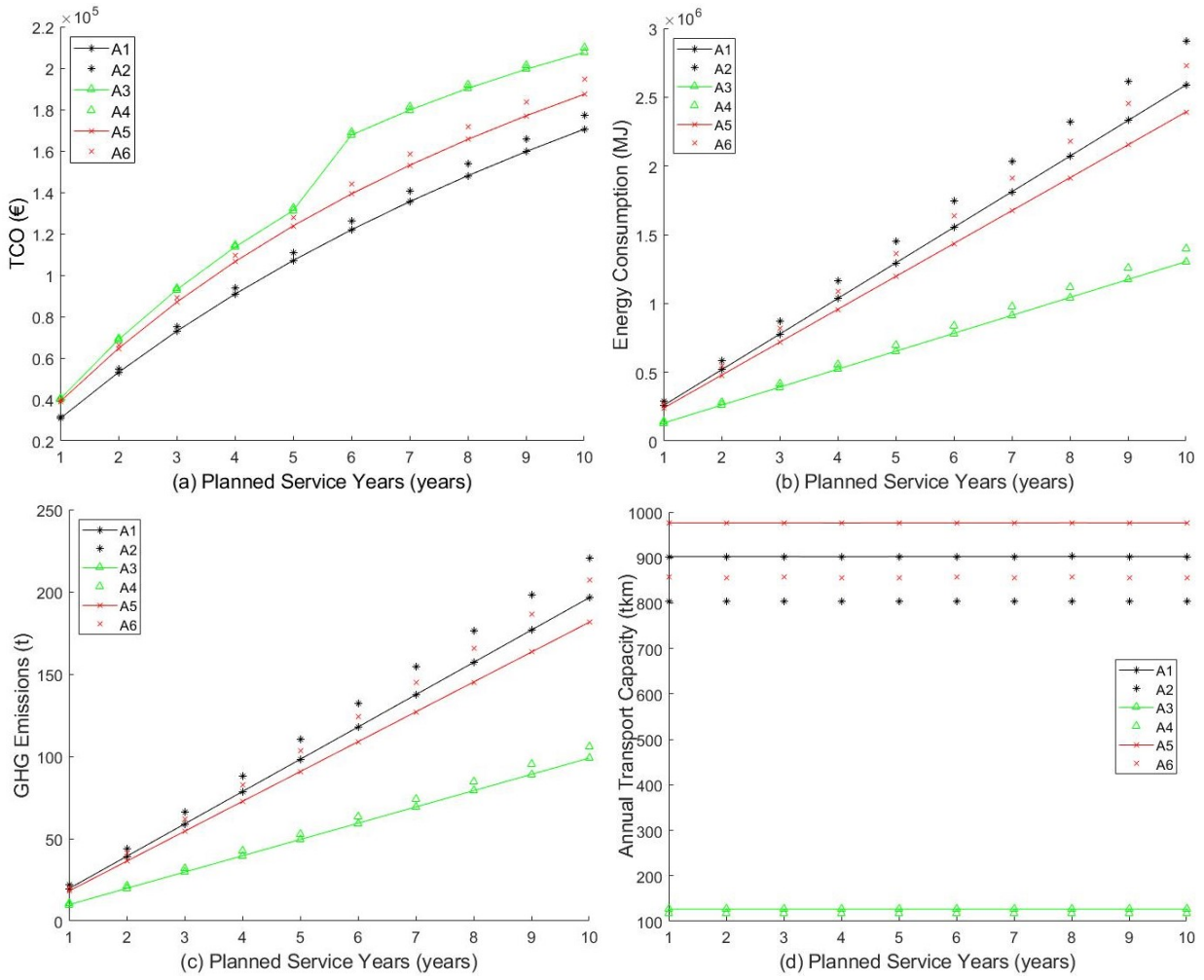




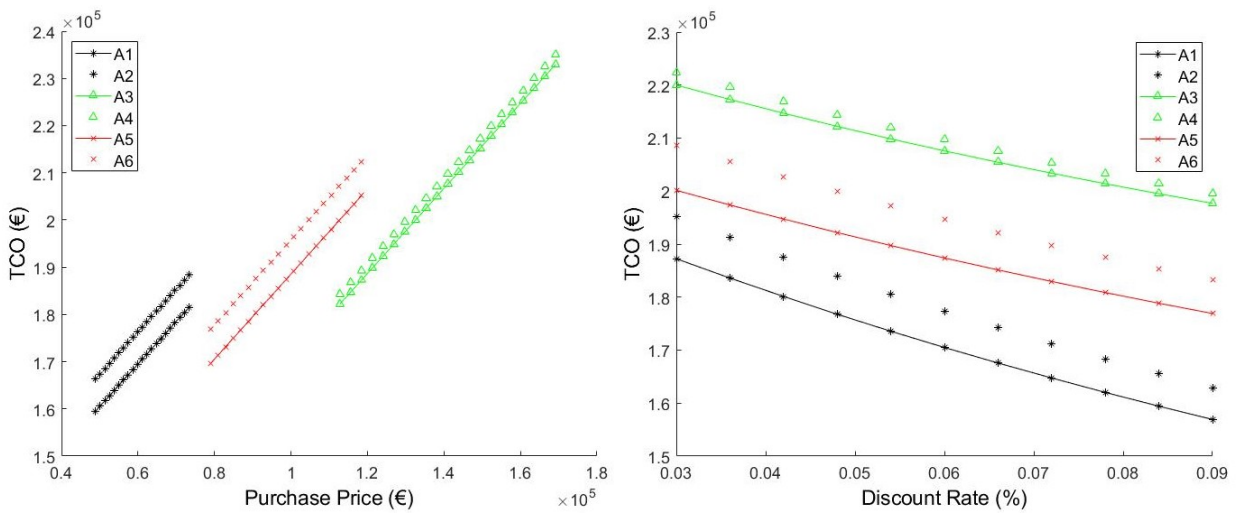
Appendix 4: Sensitivity analysis in changing the annual transported weight

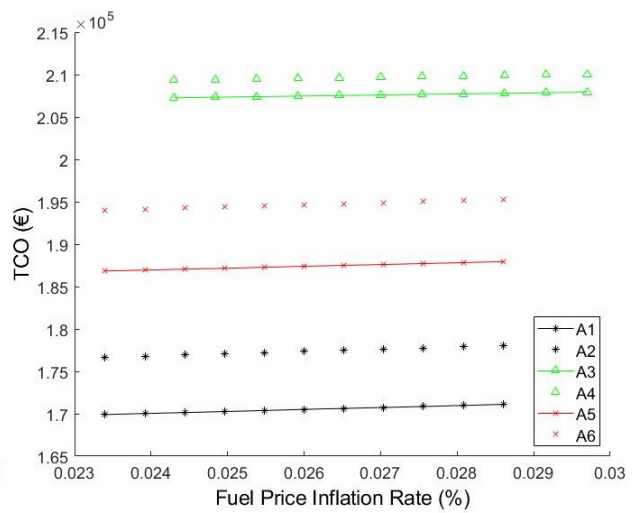
