ANALYSIS OF URBAN FREIGHT DISTRIBUTION AND A CITY LOGISTICS MODEL FOR İSTANBUL

by

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ABSTRACT

ANALYSIS OF URBAN FREIGHT DISTRIBUTION AND A CITY LOGISTICS MODEL FOR İSTANBUL

Intensive population growth in metropolitan cities brings with it many problems, such as increased demand, traffic congestion, and environmental degradation. This requires more efficient use of resources and faster resolution of issues. With 15.6 million inhabitants, İstanbul is by far the most populated city in Turkey. Due to the problems experienced in the logistics sector and the current situation of İstanbul's logistics activities, a city logistics plan for İstanbul is required to provide a sustainable and efficient logistics and freight transportation system. The term "city logistics" aims at effectively managing freight transportation, reducing traffic congestion and minimizing the environmental effects of logistics activities in order to increase the quality of life and reduce costs in cities.

This thesis aims to analyze the current state of İstanbul's freight flows and to develop a linear optimization model and solution methodology with the goal of improving the city logistics problems of İstanbul. Initially , based on İstanbul's urban transportation network and certain criteria, İstanbul is divided into 105 zones, and supply and demand points are determined. Using this network, İstanbul's city logistics is modeled using mathematical programming by considering ten different product categories, four different vehicle categories, and four different time intervals. The model optimizes the total transportation and CO_2 emission costs under various constraints. It is solved using real data of İstanbul. In order to see the effects of possible outcomes (such as insufficient transshipment center capacity, heavy reliance on electric van usage, different truck utilization rates, traffic density, limitations on emissions, etc.), different scenarios are prepared. Finally, the results are analyzed.

ÖZET

KENTSEL YÜK DAĞILIMI ANALİZİ VE İSTANBUL İÇİN BİR ŞEHİR LOJİSTİĞİ MODELİ

Metropollerdeki yoğun nüfus artışı; talebin artması, trafik sıkışıklığı ve çevresel bozulma gibi birçok sorunu beraberinde getirmektedir. Bu da kaynakların daha verimli kullanılmasını ve sorunların daha hızlı çözülmesini gerektirmektedir. İstanbul, 15.6 milyon nüfusuyla Türkiye'nin en kalabalık şehridir. Lojistik sektöründe yaşanan sorunlar ve İstanbul'un lojistik faaliyetlerinin mevcut durumu nedeniyle, İstanbul için sürdürülebilir ve verimli bir lojistik ve yük taşıma sistemi sağlayan bir şehir içi lojistik planına ihtiyaç duyulmaktadır. "Şehir lojistiği" kavramı, nüfusun yoğun olduğu şehirlerde yaşam kalitesinin artırılması ve maliyetlerin düşürülmesi için yük taşımacılığının yönetilmesi, trafik sıkışıklığının azaltılması ve lojistik faaliyetlerin çevresel etkilerinin en aza indirilmesini amaçlamaktadır.

Bu tez, İstanbul'un şehir içi lojistik problemlerini iyileştirmek amacıyla yük akışlarının mevcut durumunu analiz etmeyi ve doğrusal bir optimizasyon modeli ve çözüm metodolojisi geliştirmeyi amaçlamaktadır. Başlangıçta, şehir içi ulaşım ağı ve belirli kriterler baz alınarak İstanbul 105 bölgeye bölünmüş, arz ve talep noktaları belirlenmiştir. Bu ağ kullanılarak, on farklı ürün kategorisi, dört farklı araç kategorisi ve dört farklı zaman aralığı dikkate alınıp İstanbul'un şehir lojistiği matematiksel programlama kullanılarak modellenmiştir. Model, çeşitli kısıtlamalar altında toplam taşıma ve CO_2 emisyon maliyetlerini en iyilemektedir. İstanbul'un gerçek verileri kullanılarak çözülmüştür. Olası problemlerin (yetersiz aktarma merkezi kapasitesi, yoğun elektrikli araç kullanımı, kamyon doluluk oranlarındaki farklılıklar, trafik sıkışıklığı, emisyon sınırlamaları gibi) etkilerini görmek için ise farklı senaryolar hazırlanmıştır. Son olarak sonuçlar analiz edilmiştir.

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LIST OF SYMBOLS

A	Area of the zone
a_{skr}	The binary parameter that shows if zone r is on the path from zone s to zone k
c	Constant
c^v	Load carrying capacity of vehicle type v
cb_r^t	Max CO emission level for zone r in time interval t
ce^v	CO emission rate of vehicle type v
d_k^p	Demand for product category p of consumption center k
f_s^p	Amount of product category p produced in production center s
g_i^{vt}	The maximum number of vehicles that may be used by transshipment center i on the European side in time interval t for vehicle type v
g_j^{vt}	The maximum number of vehicles that may be used by transshipment center j on the Asian side in time interval t for vehicle type v
h^v	Passenger car equivalent value of vehicle type v
i	Set of transshipment centers on the European side
j	Set of transshipment centers on the Asian side
k	Set of consumption centers
m_{sk}	Distance between production center s and consumption center k
m_{ik}	Distance between transshipment center i on the European side and consumption center k
m_{jk}	Distance between transshipment center j on the Asian side and consumption center k
m_{ij}	Distance between transshipment center i on the European side and transshipment center j on the Asian side

m_{si}	Distance between production center s and transshipment center i on the European side
m_{sj}	Distance between production center s and transshipment center j on the Asian side
$m_i^{'}$	Distance between the border of the European side and transshipment center i
$m_j^{'}$	Distance between the border of the Asian side and transshipment center j
nb_r^t	The maximum NO_x emission level for zone r in time interval t
ne^v	NO_x emission rate of vehicle type v
oe^v	CO_2 emission rate of vehicle type v
p	Set of different product categories
r	Set of all zones in İstanbul
s	Set of production centers
t	Set of time intervals
U_{ij}^{pvt}	Amount of product p transported from transshipment center i on the European Side to transshipment center j on the Asian Side by vehicle type v in time interval t
v	Set of vehicle types
W_{si}^{pvt}	Amount of product p transported from production center s to transshipment center i on the European Side by vehicle type v in time interval t
W_{sj}^{pvt}	Amount of product p transported from production center s to transshipment center j on the Asian Side by vehicle type v in time interval t
X_{ik}^{pvt}	Amount of product p transported from transshipment center i on the European Side to consumption center k by vehicle type v in time interval t
X_{jk}^{pvt}	Amount of product p transported from transshipment center j on the Asian Side to consumption center k by vehicle type

	v in time interval t
Y_i^{pt}	Amount of product p transported from external zone to transshipment center i on the European Side in time interval t
Y_j^{pt}	Amount of product p transported from external zone to transshipment center j on the Asian Side in time interval t
Z_{sk}^{pvt}	Amount of product p transported from production center s to consumption center k by vehicle type v in time interval t
α_{ir}	The binary parameter that shows if zone r is on the path from the border of European Side to zone i
α_{jr}	The binary parameter that shows if zone r is on the path from the border of Asian Side to zone j
β	Average price of CO_2 per gram
γ_r	The surface area of zone r
ε	Deadheading trip rate for the amount of NO_x and CO emissions
η^{vt}	Transportation cost per tonne-km of vehicle type v in time interval t
θ_r^t	The maximum allowed number of vehicles originating from and terminating at zone r in time interval t per square kilometer
ϑ_{ji}^{pvt}	Amount of product p transported from transshipment center j on the Asian Side to transshipment center i on the European Side by vehicle type v in time interval t
κ	Deadheading trip rate for the cost of CO_2 emissions
ξ	Deadheading trip rate for the cost of transportation
τ	Deadheading trip rate for density
Ω	Objective function

LIST OF ACRONYMS/ABBREVIATIONS

API	Application Programming Interface
CC	Consumption Center
CO	Carbon Monoxide
CO_2	Carbon Dioxide
dB	Decibel
EPA	Environmental Protection Agency
EV	Electric Van
FTL	Full Truck Load
GAMS	General Algebraic Modeling System
ha	Hectare
HC	Hydrocarbon Compounds
HT	Heavy Truck
IMM	İstanbul Metropolitan Municipality
kml	Keyhole Markup Language
L	Liter
LP	Linear Programming
LTL	Less than Truck Load
NACE	Nomenclature of Economic Activities
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxide
OIZ	Organized Industrial Zone
PC	Production Center
PCE	Passenger Car Equivalent
PM	Particulate Matters
PV	Panel Van
SO_2	Sulphur Dioxide
SO_x	Sulphur Oxide

TR	Truck
YTU	Yıldız Technical University

1. INTRODUCTION

Freight transportation significantly affects the life in a city. Although it is a disquieting activity in urban areas, it is inevitable. Since it covers quite a large portion in our daily lives, its impacts must be eased and it should be done in an effective, reliable, efficient manner, and has to be managed better. Additionally, freight transportation in an urban environment must be as fast, economical, and environmentally friendly as possible. Several measures have been taken in order to better manage and control freight transportation over the years. The main goal is to reduce transportation costs as well as its negative effects on city life, such as greenhouse gas emission, congestion and pollution, while sustaining social and economic activities of the city in a proper way. These goals can be achieved by considering an integrated logistics system, rather than treating each shipment or vehicle individually [1].

City logistics (a.k.a. urban logistics) aims to provide high quality service with least (generalized) delivery cost in congested urban areas [2]. It deals with movements of goods between origin and destination points in urban areas. Regarding the concepts of city logistics, coordination and consolidation are essential to achieve freight transportation goals. For instance, one way of mitigating congestion in cities is reducing the number of freight vehicles circulating in traffic. Thus, the coordination of freights of different shippers and carriers is essential. This can be accomplished by the coordination of logistics operations, and running a better integrated logistics network [1].

Due to traffic congestion, lack of sufficient parking areas, restrictions on deliveries to central areas in daytime or rush hours, lack of coordination among producers and some specific regulations related to road transportation and freight movements, İstanbul is experiencing a myriad of problems in terms of logistics activities. The major problems are late deliveries of products, potential damage to products during deliveries, reverse logistics problems such as product returns and recycling, high transportation costs and environmental degradation. Due to the problems experienced in the logistics

sector and the current situation of İstanbul's logistics activities, it can be concluded that a city logistics plan for İstanbul is required to provide a sustainable and efficient logistics and freight transportation system. For these reasons, this thesis aims to analyze the current state of İstanbul's freight flows and to develop a linear programming model with the goal of improving the city logistics problems of İstanbul. To this end, the assignment of product categories to transportation modes (vehicle types) and time intervals, while satisfying supply limitations and customer demand are investigated. To do so, a better integrated network design is needed while minimizing the total cost and considering product and vehicle types, the time intervals, and the supply and demand nodes. This proposed model is applied on a real data set provided by the İstanbul Metropolitan Municipality (IMM).

The main contributions of the thesis are, (i) the detailed city logistics model of İstanbul at strategic level, (ii) extensive data collection and compilation regarding freight movement activities, (iii) scenario analyses focusing on alternative proposals and strategies for the logistics problems of İstanbul.

The remainder of the thesis is organized as follows. In the second chapter, a brief information and literature survey on city logistics is presented. The third chapter analyzes the urban freight distribution and introduces the data sets compiled for the city logistics model with the explanations for their use. The fourth chapter provides a detailed description of the city logistics model of İstanbul together with underlying assumptions, index sets, parameters, decision variables, the objective function, and the constraints. The fifth chapter states the results of the base scenario and all other scenarios with brief summaries. The final chapter summarizes the work accomplished and mentions the concluding remarks.

2. LITERATURE REVIEW

City logistics and urban freight transportation have proved to be an interesting topic in urban policy. Crainic and Laporte [3] classify freight transportation planning models into three main levels: strategic, tactical, and operational. Strategic models represent long term models, which are related to high level strategic decisions that require large investments, such as decisions about designing network and facility locations. Location models (such as covering models, center models and median models) and network design models (shortest spanning tree and multi commodity network flow problems) are considered under strategic level models. Tactical models represent medium term models which are related to details concerning the design of the network. These models usually focus on issues about allocation of resources, load or transportation plans, transportation operations between producer of goods and freight carriers, routing specifications, and terminal policies. In tactical levels, vehicle routing problems are also considered. Operational models include short term models which are related to decisions that help to improve the performance of firms. For instance, distribution of empty vehicles, allocating resources, and crew scheduling are some of the issues encountered in the operational models. These aim to ensure demand satisfaction, by considering time limitations, optimizing scheduling operations and using resources efficiently. It can be said that this thesis is at a strategic level in terms of monitoring and planning freight flows and addressing the problems encountered in city logistics.

Crainic et al. [1] conduct a study in order to evaluate city logistics systems. In their study, they aim to solve city logistics issues at tactical level and discuss a two-tiered city logistics system, where satellites are utilized to transfer loads from urban vehicles to smaller city freighters. Then, with the aim of planning day-before logistics activities, they propose a model which is two-echelon, synchronized, scheduled, multi-depot, multiple-tour, heterogeneous vehicle routing problem with time windows. The model comprises scheduling and routing of both urban vehicles and city freighters, satellites visited, and adequate supply of vehicles at satellites.