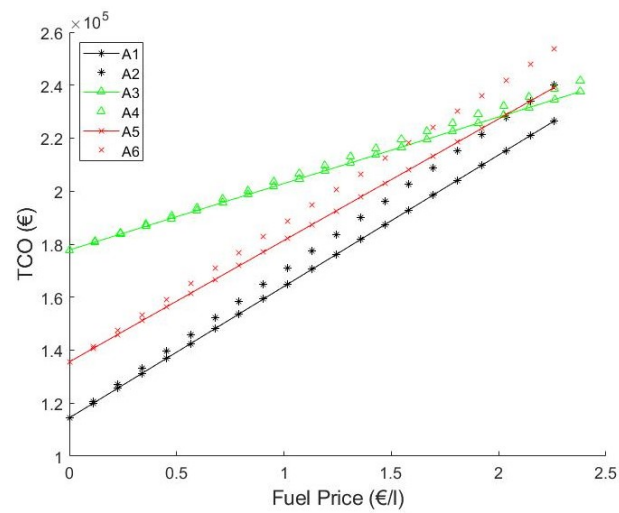
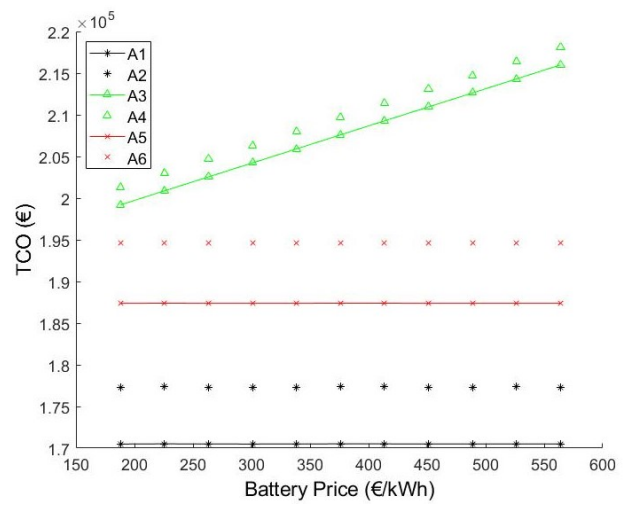
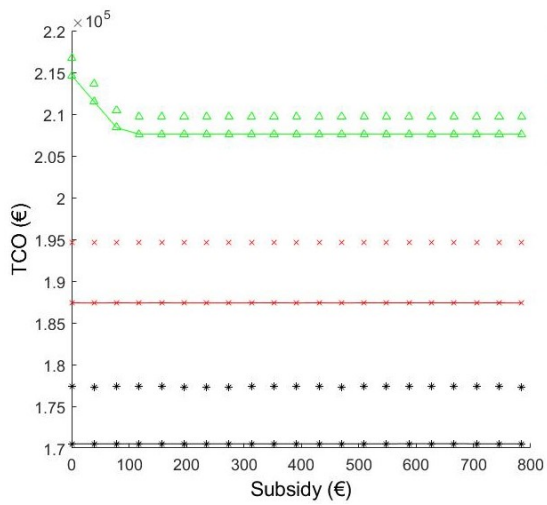
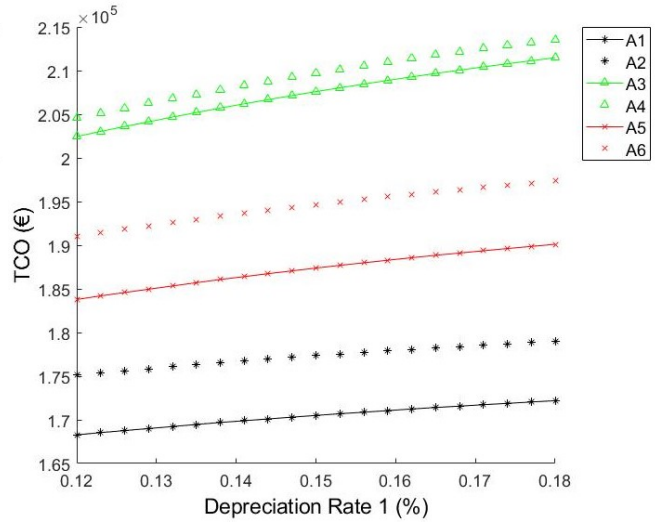
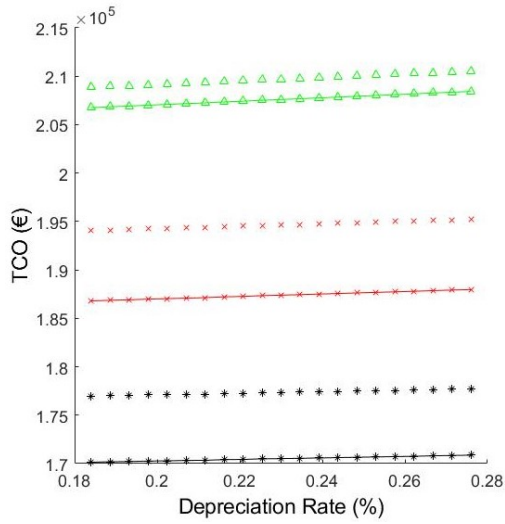