According to Taniguchi et al. [4], there are four main stakeholders in city logistics: Shippers, freight carriers, residents and administrators. Shippers send freight to other companies or customers. Shippers' objective is to maximize their revenue by sending their goods with low transportation cost and high service quality. Therefore, they hope to choose the most appropriate freight carriers. Freight carriers distribute freights to customers and aim to minimize transportation and pick-up costs while providing high service quality on a designated time window. Residents are people who live and work in a city. They want to live in a sustainable, livable and accessible city. Also, they hope to live in a system where freight movement activities are efficiently performed. Administrators in urban areas aim to increase the level of economic development and take measure for traffic congestion and environmental issues.

Tamagawa et al. [5] discuss the evaluation of city logistics by introducing a multi-agent model that involves a Q-learning technique in order to evaluate behaviors of stakeholders and feature a vehicle routing and scheduling with time window forecasted (VRP-TW-F). There are five stakeholders, which are freight carriers, shippers, residents, administrators, and motorway operators and each of these stakeholders is assumed to have different objectives. This model is implemented in a network environment. In this environment, each stakeholder has its own purpose, and their behavior is shaped according to this purpose. When the environment changes, stakeholders adapt their behavior accordingly. In order to model their behavior, a learning method is utilized, that is Q-learning technique. The other VRP-TW-F model plans and applies a delivery schedule for each freight carrier according to the incoming orders of shippers, and the network environment is updated. These two models are applied alternately. Finally, a network environment is generated, which is confirmed by all stakeholders.

In another study, Taniguchi [6] focuses on the concept of city logistics. He claims that three points are important for city logistics: (a) Application of innovative technologies of Information and Communication Technology (ICT) and Intelligent Transport Systems (ITS), (b) Change in the mind-sets of logistics managers, and (c) Public-private partnerships. In this study, Taniguchi not only reveals the concepts of

city logistics, but also touches on the urban freight transport management. It has four important stages: (a) Design stage, (b) Assessment stage, (c) Implementation stage, and (d) Evaluation stage, based on the Plan-Do-Check-Act (PDCA) cycle. Also he claims that urban freight transportation management benefits from the evaluation of policy measures.

Some studies are addressed to evaluate city logistics initiatives. One of them is conducted by Taniguchi and Heijden [7]. They propose a methodology to assess city logistics initatives, considering dynamic truck simulation with optimal truck routing and scheduling. They analyze three cities and evaluate their logistics initiatives with these proposed methods. Another study that evaluates the city logistics initiatives is carried out by Tadic et al. [8]. They propose a multi-criteria decision making approach that uses Delphi, Analytic Hierarchy Process (AHP) and Stepwise Weight Assessment Ratio Analysis (SWARA) methods, while taking the requirements and objectives of different stakeholders into consideration.

In the literature, there is an important four-step modelling approach to model transportation systems (proposed by Patriksson [9]). The steps are trip generation, trip distribution, modal split and traffic assignment. In the trip generation step, the number of trips that originates or terminates in each traffic zone is predicted. In the trip distribution stage, trips are assigned from origin zones to destination zones, considering the number of trips obtained in the previous step. In the modal split step, the mode of transportation is designated. In the traffic assignment step, the estimated trips are assigned to transport network and routes are selected [9]. People in urban areas have the feeling that "cities are not safe" because of the accidents and congestion resulting from logistics activities. Traffic congestion in urban areas could be reduced by utilizing vehicles efficiently: decreasing the number of empty trips (deadheading) and increasing the average load of vehicles. Another way to reduce congestion is implementing consolidation centers. Shippers and carriers coordinate their distribution activities and consolidate freights at city level in these intermodal platforms. Regarding these, in our study, the data collected in the trip generation step

is obtained from IMM. Next, trip distribution and modal split steps are developed. Additionally, for the traffic assignment step, a preprocessor is utilized to estimate the routes.

Jiangping and Shuai [10] provide a study reviewing urban and metropolitan freight transportation models. They analyze existing models in five groups: Growth factor models, commodity-based models, trip-based models, tour based models, and logistics chain models. Then, these model groups are compared with each other based on some criteria in the literature, such as behavioral, multimodal, simultaneity, feedback effect, dynamic, general applicability, comprehensive, data driven, geographically detailed and forecasting tool.

Crainic et al. [11] propose a logistical structure for Rome. They present a two-tiered capacitated multi-commodity location formulation. There are two main decision variable sets in the formulation; the first set addresses where to locate satellite platforms-the locations where the freights are consolidated and transferred-and the other set addresses on the quantity of product flow from which external zone to which commercial zone through which satellite and with which vehicle type. They aim to minimize the total cost considering demand satisfaction and the limitation on the number of vehicles that a satellite can handle. In their study, 51 commercial zones, 12 external zones, 41 potential satellite sites, one commodity type, one city freighter type and one urban vehicle type are taken into account. Their optimal solution suggests the opening of 38 (out of 41) satellites.

Amaral and Aghezzaf [12] perform a study of two-tiered strategy in order to model traffic management and urban freight transportation. They introduce a vehicle routing problem with time windows. There are two layers in the model. In the outer layer, freights are transported from external zones to depots or satellites with urban vehicles which have large capacities. In the inner layer, the freights are distributed from depots or satellites to customers with city freighters which are small vehicles.

Taniguchi and Thompson develop a study about modelling city logistics [13]. They propose and analyze on a probabilistic vehicle routing and scheduling model based on ITS. They use variation of travel times using stochastic programming techniques with historical data of travel times on each link of a network. Hence, they aim to decrease the number of trucks, the distance traveled, and operating costs. They also target to reduce fuel consumption and emissions.

Lim et al. [14] present a study about transshipment through cross-docks. This study intends to model transshipment from suppliers to customers considering their time window restrictions, transportation schedules and warehouse capacities, while minimizing the total cost. They also deploy transformation techniques in order to reduce the problem size.

Zhang and Li [15] examine the location model of a multi-period, multi-commodity and multiple logistics nodes problem. They formulate an optimization model that aims to minimize transportation, handling and fixed costs, while assigning commodity flows between first-degree logistics nodes, second-degree logistics nodes and customers. As a solution procedure, they present an algorithm based on the minimum cost-maximal flow problem and genetic algorithms.

In the study by Üster and Agrahari [16], the researchers formulate a mathematical model for an integrated load planning problem. They intend to determine the route of commodities on a network and decide which consolidation and deconsolidation centers are used, as well as which truckload type (i.e. less than truckload or full truckload) is selected. After providing a mathematical formulation to this problem, they introduce effective solution algorithms and compound neighborhood functions.

Some of the studies in the literature address urban freight activities. Ozturk and Patrick [17] provide an optimization model about freight transport with an urban rail transport system. In this model, it is possible to transport passengers and freight on the same train line. Some stations are used for freight activities. Firstly, they consider

just two stations and develope an approximation algorithm and a pseudo-polynomial dynamic programming algorithm. Then, they consider the general multiple stations model. They propose a heuristic solution procedure, two mixed-integer linear programs and a ε-constraint model that finds a lower bound on the minimum number of trains. As a secondary objective, it aims to minimize total tardiness. Train schedules are fixed in the first model. The second model does not assume fixed train schedules and it is integrated with an ε-constraint model that prioritizes the minimization of the number of trains. They also present numerical results.

Traffic congestion is an important issue for municipalities. With the aim of reducing the number of trucks in an inner-city, a two-echelon vehicle routing problem with covering options is investigated in Enthoven et al [18]. In the first echelon, trucks depart from the single depot and leave the products to intermediate locations. There are two types of intermediate locations here. One is satellite locations where freights coming here by trucks and then transferred to cargo bikes (a zero-emission vehicle). The other one is covering locations, such as parcel lockers, where trucks transport parcels and customers get their parcels from these locations. An adaptive large neighborhood search (ALNS) heuristics and a new set of benchmark instances are presented in this study. It is claimed that ALNS obtains high quality and often optimal solutions.

In most cases traffic congestion varies considerably over time. Although there is little traffic at some times of the day, this congestion increases considerably depending on the time of the day and in some special cases such as traffic accident and road construction. This traffic congestion affects travel times considerably. In many studies, the travel time between two nodes or the speed that vehicles can travel has been taken as fixed. However, in the study handled by Liu et al. [19], the vehicle travel speed or travel time varies depending on the start time of the trip. In this study, a time-dependent vehicle routing problem with time windows is considered. In order to eliminate the adverse effects of traffic congestion, an improved ant colony algorithm with a congestion avoiding approach is employed to solve the model. Another study about a time-dependent vehicle routing problem with time windows is introduced by

Gmira et al. [20]. It is aimed to minimize the total duration of the routes. As a solution approach, they use the tabu search heuristic. They consider this problem on a road network with benchmark instances up to 200 nodes and 580 arcs. Furthermore, some techniques are explained to evaluate the feasibility of solutions in constant time. It is claimed that the quality of the results is quite good.

Groß et al. [21] feature a study about city logistics vehicle routing problem. Because of the uncertainty in travel times, cost-efficient and reliable vehicle routing is an issue that is difficult to overcome. They integrate interval travel times with vehicle routing problem. In this study, goods are transported to the satellite locations. Finally, they provide a case study for the city of Stuttgart.

Customers may have demands for different types of products, and these products may require some special conditions during their transportation, depending on their type. For instance, during the transportation of some food and beverages, the temperature must be kept under control. Therefore, special vehicles are required for food and beverage deliveries in order to control the temperature. In addition, such products may have small volumes to fill a single vehicle capacity. In this case, multi-compartment vehicles are needed. Eshtehadi et al. [22] discussed a vehicle routing problem with multi-compartment vehicles. They aim to minimize the operational costs in city logistics, considering fuel costs, driver wage(s) and temperature costs. They use an adaptive large neighborhood search algorithm, including various sets of instances based on London geographic data.

Li et al. [23] present a two-echelon city logistics system. In their study, they introduce this system with on-street satellites by using time windows. They formulate a mathematical model that includes satellite transshipment constraints. Regarding on-street satellites, real-time transshipment capacity is changing according to transshipment operations. Then, a variable neighbourhood search heuristic is conducted, and the results are tested by considering 20 randomly generated small-scale instances.

Groß et al. [24] focus on reliable routing in city logistics by using internal travel times (ITT). The reason for using ITT is that it is less costly and requires less effort by city logistics providers. They combine it with a robust routing approach. They acquire the sample data set of travel times using shifted gamma distribution. Then, they deal with robust traveling salesman problem with ITT. The aim is to obtain a delivery tour, while minimizing the total tour duration.

Fontaine et al. [25] focus on a study about some issues of city logistics, including the system design of city logistics networks, consolidation between logistics service providers, and allocating demand to various delivery modes and city freighters. They propose a continuous approximation model to evaluate the tour length and operational cost in a distribution area. Next, they derive a nonlinear optimization model, and then, they apply it to a real case study for the city of Munich, Germany. They discuss the 1-tier scenario, 2-tier scenario, 1-tier or 2-tier scenario, outsourcing scenario, and consolidated scenario. When the results of this study are analyzed, it is seen that the consolidation results in a decrease in the total costs. This reduction reaches up to 50% in emission costs in the lower echelon (which is from micro-depots to customers) regardless of the transportation strategy. When the last mile operations are outsourced, it causes an increase in kilometers traveled in the lower echelon. In addition, as the distances between deports and distribution points with higher customer density increase, 2-tier transportation strategies become advantageous.

Another example of city logistics is given by Trecozzi et al. [26] that present the experience of the Calabria Region. A prototypal process is conducted with the aim of making freight distribution efficient and increasing liveability. According to the studies of the Calabria Region, an integration between regional administration (playing as a financier) and local authority (playing as a decision maker) plays an essential role in the transportation of goods in city logistics. In this study, two types of projects are conducted as a part of the Regional Transport Plan. Different infrastructural interventions are applied in these projects, such as time windows, electric vehicles, urban distribution centers, parking network realization, pick-up point realization, and

nearby delivery areas. In addition, traffic flow management also provides the required social distance during freight delivery in case of the emergency of COVID-19. The results of this study reflect that such projects create positive effects in the field of sustainability and liveability in city logistics.

Slávik and Gnap [27] examine the distribution of products in the night time. One of the most important criteria taken into account in night distribution is the noise problem. The main contributors to the noise are transportation vehicles (because of engine noise, tires) and logistics operations (loading, unloading, etc.). This study consists of some noise values measured at different times and in different locations. They observe that the noise values exceed limit values at a maximum of 5.5 dB after the hour of 22:00. In order to decrease the noise level in the night-time distribution, warehouse employers or drivers should be trained to do their jobs as quiet as possible. Another way to minimize the noise level is setting up noise barriers or natural barriers (hedge, alley). There is also one more issue to be considered in night-time distribution, which is not only the noise in the loading area but also the noise on the roads. The noise of vehicles is perceived louder in the night time than in the day. Therefore, less noisy, electric and hybrid vehicles are recommended.

Some studies focus on green solutions to logistics issues. Munuzuri et al. [28] propose a methodology to estimate urban freight emissions. They also apply it to the Spanish city of Seville, which is a 40 km^2 city with 700,000 inhabitants, to analyze freight delivery operations. They consider the type and length of urban freight routes, vehicle indicators, and emission values of some pollutants (nitrogen oxide (NO_x), hydrocarbon compounds (HC), carbon monoxide (CO), and carbon dioxide (CO_2)). Based on these factors, they predict the amount of emissions related to urban freight activities. Yang et al. [29] examine the carbon emissions performance of the logistics industry based on data envelopment analysis and Malmquist index from both a static and dynamic perspective. They apply on sixteen cities within Yunnan Province of China.

There is another study performed by Yang et al. [30] that considers carbon tax policy in China. They propose a carbon-tax constrained city logistics network planning model which is a bilinear mixed integer program. This study considers carbon taxes, low carbon resource deployment and common network configurations. Results of the study show that such approaches are highly effective in decreasing carbon dioxide emissions while reducing operation costs.

The COVID-19 pandemic, which brokeout in 2019, negatively affected the logistics sector. Cui et al. [31] focus on a study about the effects of COVID-19 on the performance of cities' logistics. They use the entropy weight method to evaluate the logistics level of 18 node cities in the Belt and Road Initiative (BRI) in 2019 and 2020. Then, the logistics spatial connection of node cities is calculated based on the modified gravity model. According to the results of the study, the three-node cities (which are the cities of Harbin, Changchun, and Shenyang) in the northeast of China and the cities that have connection with Wuhan have been greatly affected. Furthermore, policy followed under the pandemic have negative effects on logistics. For instance, the duration of expressway control policies and strict lockdown policies result in a decline of logistics performance of cities.

The rapidly spreading COVID-19 pandemic in 2020 caused worldwide lockdowns and adversely affected the Indian economy, which has led to contractions. In the study of Bandyopadhyay and Bhatnagar [32], they conduct a survey to observe the effects of COVID-19 on profitability and operations, employment, and capital expenditure. A total of 177 organizations answered the survey considering the cases before COVID-19 and during COVID-19. The results of the survey demonstrate that there is a decrease in revenue and an increase in operating cost, considering the average cargo handled per day, cargo pendency, traffic movement through rail, etc. Furthermore, a decrease in cargo operations causes a reduction in employment. Due to the delays of more than six months during the financial years 2021 and 2022, capital expenditures have been reduced, which result in a decrease in the procurement of material handling equipment and construction contracts. All this literature review is summarized in Appendix A.1.

3. URBAN FREIGHT DISTRIBUTION IN İSTANBUL

3.1. Overview of the Logistics Activities in İstanbul

İstanbul is the center of many sectors in Turkey, especially trade. Under the influence of increasing trade volume and globalization, competition is increasing, that requires more effective usage of logistics. Moreover, its population is increasing every year (which reached to more than 15 million people in 2018 [33]). Therefore, a significant increase in residential areas is observed in İstanbul. Furthermore, about 60% of the logistics activities of Turkey is realized in İstanbul. When analyzing the city logistics of İstanbul, it is useful to consider the logistics nodes [34]. The logistics nodes of İstanbul include organized industrial zones (OIZ), small industrial sites, free zones, wholesale market halls, customs and warehouses, and chemical storage areas.

Table 3.1. Organized industrial zones in İstanbul [35].

Organized Industrial Zone	District	Year of Establishment
İstanbul Leather Organized Industrial Zone	Tuzla	1982
İstanbul Dudullu Organized Industrial Zone	Ümraniye	1995
İstanbul Asian Side Organized Industrial Zone	Tuzla	2000
İstanbul Tuzla Organized Industrial Zone	Tuzla	2000
Birlik Organized Industrial Zone	Tuzla	2001
Tuzla Chemical Industrialists Organized Industrial Zone	Tuzla	2001
İstanbul İkitelli Organized Industrial Zone	Başakşehir	2001
İstanbul Beylikdüzü Organized Industrial Zone	Beylikdüzü	2002

When the distribution of sectors in İstanbul is taken into consideration, the service and industry sectors have the highest weight. Organized industrial zones and small industrial sites, which are the important part of the industry sector, represent the essential logistics nodes of İstanbul. There are eight organized industrial zones in İstanbul as presented in Table 3.1. The total area they cover is about 2,088.9 ha. Small industrial sites are scattered throughout İstanbul in 113 different areas. There are about 150,000 people are employed in over 35,000 workplaces in these areas [35].

Free zones are set up within the political boundaries of the country where they are located, but they have special regulatory treatment. In such zones, the legal and administrative regulations concerning various commercial, financial and economic aspects are not applied or are partially implemented [36]. There are three free zones in İstanbul. Their listing and establishment date are displayed below in Table 3.2.

Table 3.2. Free zones in İstanbul.

Free zones in İstanbul	Year of Establishment
İstanbul Atatürk Airport Free Zone	1990
İstanbul Thrace Free Zone	1990
İstanbul Industry & Trade Free Zone	1992

Wholesale market halls are places where goods are offered to retailers in a wholesale manner. In wholesale markets, perishable products, especially fruits and vegetables, are marketed quickly and effectively. They have crucial functions in the physical exchange of products and facilitating sales. Therefore, there is a high level of logistical mobility due to incoming and outgoing vehicles. The wholesale market halls in İstanbul are as follows:

- İstanbul Vegetable and Fruit Wholesale Market Hall (Bayrampaşa Wholesale Market Hall): It is managed by IMM. There are 571 companies in an area of 670 acres.
- Kadıköy Vegetable and Fruit Wholesale Market Hall (Ataşehir Wholesale Market Hall): It is managed by IMM. There are 193 companies in an area of 55 acres.
- Fisheries Wholesale Market Hall (Yenikapı): It is managed by IMM. It is located in an area of 27 acres, 10-15% of the products come from the sea, the rest comes by road.
- Flower Wholesale Market Hall: It is managed by the private sector.
- Rami Dry Food Wholesale Market Hall: It is managed by the private sector. There are 1,200 companies.
- Mega Center Food and Trade Center (Bayrampaşa): It is managed by the private sector. There are 800 companies [35].

Inspection of goods or vehicles entering and leaving the country and the implementation of specific legislation is called customs. The World Bank prepared a report called "The Logistics Performance Index (LPI)" to evaluate the logistic performances of 155 countries. Among the criteria considered in this report, "The efficiency of customs and border management clearance" takes the first place. This shows that customs operations lead to significant logistical mobility [37].

Customs services constitute an essential part of the logistics activities. Especially, Halkalı, Ambarlı, Erenköy and İstanbul Atatürk Airport Cargo Customs are very crucial in terms of location and logistic mobility. The list of customs offices in İstanbul is displayed below [38]:

- İstanbul Atatürk Airport Cargo Customs Office
- İstanbul Atatürk Airport Passenger Hall Customs Office
- İstanbul Atatürk Airport Free Zone Customs Office
- Ambarlı Customs Office
- Beylikdüzü Fuel Customs Office
- Erenköy Customs Office
- Halkalı Customs Office
- Halkalı Gar Customs Office
- Haydarpaşa Customs Office
- İstanbul Leather Free Zone Customs Office
- İstanbul Airport Customs Office
- İstanbul Postal Customs Office
- Karaköy Passenger Hall Customs Office
- Pendik Customs Office
- Sabiha Gökçen Airport Customs Office
- Trakya Free Zone Customs Office
- Yeşilköy Customs Office
- Zeytinburnu Customs Office.

With an attempt to solve the logistics problems of İstanbul, some studies have proposed various strategies and approaches. According to the report of "İstanbul's urban logistics plan" prepared in 2006 [34], these strategies are as follows:

- Shifting of freight transport to the rail system;
- Ro-Ro use in maritime transport;
- Establishment of freight villages;
- Integration of Ro-Ro and Ro-La systems;
- Regulation of fuel distribution traffic and pipeline transport;
- Efficient use of ports.

3.1.1. Logistics Infrastructure of İstanbul

In this section, a brief information is given about the infrastructure of freight logistics in İstanbul, and some statistical data is shared. While compiling this section, some reports are taken as references [35, 39].

3.1.1.1. Road Transportation. Road transportation is one of the most significant transportation modes in İstanbul. In this section, some statistical information about the factors related to road transport in İstanbul is presented. In Table 3.3, the numbers of motor vehicles in İstanbul and Turkey are given for the year 2021. All motor vehicles registered in İstanbul constitute 18% of all motor vehicles registered in Turkey. When the vehicles in İstanbul are examined, cars have the highest share among all vehicles (69%). They are followed by the small trucks (16%).

Table 3.3. The number of road motor vehicles in İstanbul and Turkey [40].

	Car	Minibus	Bus	Small Truck	Truck	Motorcycle	Special Purpose	Total
İstanbul	3,071,494	96,702	38,821	713,437	136,042	382 503	9,466	4,474,536
Turkey Total	13,293,727	491,227	211,658	3,993,229	867,377	3,548,609	72,406	24,454,396

In Table 3.4, the annual average daily traffic volume on İstanbul highways is given. As can be seen in this table, the longest section is Metris-Hasdal. The section

with the highest density of light vehicles is the Kavacık-Şile separation, and the section with the highest density of heavy vehicles is the Metris-Hasdal section.

Table 3.4. The annual average daily traffic volume on İstanbul highways in 2019 (Vehicles/Day) [41].

Section Name	Length (km)	Light Vehicle	Heavy Vehicle	Total Annual Average Daily Traffic
Mahmutbey (West-East)	2.7	118,848	30,149	148,997
Mahmutbey East-Metris	3.5	93,666	61,698	155,364
Metris-Hasdal	8.6	134,857	63,672	198,529
Hasdal-Levent	5.4	144,701	11,599	156,300
Levent-FSM Bridge	1.5	123,281	33,868	157,149
FSM Bridge-Kavacık	4.8	152,568	31,621	184,189
Kavacık-Şile Seperation	7.4	173,051	22.258	195,309
Şile Seperation-Çamlıca	3.9	167,076	19,734	186,810

3.1.1.2. Maritime Transportation. İstanbul has an important position in Turkey's maritime transportation due to its geographical location and the growing trade volume. Table 3.5 presents ten cities that handled the most cargo in maritime trade in 2019. As can be seen in this table, the cities with the most cargo handled is İzmir, and İstanbul is in the fifth rank.

Table 3.5. Ten cities with the most cargo handled in 2019 [42].

Province	Handling (Tonnes)	Ratio in Total Handling (%)	Growth Rate (%)
İzmir	77,098,663	15.92	18.98
Kocaeli	72,196,415	14.91	-1.29
Adana	66,945,044	13.83	10.23
Hatay	62,167,713	12.84	7.71
İstanbul	40,563,974	8.38	-9.00
Mersin	40,068,337	8.28	9.81
Tekirdağ	29,933,977	6.18	13.76
Zonguldak	21,231,766	4.39	-2.33
Çanakkale	17,144,803	3.54	-10.22
Bursa	13,908,352	2.87	-2.79
Total	441,259,044	91.14	5.70

Table 3.6 presents the number of incoming ships to the ports in İstanbul at the end of 2019. As can be seen in this table, the number of ships (both Turkish and foreign-flagged) arriving at Ambarlı port is higher than the number of those arriving at İstanbul port. Also, more cargo is transported to Ambarlı port than İstanbul port.

Table 3.6. The number of incoming ships to the ports in İstanbul [43].

		Ambarlı Port	İstanbul Port
Turkish Flag	Number of Ships	1,309	439
	Gross Ton	14,802,802	2,480,799
Foreign Flag	Number of Ships	2,506	307
	Gross Ton	82,051,079	5,074,956
Total	Number of Ships	3,815	746
	Gross Ton	96,853,881	7,555,755

Table 3.7. Total handling statistics of ports in İstanbul (tonnes) [44].

		Ambarlı Port	İstanbul Port
Loading	Import	11,059,288	177,852
	Cabotage Loading	1,009,006	67,210
	Transit Loading	5,056,243	2,083
	Total Loading	17,124,537	247,145
Unloading	Export	11,471,867	694,348
	Cabotage Unloading	1,577,790	2,465,453
	Transit Unloading	4,475,290	5,475
	Total Unloading	17,524,947	3,165,276
Total	Total Import and Export	22,531,155	872,200
	Total Cabotage	2,586,796	2,532,663
	Total Transit	9,531,533	7,558
	Total Handling	34,649,484	3,412,421

Cargo handling statistics at Turkish ports according to the harbour master's area of jurisdiction in 2019 are presented in Table 3.7. At Ambarlı ports, a total of 34,649,484 tonnes of handling is carried out in 2019, including 17,124,537 tonnes of loading and 17,524,947 tonnes of unloading. As for İstanbul ports, a total of 3,412,421 tonnes of handling is carried out, including 247,145 tonnes of loading and 3,165,276

tonnes of unloading. As can be seen, more cargo is handled in Ambarlı ports. Ambarlı port does not have a railway connection. In addition, the port has no possibility of expansion. This heavily affects the surrounding road traffic [35].

3.1.1.3. Rail Transportation. The logistics activities carried out by rail transport in İstanbul are very low compared to road and sea transport [39]. The total railway length in Turkey is 12,803 km, and 402 km of it is in İstanbul, in 2019 [45].

Considering the freight transported by railways according to the regional directorates of TCDD General Directorate, the amount of freight transported in İstanbul Region, including the city of İstanbul, is given in the table below.

Table 3.8. Nettonne-kilometers in the line section of İstanbul region [45].