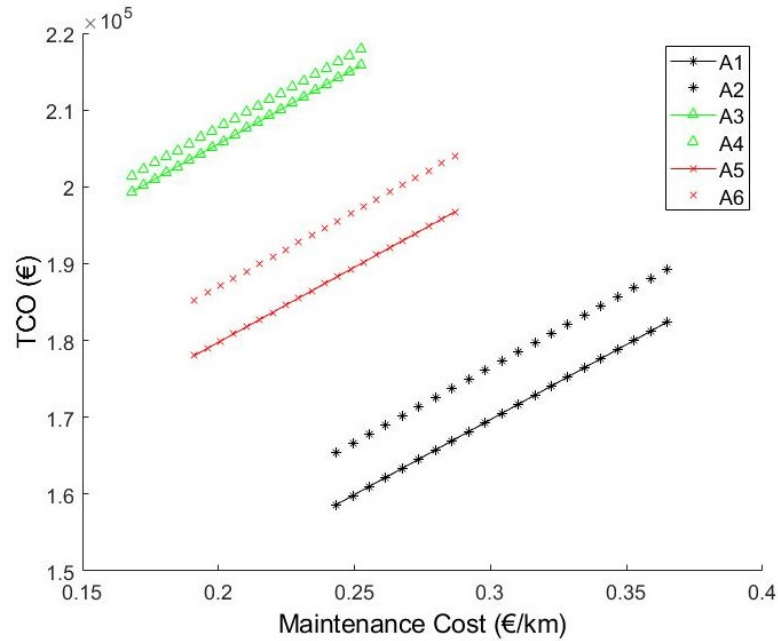
Appendix 5: Sensitivity analysis in changing the planned service years