Line Sections	Freight	Service Train	Total
Gebze-Arifiye	131,531	201	131,732
Arifiye-Adapazarı	25	78	103
Arifiye-Eskişehir	441,509	525	442,033
Sirkeci-Halkalı		638	638
Halkalı-Pehlivanköy	293,018	213	293,230
Pehlivanköy-Border(Greece)	188		188
Pehlivanköy-Border(Bulgaria)	132,741	23	132,764
Tekirdağ-Muratlı	4,459		4,459
Marmaray	10	33,835	33,845
Total	1,003,479	35,513	1,038,992

When focusing on the freight transportation in the İstanbul Region, it is seen that the highest total freight (442,033 tonnes-km) is transported on the Arifiye-Eskişehir line. When the line sections passing through the city of İstanbul are examined, it is seen that the highest freight is transported between Halkalı-Pehlivanköy (293,230 tonnes-km).

With the aim of developing combined transportation and establishing an effective connection between transportation modes, logistics centers are established by TCDD. These logistics centers enable activities such as storage, maintenance-repair, loading-unloading, and handling to be carried out more economically. There are eleven logistics centers that are in operation in Turkey (it is planned to increase this number to 25 logistics centers in Turkey). These are Samsun (Gelemen), İzmit (Köseköy), Uşak, İstanbul (Halkalı), Eskişehir (Hasanbey), Balıkesir (Gökköy), Denizli (Kaklık), Kahramanmaraş (Türkoğlu), Erzurum (Palandöken), Mersin (Yenice), and Konya (Kayacık). In addition to the Halkalı logistics center which is operating in İstanbul, Yeşilbayır logistics center is in the planning phase [46].

Table 3.9. The opening dates and railway transports of logistics centers (net tonnes) [45], [47].

Logistic Center	Opening Date	2013	2014	2015	2016	2017	2018	2019
Samsun	2007	1,327,485	1,288,107	814,403	0	0	0	0
İzmit	2010	13,388	121,949	345,416	351,192	316,482	331,201	219,230
Uşak	2012	210,915	277,904	93,925	110,440	28,716	25,854	26,271
İstanbul	2013	493,933	12,964	13,253	412,642	435,068	462,133	432,925
Eskişehir	2014	110,528	184,648	159,061	184,629	69,040	45,341	41,573
Balıkesir	2014	-	-	90,521	70,289	218,938	287,468	175,955
Denizli	2014	-	23,530	229,582	219,180	176,657	66,658	61,071
Kahramanmaraş	2017	-	-	-	-	17,263	48,600	73,196
Erzurum	2018	-	-	-	-	-	34,918	47,091
Mersin	2019	-	-	-	-	-	-	202,839
Total		2,156,249	1,909,102	1,746,188	1,348,372	1,262,164	1,302,173	1,280,151

In Table 3.9, the opening date of logistics centers and the railway transports from these centers are presented for the period of 2013-2019. As can be seen in this table, İstanbul handles the largest share in freight transportation. Still the total amount of freight handled through İstanbul has not increased much over the years.

3.1.1.4. Air Transportation. Air transportation has experienced significant growth and has become a crucial player in the global landscape. There is a constant increase in demand for air transportation of both passengers and goods on an international scale,

and new airports are being built all over the world [39]. There are three airports in İstanbul: İstanbul Atatürk, Sabiha Gökçen, and İstanbul Airports. İstanbul Airport is the newest one that has started to operate in 2018.

After the COVID-19 pandemic, a significant decrease was observed in the amount of cargo in 2020 compared to previous years. As can be observed from Table 3.10, at the end of 2021, considering the airports in İstanbul, the highest cargo traffic is seen at İstanbul Atatürk Airport. While a total of 1,647,145 tonnes of cargo is transported at all airports in İstanbul, 815,449 tonnes of it was transported from Atatürk Airport. Compared to the previous year (the year of 2020), domestic cargo traffic increases by 147.2% at İstanbul Atatürk Airport, 137% at İstanbul Airport, and 20.4% at Sabiha Gökçen Airport. International cargo traffic increases by 1.9% at İstanbul Atatürk Airport, 55.4% at İstanbul Airport, and 21.0% at Sabiha Gökçen Airport. Furthermore, the increase in total freight is 24% (from 1,331,768 to 1,647,145 tonnes) at all airports in İstanbul [48].

Table 3.10. Air cargo traffic in İstanbul(tonnes) [48].

Year		İstanbul Atatürk	İstanbul	Sabiha Gökçen
2018	Domestic	18,517		6,559
	International	1,262,669		63,852
	Total	1,281,186		70,411
2019	Domestic	8,662	15,814	8,004
	International	816,833	575,149	52,044
	Total	825,495	590,692	60,048
2020	Domestic	1,965	18,292	5,585
	International	795,179	476,310	34,438
	Total	797,144	494,602	40,022
2021	Domestic	4,856	43,345	6,722
	International	810,593	739,959	41,670
	Total	815,449	783,304	48,392
2021/2020 (%)	Domestic	147.2	137.0	20.4
	International	1.9	55.4	21.0
	Total	2.3	58.4	20.9

3.2. Problem Definition

Large cities experience various problems in terms of urban logistics. One of the main reasons is the existence of many items, that need to be transported with the following considerations in mind:

- receiving goods at the scheduled times and without damage, from the customers' point of view,
- low transportation cost and high quality, from the shippers' point of view,
- less complaints from residents (about air quality and traffic congestion) and better traffic-management, from the authorities' or administrators' point of view,
- less greenhouse gas emission, noise and traffic congestion, from the residents' point of view [5, 49].

Considering these issues, this thesis aims to deal with city logistics issues in İstanbul. Primarily, a mathematical model is developed regarding the current situation and urban freight transportation problems of İstanbul. Then, it is solved with respect to various scenarios with the help of commercial solver CPLEX. Finally, the results are evaluated, and recommendations are made.

Before investigating freight transportation in an urban network, supply and demand points must be defined. According to a classification made by IMM, there are 541 traffic zones in İstanbul which are defined according to various criteria regarding administrative boundaries, population, transport network, etc. [50]. For each of these zones, population data for the years 2012 and 2014, population projections for the years 2019, 2023 and 2040, data regarding district boundaries, employment figures and the number of schools are available. Nevertheless, incorporating each of these 541 zones individually into our model would make it too large and difficult to manage and solve. In order to simplify our problem, the number of traffic zones is decreased to 105 zones by aggregating the 541 traffic analysis zones according to several criteria such as population data, existing road network, and district boundaries.

All 105 zones have zone centers which are determined on the basis of population density and road network. They are shown in Figure 3.1. The longitude and latitude coordinates of the zone centers are given in Appendix A.2. All distance calculations are based on the coordinates of zone centers.

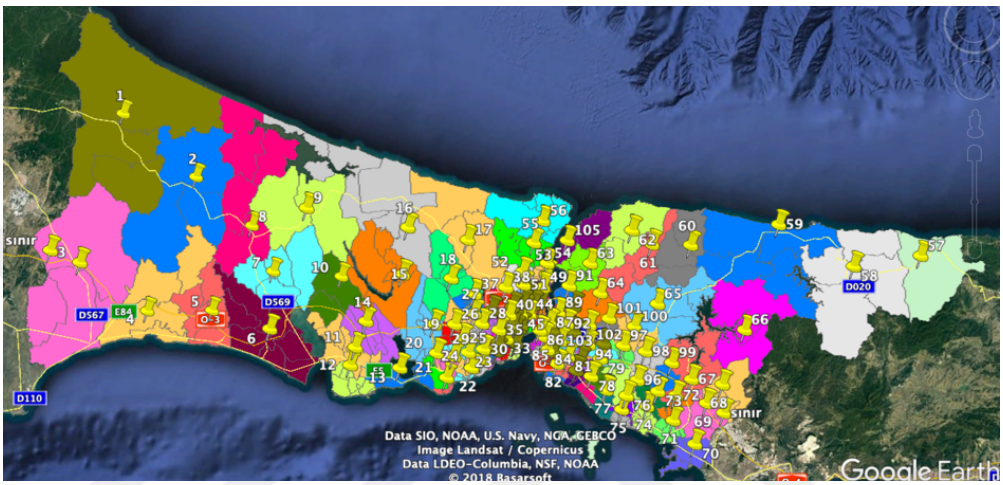

Figure 3.1. 105 Traffic zones in İstanbul that are considered in the thesis.

Each zone is assumed to have one aggregated production center (PC), one aggregated consumption center (CC), and at most one transshipment center (TC). The CCs are demand points in the logistics network and include all stores and commercial activities, such as retail stores, chain stores, hospitals and healthcare centers in that zone, where freights are ultimately delivered. On the other hand, PCs are locations where freights originate such as factories and workshops (see Table 3.11). There could also be TCs in the zones where freights are consolidated according to their destination zones.

The incoming freight from other cities is assumed to originate at "external" zones, which are fictitious supply nodes, and then channeled to TCs. Hence, all demand of CCs can be satisfied directly from PCs or through TCs. As mentioned above, there are fictitious external supply zones of İstanbul, where all product flows arriving from sources external to İstanbul are handled. These zones aim to balance the total demand with the supply and they have no real capacity.

Table 3.11. List of PCs, TCs and CCs.

Production Centers	Transshipment Centers	Consumption Centers
Factory	Vegetables and fruit market hall	Retail stores
Workshop	Flowers market hall	Chain stores
Shipyard	Water and fisheries market hall	Landfill
Mining Sites	Dried food market hall	Hospitals and healthcare centers
	Warehouses	Food and beverage
	Fuel filling plants	Accommodation
	Distributors	Fuel stations
	Sea port/Terminal/Pier	Service and maintenance
	Airport/Terminal	Excavation and debris disposal areas
	Railway stations	
	Household waste transfer center	
	Transport warehouses	
	Distribution centers	
	Cargo transfer centers	
	Repository and temporary storage	
	TIR/Truck Garage - Site	
	Customs	

In our model, as can be seen in Figure 3.2, all of the logistics activities are assumed to be among the external zone, PCs, CCs, and TCs.

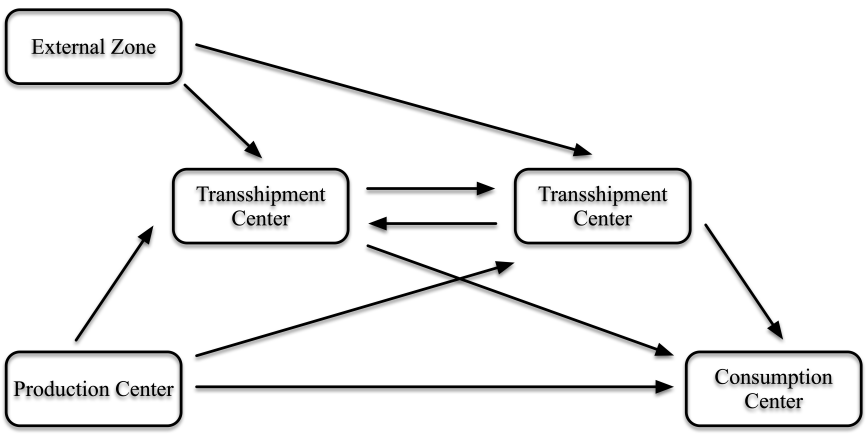

Figure 3.2. The freight flow relationship between PC, TC and CC in the model.

3.3. Parameter and System Settings of the City Logistics Model of İstanbul

For the purpose of analyzing the freight activity of the city of İstanbul, the freight flows should be investigated. The related daily supply and demand data for each one of the 105 zones and 10 product categories are obtained from IMM. Then, this data is compiled and the demand data table of CCs and the production data table of PCs are generated (see Appendix A.3 and A.4).

3.3.1. Product Categories

All product categories are grouped into 10 aggregate product classes which are designated considering freight activities of İstanbul and inspired by NACE Rev.2 classification, which is a statistical classification of economic activities in the European Union. These product categories also have similarities with those used in a joint project carried out by the Yıldız Technical University (YTU) and IMM. Table 3.13 displays these 10 product categories.

Table 3.13. Codes and descriptions of product categories.

Code	Description
1	Forestry and paper products
2	Agriculture and hunting products, fish and aquaculture, food products, beverages and tobacco
3	Metal ore, stone coal etc., stone quarry, sand and clay, crude oil, coke and natural gas products, other non-metallic mineral products
4	Textiles and textile products; leather and leather products
5	Basic pharmaceutical products and preparations, chemicals and chemical products
6	Rubber and plastic products
7	Basic metals, Fabricated metal products, Machinery and equipment etc., Motor vehicles, trailers and semi-trailers, etc.
8	Computers and electronic and optical products
9	Furniture
10	Other manufactured goods

3.3.2. Vehicle Types

In the freight flows from PCs to CCs, from PCs to TCs, and from TCs to CCs, different types of vehicle may be deployed. The only exception is the freight

transportation from the external zone to TCs, which is assumed to be realized only by heavy trucks. For the remaining flows, the following four types of vehicles are taken into account: "heavy trucks" with a load carrying capacity of 20 tonnes, "trucks" with a load carrying capacity of 10 tonnes, "panel vans" with a load carrying capacity of 3.5 tonnes and "electric vans" with a load carrying capacity of 1 tonne. These vehicles, together with their load carrying capacities and passenger car equivalent values (PCEs), which is a factor used to assess the impact of a vehicle on a highway in terms of equivalent passenger vehicles, are displayed in Table 3.14 below.

Table 3.14. Vehicle types, load capacities, and passenger car equivalent values [51–53].

Vehicle Types	Load Capacities (tonne)	PCEs
Heavy Truck	20	3.5
Truck	10	2.5
Panel van	3.5	1
Electric van	1	1

3.3.3. Time Intervals

A 24-hour period (one day) is divided into four intervals: Noon peak, noon off-peak, evening peak, evening off-peak with peak hours corresponding to high traffic congestion intervals. When creating these time intervals, traffic congestions in İstanbul and restricted hours for trucks are primarily considered. Because of traffic regulations during rush hours, i.e. at 06:00-10:00 and at 16:00-22:00, trucks are not permitted on major highways [54]. Based on these issues, our time intervals are 06:00-10:00 (noon peak), 10:00–16:00 (noon off-peak), 16:00-22:00 (evening peak) and 22:00–06:00 (evening off-peak).

3.3.4. Fuel Consumptions and Transportation Costs

Transportation costs vary with respect to not only vehicle types but also time intervals since vehicles have different average speeds in different time intervals. In

order to find the transportation cost values for different vehicle types in different time intervals, the fuel consumption rate of each vehicle at different speeds is investigated. Table 3.15 displays the fuel consumption rate (L/100 km) of each vehicle type [55–57].

Table 3.15. Fuel consumption rate of vehicles (L/100 km) [55–57].

	Heavy Truck	Truck	Panel van	Electric van
Noon peak	32.0	24.1	15.9	19.3
Noon off-peak	28.5	21.5	13.6	22.4
Evening peak	50.0	37.6	17.7	16.8
Evening off-peak	24.5	18.5	11.7	22.4

Different sources are deployed and various assumptions are made to compile the data in this table. For instance, Robinson [55] presents the fuel consumption of heavy trucks. When the speed is more than 70 km/h, the fuel consumption rate varies between 22 L and 27 L. Hence, an average fuel consumption of 24.5 L is assumed corresponding to the evening off-peak time interval. When the speed is in the 50-60 km/h range, the fuel consumption rate varies between 26 L and 31 L, implying an average fuel consumption rate of 28.5 L, which is the value deployed in the noon off-peak time interval. When the speed is within the 30-45 km/h range, the fuel consumption rate varies between 29 L and 35 L; giving rise to an average fuel consumption rate of 32.0 L considering to the noon peak time interval. Finally, when the speed is within the range of 15-25 km/h, the fuel consumption varies between 45 L and 55 L, leading to an average fuel consumption rate of 50.0 L, which is the value deployed for the evening peak time interval.

In another study [57], the fuel consumption rate for panel vans is taken as 17.7 L in the city, which can be considered as the evening peak time interval. The fuel consumption is taken as 13.6 L on the highway, which can be regarded as the noon off-peak time interval. The average of these fuel consumption rates is 15.9 L, which is assumed to correspond to the noon peak time interval. It is not possible to find out the fuel consumption rate for the evening off-peak time interval for panel vans from this

reference. Therefore, the fuel consumption rate of panel vans for the evening off-peak time interval is calculated by using the ratio of the fuel consumption rates between the noon off-peak and the evening off-peak time intervals of heavy trucks.

Similarly, the same reference [57] is utilized to estimate the fuel consumption rate for electric vans. It is 16.8 kWh/100 km in the city, which is assumed to correspond to the evening peak time interval. The fuel consumption rate is 22.4 kWh on the highway, which can be used for the noon off-peak time interval. The average of these two fuel consumption rate is 19.3 kWh/100 km, which can be considered as the rate for the noon peak time interval. The fuel consumption rate for the evening off-peak time interval of electric vans is not available in this reference. So, the fuel consumption rate for the evening off-peak time interval of electric vans is assumed as the same as the fuel consumption rate for the noon off-peak time interval (which is the one on the highway).

According to Transport Policy [56], the fuel consumption rate for trucks is 21.5 L for the noon off-peak time interval. By using the ratio of the fuel consumption rate of heavy trucks for other time intervals, the fuel consumption rate for trucks in other time intervals are estimated. Next, these fuel consumption rates are divided by the capacity of each vehicle in order to estimate the fuel consumption of a vehicle per tonne-km.

Table 3.16. Unit fuel prices [58, 59].

Diesel (Heavy Truck)	Diesel (Truck)	Gasoline	Electricity
5.27 (₺ /L)	5.27 (₺ /L)	5.92 (₺ /L)	0.45 (kWh)

Finally, after multiplying these fuel consumptions by fuel prices, the transportation cost of each vehicle in each time interval is obtained as displayed in Table 3.17.

Table 3.17. Unit transportation cost of each vehicle (₺ /tonne-km).

	Heavy Truck	Truck	Panel van	Electric van
Noon peak	0.084	0.127	0.314	0.087
Noon off-peak	0.075	0.113	0.268	0.101
Evening peak	0.132	0.198	0.349	0.076
Evening off-peak	0.065	0.097	0.231	0.101

Additionally, the average price of CO_2 per tonne is taken as 60 ₺ based on [60].

3.3.5. Greenhouse Gas Emissions

When the chemical compounds, pollutants, and gases in the air reach high concentrations, air pollution poses a significant threat to human health. Pollutants are the elements, molecules and particles introduced into the environment that cause adverse effects to humans, animals and plants. There are different types of pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), sulfur oxides (SO_x), particulate matter (PM), ground-level ozone (O_3), etc. [61, 62]. Regarding CO, it is reported that the biggest source of CO is emissions from cars, trucks, and other vehicles or machinery burning fossil fuels [62]. NO_2 is one of the gases in NO_x and constitutes the vast majority of NO_x. NO_2 in the atmosphere is mainly from burning fossil fuels. Its biggest source is emissions from vehicles and trucks, and power plants [63].

One additional harmful effect of certain gases is that they trigger global warming [64]. The gases that absorb infrared radiation and trap heat in the atmosphere (leading to global warming) are called greenhouse gases. The most important greenhouses gases are carbon dioxide (CO_2), water vapor (H_2O), and methane (CH_4) [65]. These gases contribute to the greenhouse effect that results in the warming of climate. The main greenhouse gas caused by human activities is CO_2. According to the Environmental Protection Agency (EPA), in 2020, the largest source of CO_2 emissions is transportation activities. The share of transportation is about 33% of total U.S. CO_2 emissions and 26% of total U.S. greenhouse gas emissions [66].

Since freight transportation activities deteriorate the air quality, related environmental constraints are deployed in the mathematical model. In order to control air pollution, especially in congested and crowded downtown zones, the amount of CO and NO_x are constrained since they are the main pollutants.

Electric vehicles are considered environmentally friendly since they do not directly emit neither CO_2 nor pollutants such as NO_x and CO. However, depending on their primary energy source, electric vehicles are not as green as we think. In the literature, emission for electric vehicles exist because of the utilization of energy resources to provide the electricity to charge electric vehicles. For instance, in a country which generates its electricity mostly from renewable energy resources, emissions for electric vehicles are low. However, in a country which relies heavily on coal-fired electricity generation, emissions caused by electricity generation are quite high [67]. Since NO_x and CO emissions are taken into account locally, the amount of NO_x and CO emitted from transport vehicles to the atmosphere directly is evaluated. For this reason, NO_x and CO emission rates for electric vehicles are taken as zero in the thesis study. Nevertheless, CO_2 emission is considered globally and its adverse effects on climate are aimed to minimize. Therefore, CO_2 emissions emitted from electric vehicles cannot be disregarded.

One of our aims in this thesis is to reduce the harmful effects of greenhouse gases caused by freight vehicles used in logistics activities. For this reason, the amount of emissions emitted by freight vehicles in each time interval is investigated. Hereby, the fuel consumption rates are taken into account while calculating the carbon dioxide emissions emitted by the vehicles. The amount of CO_2 emitted in the unit fuel consumption is examined and so the unit carbon dioxide value emitted by different vehicle types at different time intervals is found [68, 69]. Table 3.18 represents the unit CO_2 emission of vehicles in time intervals.

Table 3.18. Unit CO_2 emissions (g/km).

	Heavy Truck	Truck	Panel van	Electric van
Noon peak	860.6	670.7	373.3	101.9
Noon off-peak	766.4	578.2	319.3	118.3
Evening peak	1,344.6	1,011.8	415.5	88.7
Evening off-peak	658.9	497.2	274.6	118.3

In order to calculate the NO_x emissions caused by the vehicles, the average speed of the vehicles in each zone and in each time interval is calculated (see Appendix A.5). On the basis of the average speed, the NO_x emission in each time interval is estimated, which are displayed in Appendix A.6-A.8 [70].

For the purpose of calculating the CO emissions, the average speed values that vehicles reach in each time interval are predicted. Then CO emissions at these speed values in different time intervals are determined from various references [71, 72]. Table 3.19 displays CO emissions values.

Table 3.19. CO emissions (g/km) [71, 72].

	Heavy Truck	Truck	Panel van	Electric van
Noon peak	3.800	2.000	0.892	0.0
Noon off-peak	3.900	1.920	1.390	0.0
Evening peak	4.600	2.400	1.799	0.0
Evening off-peak	4.000	1.840	1.887	0.0

3.3.6. Capacities of the Transshipment Centers

The capacities of TCs are another important issue considered in this study. Based on the discussion with IMM authorities and TC blueprints, it is assumed that,

(i) there are 12 docks/slots for trucks/heavy trucks, and that three heavy trucks or five trucks can be loaded/unloaded at each dock simultaneously;

(ii) there are 84 slots for panel vans and electric vans;

(iii) the average time for loading/unloading operation for one vehicle is 40 minutes (based on [73]).

It is estimated that at each heavy truck/truck dock 3 heavy trucks or 5 trucks can be serviced simultaneously, while each loading unloading operation taking, on average, 40 minutes. Accordingly, given 3 docks for heavy trucks and 9 docks for trucks, 9 heavy trucks and 45 trucks can be serviced simultaneously. This implies that in a 4 hour time interval (the noon peak) 54 heavy trucks and 270 trucks can be serviced, while in a 6 hour time interval (the noon off-peak and evening peak) 81 heavy trucks and 405 trucks, and in a 8 hour time interval (the evening off-peak) 108 heavy trucks and 540 trucks can be serviced. Similarly, regarding panel vans and electric vans, 70 panel vans and 14 for electric vans can be serviced simultaneously. This implies that in a 4 hour time interval (the noon peak) 420 panel vans and 84 electric vans can be serviced, while in a 6 hour time interval (the noon off-peak and evening peak) 630 panel vans and 126 electric vans, and in a 8 hour time interval (the evening off-peak) 840 panel vans and 168 electric vans can be serviced. Thus, in total, 324 heavy trucks/trucks and 504 panel vans/electric vans in the noon peak time interval, 486 heavy trucks/trucks and 756 panel vans/electric vans in the noon off-peak and evening peak time intervals, and 648 heavy trucks/trucks and 1,008 panel vans/electric vans in the evening off-peak time interval can be serviced. Then, considering these capacities, the base scenario is developed and analyzed. Next, the capacity values of heavy truck/trucks and panel vans/electric vans are altered (by allocating 60% of the total capacity to heavy trucks/trucks and 40% of the total capacity to panel vans/electric vans), and a new scenario is developed. After the evaluation of this scenario, it is observed that changes in the capacities of the TCs highly influence the transportation costs and CO_2 emissions. In summary, the capacity of a TC for different vehicle types in each time interval is estimated as displayed in Table 3.20 (the numbers are rounded). The computation details can be seen at Appendix A.10.

Table 3.20. Capacities of TCs (in number of vehicles).

Default Capacity	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Truck and Heavy Truck	360	500	500	650
Panel van and Electric van	500	760	760	1,000

3.3.7. The Determination of the Distance Matrix

The issue of what distance to use between individual zone pairs (i.e. the distance matrix) is also investigated. In order to find a reliable and realistic set of distances between zone pairs, Google Direction Application Programming Interface (API) is deployed and a distance matrix is generated. The unit in this matrix is kilometers. While determining the distance between each origin-destination pair, zone centers are taken as reference points. Google Direction API suggests specific routes between locations for several modes of transportation, including transit (distance calculation via public transit routes), driving, walking, and cycling. While calculating travel distances, Google API primarily takes travel time into account. In other words, it mainly considers the length of the path (km) that a vehicle can travel in the shortest possible time [74].

With the aim of finding the realistic route and distance between zone pairs, the latitude and longitude coordinates of the zone centers are determined. In this process, road network of İstanbul and road directions are also considered. In order to obtain the shortest distances, this distance matrix is calculated on Monday at 2:00 am. While API is creating the distance matrix, it can take into account the longer distances that can be traveled in a shorter time due to the traffic. For the purpose of avoiding the effects of traffic congestion, this matrix is generated during off-traffic hours.

3.3.8. Average Traveling Distance within a Zone

As stated before, each of 105 zones has one PC, one CC and at most one TC. PCs represent all producers, and similarly, CCs represent all consumers in each zone.

On the other hand, real producers/consumers in any zone may be located at any point of that zone. Accordingly, while distributing products to consumers or collecting products from producers, vehicles need to travel from one point to another point within the zone. For this reason, the average distance traveled for distribution and collection activities in a zone need to be estimated. In other words, a vehicle, departing from a PC or arriving at a CC, needs to accomplish some intra-zone travel (traveling not only on the main artery roads but also on secondary or other roads).