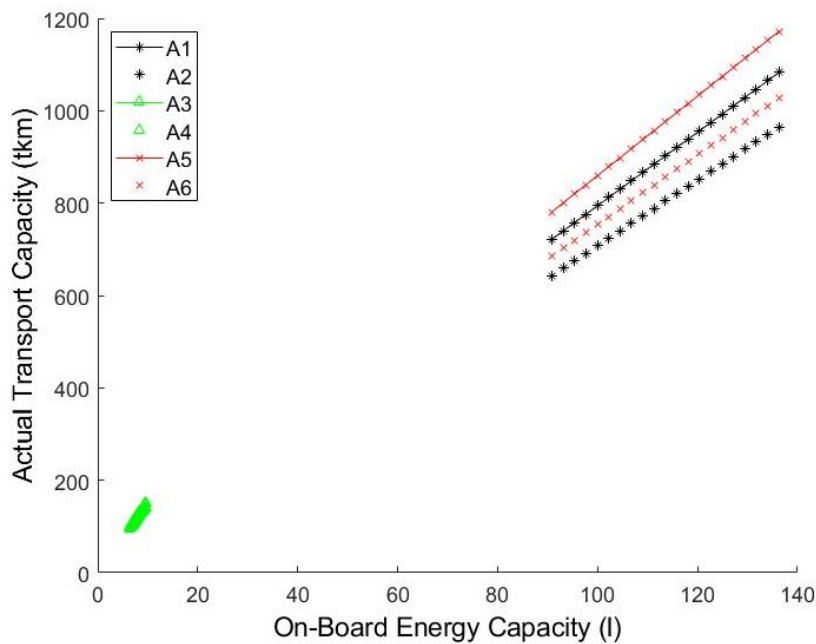
Appendix 6: Sensitivity analysis regarding the TCO







Appendix 7: Sensitivity analysis regarding the actual transport capacity



Appendix 8: The equivalent point of A₅ in the economic perspective

Required parameters	Unit	Original data	Equivalent points	Differences
Purchase price	€	141000	99814.29438	-29.21%
Subsidy	€	392	551.6768	+40.73%
Annual distance	Km	26554	12661.71794	-52.32%
Maintenance cost	€/km	0.2103	0.0206	-90.20%
Planned service years	Year	10	6.2244	-37.76%

 Appendix 9: The equivalent point of A₅ in the social perspective

Required parameters	Unit	Original data	Equivalent points	Differences
Payload capacity	kg	4423	34139.6428	+671.87%
Capacity utilization	%	37.28	287.79	+671.96%
Fuel economy	kWh/km	1.0431	0.1351	-87.04%
Energy capacity	kWh	80	617.493	+671.87%

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Abbreviations

2D	Two-Dimensional
3PL	Third-Party Logistics
ADVISOR	Advanced Vehicle Simulator
AFLEET	Alternative Fuel Life-Cycle Environmental and Economic Transportation
AHP	Analytic Hierarchy Process
BEV	Battery Electric Vehicle
CLECAT	European Association for Forwarding, Transport, Logistics and Customs Services
CNG	Compressed Natural Gas
DCV	Diesel Commercial Vehicle
DriveCAT	Drive Cycle Analysis Tool
ECV	Electric Commercial Vehicle
ECV-UFT	Electric Commercial Vehicle-Urban Freight Transport
EcoTransIT	Ecological Transport Information Tool
ELECTRE	Elimination and Choice Translating Reality
EN	Derived from the German phrase “Die Europäischen Normen”
EU	European Union
EVRP	Electric Vehicle Routing Problem
EVs	Electric Vehicles
FCEV	Fuel Cell Electric Vehicle
FTP	Federal Test Procedure
GHG	Green House Gas

Abbreviations

GIS	Geographic Information System
GVW	Gross Vehicle Weight
HEV	Hybrid Electric Vehicle
HoReCa	Hotel Restaurant Catering
HTBAMs	Heavy Truck Benefits Analysis Models
HTEBdyn	Heavy Truck Energy Balance Dynamic
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
ICT	Information and Communications Technology
JC	Japanese Cycle
LNG	Liquefied Natural Gas
MATLAB	Matrix Laboratory
MCDM	Multi-Criteria Decision Making
NEDC	New European Driving Cycle
NOW	Derived from the German name “Nationale Organisation Wasserstoff – und Brennstoffzellentechnologie”
NREL	National Renewable Energy Laboratory
OR	Operation Research
PHEV	Plug-in Hybrid Electric Vehicle
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
SBuA	Derived from the German name “Straßengüterverkehr Berechnung und Allokation”
SD	Sustainable Development
SLR	Systematic Literature Review

TCO	Total Cost of Ownership
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TTW	Tank to Wheel
UCCs	Urban Consolidation Centers
UFT	Urban Freight Transport
UK	United Kingdom
UPS	United Parcel Service
US	United States
VAT	Value Added Tax
VIKOR	Multi-Criteria Optimization and Compromise Solution
WPM	Weighted Product Model
WSM	Weighted Sum Model
WTW	Well to Wheel