In the literature, there are some studies on calculating the average distance between two random points within the same zone. According to Vaughan's study [75], there is a relationship between the area of the zone and such an average distance. Based on this study, in this thesis it is assumed that the average distance traveled in a starting (collection) zone or a terminating (distribution) zone can be approximated as follows:

$$d = c\,\sqrt{A}, \tag{3.1}$$

where;

d : Average distance traveled (km)

A : Area of the zone considered (km^2)

c : A parameter reflecting the shape of the zone.

In order to estimate the shape parameter "c" value, three perimeter points are determined in each zone. One of these perimeter points is at the closest Euclidean distance from the zone center, the other one is at the farthest Euclidean distance from the zone center, and the last one is approximately average Euclidean distance between these points from the zone center. Next, the real road network based distances between these points and zone centers are calculated *(d_1, d_2, d_3)* and the average of them is estimated *d(i)*. Finally, the "c" shape parameter value for each zone is obtained by dividing the *d(i)* by the squared root of each zone's area. The "c" shape parameter values are given in Appendix A.9.

After the estimation of the "c" shape parameter values for each zone, the average distance traveled in each starting/ending zone is determined by multiplying the square root of the zone area ($\sqrt{A}$), by the "c" value. The results are displayed in Appendix A.11.

3.3.9. Overall Distance Between Zone Pairs

To calculate the overall distance between two different zones, the distance between zone centers and the average distance traveled within the origin zone and within the destination zone are used. Firstly, the zone types are considered. A zone could be an origin zone, a destination zone or a transit zone. If the zone is an origin zone, then the trip originates at that zone. If the zone is a destination zone, the trip terminates at that zone. The zones between origin and destination zones in a trip are called transit zones. So, if a zone is origin/destination zone, then we need to make further calculations to find the distance traveled in that zone, since vehicles accomplish additonal intra zone travel. However, if a zone is a transit zone, then a vehicle passes through that zone on the main artery roads and does not spend much time (in other words, vehicles do not perform intra zone travel in the transit zones).

When a vehicle travels from a PC to a CC in different zones, then the average distance traveled in the zone of the PC (the origin zone), the distance between the centers of these two zones and the average distance traveled in the zone of the CC (the destination zone) are summed up in order to compute the overall distance between PCs and CCs. As the zones between PCs and CCs are transit zones, no compensation is done for intra zone travel in such zones.

On the other hand, when a vehicle travels from intra zone PC to a TC in different zones, then the average intra zone distance traveled in the zone of the PC and the distance between the centers of these two zones are summed up (in other words, when the destination is TC, which almost always is located on or close to main arteries, no intra zone travel is considered in the destination zone). Similarly, when a vehicle

travels from a TC to a CC in different zones, then the average intra zone distance traveled in the zone of the CC and the distance between the center of these two zones are summed up in order to find the overall distance between CCs and TCs. In other words, no intra zone travel is considered in the zone of a TC (which, in this case, is the origin zone). An example overall distance matrix is displayed in Appendix A.10.

3.3.10. The Zones on the Path

The origin-destination zone pair distance computations discussed in Section 3.3.9 do not focus on nor keep track of the actual identities of the zones transited (this information is not important for travel cost/time computations). On the other hand, actual identities of the transit zones (or equivalently the actual road segments-arcs transversed in a trip from a specific origin to a specific destination) are important for other reasons, such as the determination of travel load or pollutant emissions caused on individual road segments. Accordingly, the determination and keeping track of the individual zones traversed in each origin-destination pair becomes important.

In order to find such sequences of traversed zones (paths), a computationally independent "preprocessing" of the data is needed. The resulting paths are used to generate the key parameters of some constraints of the mathematical model. These related constraints are CO and NO_x emission constraints and also a constraint which limits the total number of vehicles in each zone. In order to identify the intermediate zones transversed while traveling from an origin zone to a destination zone; firstly, the shortest distance between each origin-destination pair is determined. As explained before, in order to determine the shortest distance between zone pairs, Google Direction API is used. It is also used to identify the path between zone pairs. Firstly, via Google Direction API, a polyline data of the path between each zone pair is generated (polyline encoding helps to store a series of coordinates as a single string). In the generation of this polyline data, "polyline.library" of Python is used. Next, each polyline is converted to a polygon by using "shapely.geometry.polygon library". Besides, the zones are represented in the format of ".kml" data. The data of the zones in ".kml" format is

then converted to a polygon data. Thus, the polygon data of all zones and the routes between each origin-destination pairs is obtained. After that, it is investigated whether there is an intersection between a zone and a route by comparing their polygon data. The intersections of these polygons indicate which zones are traversed while going from an origin zone to a destination zone [76, 77]. As this matrix is quite large, just a small part of it is displayed in Appendix A.13.

3.3.11. Deadheading Trip Rate

"Deadheading" corresponds to the part of a trip undertaken without any load (freight). Deadheading trips are taken into account especially in the flows coming to CCs (from PCs or TCs) since, in other flows (from PCs to TCs or from external zones to TCs), the possibility of vehicles returning with an empty load is very low. In the objective function, the cost of deadheading trips is included in transportation and CO_2 emission costs.

In the base scenario, the deadheading rate is assumed to be at the maximum level. According to [78], for a vehicle with 24 tonnes capacity, fuel consumption rate when fully loaded is 35 L, while it is 27.5 L when the vehicle is empty. In other words, it is assumed that an empty vehicle consumes 21% less fuel. As transportation costs are calculated based on fuel consumption, the transportation cost of an empty (deadheading) vehicle is 79% of the transportation cost of a fully loaded vehicle. Accordingly, the deadheading cost is added to the objective function in terms of transportation cost. In other words, an additional 79% of transportation cost is added to the existing transportation cost (i.e. the transportation cost is multiplied by 1.79). The deadheading trip rate is also taken into account when calculating emission amounts and costs. Considering an articulated (a type of heavy vehicle that has a pivot joint) vehicle with a capacity of 33 tonnes, the amount of CO_2 emitted from a fully loaded vehicle is 1.17 kg/km, while it is 0.71 kg/km when the vehicle is empty [78]. Accordingly, it is assumed that amount and cost of CO_2 emissions during deadheading is 61% of the amount and cost of CO_2 emissions while the vehicle is fully loaded. In

this case, the deadheading cost is added to the objective function in terms of CO_2 emission cost. In other words, an additional 61% of CO_2 emission cost is added to the existing CO_2 emission cost (i.e. in the objective function, the cost of CO_2 emissions is multiplied by 1.61).

In the model, not only the total cost associated with deadheading rates, but also the related pollutant emissions are considered. For a heavy truck with a capacity of 20-26 tonnes, the NO_x emissions emitted when the vehicle is fully loaded versus when it is empty are displayed in Table 3.21. As can be seen in the table, in the noon peak time interval, the amount of NO_x emissions is 5.68 g/km when the vehicle is fully loaded, while it is 3.96 g/km when the vehicle is empty. So, it is assumed that the amount of NO_x emissions released during the deadheading trip is 70% of the amount of NO_x emissions released when the vehicle is fully loaded. This rate is 72% in the noon off-peak and the evening peak time interval, and 76% in the evening off-peak time interval. The average of these rates is 72%. Accordingly, an additional 72% of NO_x emissions is added to the existing amount of NO_x emissions to cover deadheading (i.e. the amount of NO_x emissions is multiplied by 1.72 in the constraint that limits NO_x emissions). Similarly, since CO displays similar behaviour with NO_x, the constraint related to CO emissions is also multiplied by 1.72.

Table 3.21. NO_x emissions of a heavy truck (g/km) [70].

	Fully Loaded Vehicle	Empty Vehicle	Rate of Increase
Noon peak	5.68	3.96	70%
Noon off-peak	4.98	3.58	72%
Evening peak	7.81	5.63	72%
Evening off-peak	4.55	3.45	76%

Deadheading also influences traffic density issues. The number of vehicles arriving in a consumption zone is equal to the number of vehicles leaving that zone, since, regarding each consumption zone, the number of vehicles used in freight transportation is equal to the number of vehicles deadheading back. Thus, the total number of vehicles

is calculated by adding the number of vehicles on deadheading trips to the number of vehicles utilized during freight transportation. In other words, in the constraint dealing with density issues, when determining the total number of vehicles, the number of vehicles utilized during freight transportation is multiplied by 2.

4. A CITY LOGISTICS MODEL OF İSTANBUL

Since İstanbul is an important metropolitan city of Turkey with rapidly growing freight demand, its logistics problems deserve great attention. İstanbul experiences various logistics problems and these logistics problems can be grouped into two categories. The first group includes problems related to passenger transport activities, while the other one consists of freight transportation activities.

In this study, a linear programming (LP) model is developed in order to better understand and help improve the freight transport related logistics problems in İstanbul. The primary aim is minimization of the total cost, including transportation costs of all considered product flows and costs related to greenhouse gas emissions. There are of course many related constraints such as, transshipment capacities, demand satisfaction, balance equations, freight flows, and NO_x and CO emissions.

4.1. Assumptions

Before embarking on the mathematical model, it is essential to represent the assumptions underlying this model:

- PCs may ship their products to CCs directly or through TCs.
- All the products sent from other cities to İstanbul are assumed to originate at one of two imaginary "external zones" (an external zone behaves like a fictitious supply node). One being on the European side and the other on the Asian side. The external zone on the European side is assumed to forward all its products to the TCs on the European side. Similarly, the external zone on the Asian side is assumed to forward all its products to the TCs on the Asian side. The reason for the use of such external zones is to balance the total supply and total demand of each product category.
- The products coming from external zones are sent to TCs (they cannot be shipped directly to the CCs). Besides, only heavy trucks are allowed to transport the

products coming from external zones.

- There is one PC, one CC, and at most one TC in each zone.
- It is possible to transport more than one category of product in each vehicle type.
- The demand parameter d_k^p represents the demand for (aggregate) product category p at CC k. Only the planning of a single day is considered since the freight flow balance among the time intervals of a single day, rather than freight scheduling of a longer time period, is the primary focus.
- The travel time of products flowing from an origin zone to a destination zone is not directly considered (it is assumed to be completed in the same time interval).
- Priority of products during shipment is not considered.
- Since the travel time of an electric van on one charge is quite limited, an electric van cannot be used in freight transportation for distances longer than 30 km (otherwise multiple trips by the same vehicle in the same period wouldn't be possible).
- Trucks between PCs and TCs are fully loaded (full truck load, FTL). However, trucks deployed for direct shipment between PCs and CCs are assumed to be loaded at 75% capacity (less than truck load, LTL), due to lesser expected direct freight flow between individual zones.
- There are six TCs, three of them on the European side (in the 10^{th}, 12^{th}, and 38^{th} zones) and three of them on the Asian side (in the 64^{th}, 69^{th}, and 97^{th} zones). The reasons for choosing these zones on the European side are as follows: The 10^{th} zone is one of the periphery zones on the European side and has a suitable area for the establishment of a new TC, the 12^{th} zone is the zone where Ambarlı port is located, and the 38^{th} zone is a central zone in the inner part of the city. On the other hand, the reasons for selecting these zones on the Asian side are as follows: the 64^{th} and the 97^{th} zones are in the inner region of the city, and the 69^{th} zone is a periphery zone, where a new vegetable and fruit wholesale market hall is planned to be established.
- Shipments between two TCs are from a TC on the Asian side to a TC on the European side or from a TC on the European side to a TC on the Asian side.

4.2. Index Sets

The sets are defined as follows:

S : set of PCs, $s \in \{1, 2, \ldots, 105\}$

K : set of CCs, $k \in \{1, 2, \ldots, 105\}$

I : set of TCs on the European side, $i \in \{10, 12, 38\}$

J : set of TCs on the Asian side, $j \in \{64, 69, 97\}$

R : set of all zones in İstanbul, $r \in \{1, 2, \ldots, 105\}$

P : set of product categories, $p \in \{1, 2, \ldots, 10\}$

V : set of vehicle types, $v \in$ {heavy truck (HT), truck (TR), panel van (PV), electric van (EV)}

T : set of time intervals, $t \in$ {noon peak (06:00-10:00), noon off-peak (10:00-16:00), evening peak (16:00-22:00), evening off-peak (22:00-06:00)}.

4.3. Parameters

The parameters used in formulating this model are as follows:

c^v : load carrying capacity of vehicle type v (tonne)

d_k^p : demand for product category p at CC k (tonne)

g_i^t : maximum number of heavy trucks and trucks that may visit TC i on the European side in time interval t

$g_i^{'t}$: maximum number of panel and electric vans that may visit TC i on the European side in time interval t

g_j^t : maximum number of heavy trucks and trucks that may visit TC j on the Asian side in time interval t

$g_j^{'t}$: maximum number of panel and electric vans that may visit TC j on the Asian side in time interval t

ne^v : NO_x emission rate of vehicle type v (g/km)

ce^v : CO emission rate of vehicle type v (g/km)

oe^{vt} : CO_2 emission rate of vehicle type v in time interval t (g/km)

m_{sk} : distance between PC s and CC k (km)

m_{ik} : distance between TC i on the European side and CC k (km)

m_{jk} : distance between TC j on the Asian side and CC k (km)

m_{ij} : distance between TC i on the European side and TC j on the Asian side (km)

m_{si} : distance between PC s and TC i on the European side (km)

m_{sj} : distance between PC s and TC j on the Asian side (km)

$m_i^{'}$: distance between the border of the European side and TC i (km)

$m_j^{'}$: distance between the border of the Asian side and TC j (km)

η^{vt} : transportation cost per tonne-km of vehicle type v in time interval t (₺ /tonne-km)

f_s^p : amount of (aggregate) product category p produced in PC s (tonne)

h^v : passenger car equivalent value of vehicle type v

nb_r^t : max NO_x emission level for zone r in time interval t (g)

cb_r^t : max CO emission level for zone r in time interval t (g)

β : average (penalty) price of CO_2 per g (₺ /g)

θ_r^t : maximum allowed number of vehicles originating from and terminating at zone r in time interval t per square kilometer (vehicle/km^2)

γ_r : the surface area of zone r (km^2)

ξ : deadheading trip rate for the cost of transportation

κ : deadheading trip rate for the cost of CO_2 emissions

ε : deadheading trip rate for the amount of NO_x and CO emissions

τ : deadheading trip rate for density

a_{skr} : 1 if zone r is on the path from zone s to zone k; c parameter of zone s if the origin zone s is a PC; c parameter of zone k if the destination zone k is a CC; 0 otherwise

α_{ir} : 1 if zone r is on the path from the border of the European Side to zone i; 0 otherwise

α_{jr} : 1 if zone r is on the path from the border of the Asian Side to zone j; 0 otherwise

$\bar{a}_{sir}$: 1 if zone r is on the path from zone s to zone i; 0 otherwise.

The deadheading trip rate parameters (ξ, κ, ε, τ) are added to the cost, emissions, and density related functions in order to reflect the effects of deadheading trips (see Section 3.3.11 for further explanation). The last four parameter sets are created to determine which zones are on the path while transporting products from an origin zone to a destination zone. a_{skr} consists of "c" shape parameter in order to calculate average distance traveled easily in constraint sets (4.10) and (4.11). Since the square root of surface area is multiplied by the "c" shape parameter while calculating the average traveled distance, this "c" shape parameter is embedded in this parameter (a_{skr}). α_{ir} and α_{jr} parameters are created to find the zones on the path used by vehicles coming from the external zones. $\bar{a}_{sir}$ is created to help in finding out the number of vehicles that pass through zones in constraint set (4.12). There is a difference between the parameters a_{skr} and $\bar{a}_{sir}$ that is a_{skr} is used in a constraint set that considers average traveled distance while $\bar{a}_{sir}$ is used in a constraint set that considers the number of vehicles in a zone.

4.4. Decision Variables

The decision variables are described as follows:

Y_i^{pt} : amount of aggregate product category p transported from external zone to TC i on the European Side in time interval t (tonne)

Y_j^{pt} : amount of aggregate product category p transported from external zone to TC j on the Asian Side in time interval t (tonne)

X_{ik}^{pvt} : amount of aggregate product p transported from TC i on the European Side to CC k by vehicle type v in time interval t (tonne)

X_{jk}^{pvt} : amount of aggregate product p transported from TC j on the Asian Side to CC k by vehicle type v in time interval t (tonne)

W_{si}^{pvt} : amount of aggregate product p transported from PC s to TC i on the European Side by vehicle type v in time interval t (tonne)

W_{sj}^{pvt} : amount of aggregate product p transported from PC s to TC j on the Asian Side by vehicle type v in time interval t (tonne)

Z_{sk}^{pvt} : amount of aggregate product p transported from PC s to CC k by vehicle type

v in time interval t (tonne)

U_{ij}^{pvt} : amount of aggregate product p transported from TC i on the European Side to TC j on the Asian Side by vehicle type v in time interval t (tonne)

ϑ_{ji}^{pvt} : amount of aggregate product p transported from TC j on the Asian Side to TC i on the European Side by vehicle type v in time interval t (tonne).

4.5. Formulation of the Mathematical Model

Based on the sets, parameters, and decision variables described above; the mathematical representation of the problem is shown as follows:

$$
\begin{aligned}
min\ \Omega = \xi & \left(\sum_{p}\sum_{v}\sum_{t}\sum_{i}\sum_{k} m_{ik}\eta^{vt}X_{ik}^{pvt} + \sum_{p}\sum_{v}\sum_{t}\sum_{j}\sum_{k} m_{jk}\eta^{vt}X_{jk}^{pvt} \right) \\
& + \left(\sum_{p}\sum_{v}\sum_{t}\sum_{i}\sum_{j} m_{ij}\eta^{vt}U_{ij}^{pvt} + \sum_{p}\sum_{v}\sum_{t}\sum_{j}\sum_{i} m_{ji}\eta^{vt}\vartheta_{ji}^{pvt} \right) \\
& + \left(\sum_{p}\sum_{v}\sum_{t}\sum_{s}\sum_{i} m_{si}\eta^{vt}W_{si}^{pvt} + \sum_{p}\sum_{v}\sum_{t}\sum_{s}\sum_{j} m_{sj}\eta^{vt}W_{sj}^{pvt} \right) \\
& + \left(\sum_{p}\sum_{t}\sum_{i} m_{i}^{'}\eta^{\text{“HT”}\ t}Y_{i}^{pt} + \sum_{p}\sum_{t}\sum_{j} m_{j}^{'}\eta^{\text{“HT”}\ t}Y_{j}^{pt} \right) \\
& + \xi \left(\sum_{p}\sum_{v}\sum_{t}\sum_{s}\sum_{k} m_{sk}\eta^{vt}Z_{sk}^{pvt} + (\frac{1}{3}) \left[\sum_{p}\sum_{t}\sum_{s}\sum_{k} m_{sk}\eta^{\text{“TR”}t}\ Z_{sk}^{p\text{“TR”}t} \right] \right) \\
& + \kappa\ \beta \left(\sum_{t}\sum_{i}\sum_{k} \left\{ \sum_{v} \left[\frac{\sum_{p} X_{ik}^{pvt}}{c^{v}} oe^{vt} \right] \right\} m_{ik} \right) \\
& + \kappa\ \beta \left(\sum_{t}\sum_{j}\sum_{k} \left\{ \sum_{v} \left[\frac{\sum_{p} X_{jk}^{pvt}}{c^{v}} oe^{vt} \right] \right\} m_{jk} \right) \\
& + \beta \left(\sum_{t}\sum_{i}\sum_{j} \left\{ \sum_{v} \left[\frac{\sum_{p}(U_{ij}^{pvt} + \sum_{p}\vartheta_{ji}^{pvt})}{c^{v}} oe^{vt} \right] \right\} m_{ij} \right) \\
& + \beta \left(\sum_{s}\sum_{i}\sum_{t} \left\{ \sum_{v} \left[\frac{\sum_{p} W_{si}^{pvt}}{c^{v}} oe^{vt} \right] \right\} m_{si} \right) \\
& + \beta \left(\sum_{s}\sum_{j}\sum_{t} \left\{ \sum_{v} \left[\frac{\sum_{p} W_{sj}^{pvt}}{c^{v}} oe^{vt} \right] \right\} m_{sj} \right) \\
& + \beta \left(\sum_{i}\sum_{t} \left[\frac{\sum_{p} Y_{i}^{pt}}{c^{\text{“HT”}}} oe^{\text{“HT”}\ t} \right] m_{i}^{'} \right) \\
& + \beta \left(\sum_{j}\sum_{t} \left[\frac{\sum_{p} Y_{j}^{pt}}{c^{\text{“HT”}}} oe^{\text{“HT”}\ t} \right] m_{j}^{'} \right) \\
& + \kappa\ \beta \left(\sum_{t}\sum_{s}\sum_{k} \left\{ \sum_{v} \left[\frac{\sum_{p} Z_{sk}^{pvt}}{c^{v}} oe^{vt} \right] \right\} m_{sk} \right. \\
& \qquad \left. + \left(\frac{1}{3}\right) \sum_{t}\sum_{s}\sum_{k} \left[\frac{\sum_{p} Z_{sk}^{p\ \text{“TR”}\ t}}{c^{\text{“TR”}}} oe^{\text{“TR”}\ t} \right] m_{sk} \right),
\end{aligned}
\tag{4.1}
$$

subject to

$$\sum_{v}\sum_{t}\sum_{i} X_{ik}^{pvt} + \sum_{v}\sum_{t}\sum_{j} X_{jk}^{pvt} + \sum_{t}\sum_{v}\sum_{s} Z_{sk}^{pvt} \geq d_k^p \qquad \forall k,\ p, \tag{4.2}$$

$$\sum_{v\in\{\text{HT, TR}\}} \left(\frac{\sum_p \sum_k X_{ik}^{pvt} + \sum_p \sum_j U_{ij}^{pvt} + \sum_p \sum_j \vartheta_{ji}^{pvt} + \sum_p \sum_s W_{si}^{pvt}}{c^v} \right) + \frac{\sum_p Y_i^{pt}}{c^{\text{“}HT\text{”}}} \leq g_i^t \qquad \forall t,\ i, \tag{4.3}$$

$$\sum_{v\in\{\text{PV, EV}\}} \left(\frac{\sum_p \sum_k X_{ik}^{pvt} + \sum_p \sum_j U_{ij}^{pvt} + \sum_p \sum_j \vartheta_{ji}^{pvt} + \sum_p \sum_s W_{si}^{pvt}}{c^v} \right) \leq g_i^{'t} \qquad \forall t,\ i, \tag{4.4}$$

$$\sum_{v\in\{\text{HT, TR}\}} \left(\frac{\sum_p \sum_k X_{jk}^{pvt} + \sum_p \sum_i U_{ij}^{pvt} + \sum_p \sum_i V_{ji}^{pvt} + \sum_p \sum_s W_{sj}^{pvt}}{c^v} \right) + \frac{\sum_p Y_j^{pt}}{c^{\text{“}HT\text{”}}} \leq g_j^t \qquad \forall t,\ j, \tag{4.5}$$

$$\sum_{v\in\{\text{PV, EV}\}} \left(\frac{\sum_p \sum_k X_{jk}^{pvt} + \sum_p \sum_i U_{ij}^{pvt} + \sum_p \sum_i V_{ji}^{pvt} + \sum_p \sum_s W_{sj}^{pvt}}{c^v} \right) \leq g_j^{'t} \qquad \forall t,\ j, \tag{4.6}$$

$$\sum_{t} Y_i^{pt} + \sum_{v}\sum_{t}\sum_{s} W_{si}^{pvt} + \sum_{t}\sum_{v}\sum_{j} \vartheta_{ji}^{pvt} = \sum_{v}\sum_{t}\sum_{k} X_{ik}^{pvt} + \sum_{t}\sum_{v}\sum_{j} U_{ij}^{pvt} \qquad \forall p,\ i, \tag{4.7}$$

$$\sum_{t} Y_j^{pt} + \sum_{v}\sum_{t}\sum_{s} W_{sj}^{pvt} + \sum_{t}\sum_{v}\sum_{i} U_{ij}^{pvt} = \sum_{v}\sum_{t}\sum_{k} X_{jk}^{pvt} + \sum_{t}\sum_{v}\sum_{i} \vartheta_{ji}^{pvt} \qquad \forall p,\ j, \tag{4.8}$$

$$\sum_{t}\sum_{v}\sum_{i} W_{si}^{pvt} + \sum_{t}\sum_{v}\sum_{j} W_{sj}^{pvt} + \sum_{v}\sum_{t}\sum_{k} Z_{sk}^{pvt} \leq f_s^p \qquad \forall s,\ p, \tag{4.9}$$

$$\sum_v \left\{ \left[\frac{\sum_p \sum_s \sum_i a_{sir} W_{si}^{pvt}}{c^v} + \frac{\sum_p \sum_s \sum_j a_{sjr} W_{sj}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_k a_{ikr} X_{ik}^{pvt} \varepsilon}{c^v} \right.\right.$$
$$+ \frac{\sum_p \sum_j \sum_k a_{jkr} X_{jk}^{pvt} \varepsilon}{c^v} + \frac{\sum_p \sum_s \sum_k a_{skr} Z_{sk}^{pvt} \varepsilon}{c^v} + (\frac{1}{3}) \frac{\sum_p \sum_s \sum_k a_{skr} Z_{sk}^{p\text{“}TR\text{”}t} \varepsilon}{c^{\text{“}TR\text{”}}}$$
$$+ \frac{\sum_p \sum_i \sum_j a_{ijr} U_{ij}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_i a_{jir} \vartheta_{ji}^{pvt}}{c^v} + \frac{\sum_p \sum_i \alpha_{ir} Y_i^{pt}}{c^v}$$
$$\left.\left. + \frac{\sum_p \sum_j \alpha_{jr} Y_j^{pt}}{c^v} \right] ne^v \sqrt{\gamma_r} \right\} \leq nb_{rt} \qquad \forall r,\ t, \tag{4.10}$$

$$\sum_v \left[\left(\frac{\sum_p \sum_s \sum_i a_{sir} W_{si}^{pvt}}{c^v} + \frac{\sum_p \sum_s \sum_j a_{sjr} W_{sj}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_k a_{ikr} X_{ik}^{pvt} \varepsilon}{c^v} \right.\right.$$
$$+ \frac{\sum_p \sum_j \sum_k a_{jkr} X_{jk}^{pvt} \varepsilon}{c^v} + \frac{\sum_p \sum_s \sum_k a_{skr} Z_{sk}^{pvt} \varepsilon}{c^v} + (\frac{1}{3}) \frac{\sum_p \sum_s \sum_k a_{skr} Z_{sk}^{p\text{“}TR\text{”}t} \varepsilon}{c^{\text{“}TR\text{”}}}$$
$$+ \frac{\sum_p \sum_i \sum_j a_{ijr} U_{ij}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_i a_{jir} \vartheta_{ji}^{pvt}}{c^v} + \frac{\sum_p \sum_i \alpha_{ir} Y_i^{pt}}{c^v}$$
$$\left.\left. + \frac{\sum_p \sum_j \alpha_{jr} Y_j^{pt}}{c^v} \right) ce^v \sqrt{\gamma_r} \right] \leq cb_{rt} \qquad \forall r,\ t, \tag{4.11}$$

$$\sum_v \left(\frac{\sum_p \sum_s \sum_i \bar{a}_{sir} h^v W_{si}^{pvt}}{c^v} + \frac{\sum_p \sum_s \sum_j \bar{a}_{sjr} h^v W_{sj}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_k \bar{a}_{ikr} h^v X_{ik}^{pvt} \tau}{c^v} \right.$$
$$+ \frac{\sum_p \sum_j \sum_k \bar{a}_{jkr} h^v X_{jk}^{pvt} \tau}{c^v} + \frac{\sum_p \sum_s \sum_k \bar{a}_{skr} h^v Z_{sk}^{pvt} \tau}{c^v} + (\frac{1}{3}) \frac{\sum_p \sum_s \sum_k \bar{a}_{skr} h^v Z_{sk}^{p\text{“}TR\text{”}t} \tau}{c^{\text{“}TR\text{”}}}$$
$$+ \frac{\sum_p \sum_i \sum_j \bar{a}_{ijr} h^v U_{ij}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_i \bar{a}_{jir} h^v \vartheta_{ji}^{pvt}}{c^v} + \frac{\sum_p \sum_i \alpha_{ir} h^v Y_i^{pt}}{c^v}$$
$$\left. + \frac{\sum_p \sum_j \alpha_{jr} h^v Y_j^{pt}}{c^v} \right) / \gamma_r \ \leq \theta_r^t \qquad \forall r,\ t, \tag{4.12}$$

$$\frac{\sum_p \sum_i \sum_k X_{ik}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_k X_{jk}^{pvt}}{c^v} + \frac{\sum_p \sum_s \sum_k Z_{sk}^{pvt}}{c^v} + \frac{\sum_p \sum_s \sum_j W_{sj}^{pvt}}{c^v}$$
$$+ \frac{\sum_p \sum_s \sum_i W_{si}^{pvt}}{c^v} + \frac{\sum_p \sum_i \sum_j U_{ij}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_i \vartheta_{ji}^{pvt}}{c^v} \leq 50,000 \qquad \forall t,\ v = EV, \tag{4.13}$$

$$\sum_p \sum_v \sum_t Z_{ss}^{pvt} \leq \sum_p \sum_v \sum_t \sum_k 0.04\ Z_{sk}^{pvt} \qquad \forall s, \tag{4.14}$$

$$\sum_t \sum_v W_{ii}^{pvt} + \sum_t \sum_v X_{ii}^{pvt} \leq 0.3 \left(\sum_v \sum_t \sum_k X_{ik}^{pvt} + \sum_v \sum_t \sum_s W_{si}^{pvt} \right) \qquad \forall i,\ p, \tag{4.15}$$

$$\sum_t \sum_v W_{jj}^{pvt} + \sum_t \sum_v X_{jj}^{pvt} \leq 0.3 \left(\sum_v \sum_t \sum_k X_{jk}^{pvt} + \sum_v \sum_t \sum_s W_{sj}^{pvt} \right) \qquad \forall j,\ p, \tag{4.16}$$

$$m_{sk} Z_{sk}^{p\text{“}EV\text{”}t} = 0 \qquad \forall s,k : m_{sk} \geq 30, \tag{4.17}$$

$$m_{ik} X_{ik}^{p\text{“}EV\text{”}t} = 0 \qquad \forall i,k : m_{ik} \geq 30, \tag{4.18}$$

$$m_{jk} X_{jk}^{p\text{“}EV\text{”}t} = 0 \qquad \forall j,k : m_{jk} \geq 30, \tag{4.19}$$

$$m_{si} W_{si}^{p\text{“}EV\text{”}t} = 0 \qquad \forall s,i : m_{si} \geq 30, \tag{4.20}$$

$$m_{sj} W_{sj}^{p\text{“}EV\text{”}t} = 0 \qquad \forall s,j : m_{sj} \geq 30, \tag{4.21}$$

$$X_{ik}^{p\text{“}HT\text{”}t} = 0 \qquad \forall p,t,i,k, \tag{4.22}$$

$$X_{jk}^{p\text{“}HT\text{”}t} = 0 \qquad \forall p,t,j,k, \tag{4.23}$$

$$W_{si}^{p\text{“}HT\text{”}t} = 0 \qquad \forall p,t,s,i, \tag{4.24}$$

$$W_{sj}^{p\text{“}HT\text{”}t} = 0 \qquad \forall p,t,s,j, \tag{4.25}$$

$$Z_{sk}^{p\text{“}HT\text{”}t} = 0 \qquad \forall p,t,s,k, \tag{4.26}$$

$$U_{ij}^{pvt} = 0 \qquad \forall p,t,i,j;\ v = \{PV,\ EV\}, \tag{4.27}$$

$$\vartheta_{ji}^{pvt} = 0 \qquad \forall p,t,j,i;\ v = \{PV,\ EV\}, \tag{4.28}$$

$$Y_i^{pt} \geq 0 \qquad \forall p,\ i,\ t, \tag{4.29}$$

$$Y_j^{pt} \geq 0 \qquad \forall p,\ j,\ t, \tag{4.30}$$

$$X_{ik}^{pvt} \geq 0 \qquad \forall p,\ v,\ t,\ i,\ k, \tag{4.31}$$

$$X_{jk}^{pvt} \geq 0 \qquad \forall p,\ v,\ t,\ j,\ k, \tag{4.32}$$

$$W_{si}^{pvt} \geq 0 \qquad \forall p,\ v,\ t,\ s,\ i, \tag{4.33}$$

$$W_{sj}^{pvt} \geq 0 \qquad \forall p,\ v,\ t,\ s,\ j, \tag{4.34}$$

$$Z_{sk}^{pvt} \geq 0 \qquad \forall p,\ v,\ t,\ s,\ k, \tag{4.35}$$

$$\vartheta_{ji}^{pvt} \geq 0 \qquad \forall p,\ v,\ t,\ i,\ j, \tag{4.36}$$

$$U_{ij}^{pvt} \geq 0 \qquad \forall p,\ v,\ t,\ i,\ j. \tag{4.37}$$

The objective function (4.1) minimizes the total cost related to freight transportation and related CO_2 emissions. It includes the transportation and CO_2 emission costs due to the travel, i) from TCs to CCs, ii) from TCs to TCs, iii) from PCs to TCs, iv) from external zones to TCs, and v) from PCs to CCs. Since trucks going from PCs to CCs are assumed to be 75% loaded, a cost adjustment factor of 1/3 is used.

Constraint set (4.2) requires that the total amount of products sent from TCs and PCs must be greater than or equal to each CC's demand for each product category.

Constraint sets (4.3)-(4.6) ensure that the number of vehicles arriving at a TC from PCs, external zones and other TCs and vehicles departing from that TC to CCs and to other TCs should be less than the capacity of that TC in each time interval. These constraint sets are written separately for trucks and heavy trucks, and for panel vans and electric vans. This is because one set of docks in a TC can serve both heavy trucks and trucks, accordingly, the TC capacity for heavy trucks and trucks is aggregated (see constraint sets (4.3) and (4.5)). Similarly, the other set of docks in a TC serve both panel vans and electric vans. Accordingly, the TC capacity for panel vans and electric vans is also aggregated (see constraint sets (4.4) and (4.6)).

Constraint sets (4.7) and (4.8) require that incoming amount of each product category to each TC is equal to the outgoing amount of each product category. In other words, constraint set (4.7) guarantees that the amount of each product category transported from external zones, PCs and TCs on the Asian side to a TC on the European side is equal to the amount of each product category transported from that

TC on the European side to all CCs and TCs on the Asian side. Similarly, constraint set (4.8) guarantees that the amount of each product category transported from external zones, PCs and TCs on the European side to a TC on the Asian side is equal to the amount of each product category transported from that TC on the Asian side to all CCs and TCs on the European side.

Constraint set (4.9) makes sure that the amount of each product category sent from a PC to TCs and CCs is less than or equal to the amount of each product category produced in that PC.

If a vehicle originates from or terminates at, or passes through a zone, then it emits some emissions in that zone. In order to calculate the total emissions in a zone, we need to find how many vehicles are traveling in that zone. In order to calculate the number of vehicles involved, the amount of transported products is divided by vehicle capacity. For example, if we want to transport 100 tonnes of products, we need five heavy trucks with the capacity of 20 tonnes. The amount of that emission is also proportional to the average traveling distance in that zone. Therefore, constraint sets (4.10) and (4.11) firstly compute the number of vehicles for each vehicle category v originating from, terminating at, and transversing through that zone. We also need to evaluate the average distance traveled in a zone. Therefore, "c shape parameter" is considered in the calculations (as explained in Section 3.3.8). Then the square root of the area in that zone is multiplied by the emission rate of each vehicle. The resulting constraints ensure that total NO_x and CO emissions released from vehicles that are originating from and terminating at and transversing through each zone must be lower than the predefined emission level. While writing this constraint, we were inspired by the study of Ramachandra and Shwetmala [79].

Besides the limitations on pollutant emissions, in order to reduce potential traffic density, the number of vehicles in each zone, for each time interval is also bounded. This is accomplished through constraint set (4.12), which ensures that, for each time interval, total number of vehicles originating from, terminating at and transversing

through zone i (multiplying by their respective PCEs) per covered area of that zone must be less than the maximum allowed number of vehicles in that zone.

According to Turkish Statistical Institute, there are 125,344 electric vehicles are registered to the traffic in Turkey, as of end of July 2022 [80]. In the model a limit was introduced on the number of electric vehicles. This is accomplished through constraint set (4.13), which ensures that the number of electric van trips in each time interval cannot be greater than 50,000 (since it is predicted that the number of electric vans in all time intervals cannot exceed 200,000).

Since the objective is cost minimization, it is only natural for the optimization process to prefer the satisfaction of the demand of a zone for a product category from that zone's own production. On the other hand, since the considered product categories are "aggregate products", that would not be realistic. A typical example of this product aggregation problem, is food and beverages, which are collected under the same product category (as can be seen in Table 3.13). When a zone demands only beverage, its demand may be satisfied by food instead of a beverage. This means that, although the demand of the zone cannot be satisfied in real life, the model seems be able to meet the demand due to the product aggregation. Therefore, such "intra zone" demand satisfaction needs to be severely bounded. In order to tackle this issue, the real data of İstanbul's logistics sector is consulted, from whose analysis it is conjectured that, on average, 4% of the products stay in the same zone, while the rest is distributed to other zones. Accordingly, constraint set (4.14) is set up to ensure that, for any specific product category, the total amount produced and consumed in the same zone cannot exceed 4% of the total production of that product category in that zone. In other words, regarding any specific product category, PCs should ship at least 96% of their production to other zones or to TCs.

Another complication caused by "product aggregation" is related to flows into and out of TCs. For any specific aggregate product category, most of the flow incoming to and outgoing from a TC may be from the same zone where that TC is located. This

could be problematic, since that flow may refer to the satisfaction of the demand of one product (in the related aggregate product category) by the supply of another product (in the same aggregate product category). As a result, a TC may seem to be able to meet the demand of CCs, although the demand cannot be satisfied in the real case. In order to avoid (or reduce) such situations, constraint sets (4.15) and (4.16) are developed. They ensure that, for any specific product category, inflow to and outflow from a TC regarding the same zone should be less than 30% of all inflow to and outflow from that TC to all zones. The 30% upper bound on all such flows is conjectured based on a prior analysis of the real data of İstanbul's logistics sector.

As explained in Section 4.1, the range of electric vans is assumed to be 30 km. Accordingly, constraint set (4.17) ensures that electric vans can only be utilized between PCs and CCs that are at most 30 km apart; while constraint sets (4.18) and (4.19) guarantee that electric vans can only be utilized between TCs and CCs that are at most 30 km apart. In a similar fashion, constraint sets (4.20) and (4.21) limit the deployment of electric vans between PCs and TCs to those pairs that are at most 30 km apart.

Traffic regulations should be considered regarding whether a vehicle type is allowed to enter a zone in time interval t. Accordingly, constraint sets (4.22) and (4.23) ensure that heavy trucks cannot be used to transport any product between TCs and CCs. Similarly, constraint sets (4.24) and (4.25) guarantee that heavy trucks cannot be used to transport any product between TCs and PCs. Additionally, constraint set (4.26) ensures that heavy trucks cannot be used to directly transport any product between PCs and CCs. Constraint sets (4.27) and (4.28) make sure that panel vans and electric vans cannot be used to transport any product between TCs.

Finally, constraint sets (4.29)-(4.37) are the non-negativity constraints.

5. RESULTS OF THE CITY LOGISTICS MODEL

The model described in Chapter 4 is applied to the logistics system of İstanbul based on the data compiled through the IMM. Then, the resulting 1,764,000 variable and more than 65,000 constraint linear programming problem is solved via the GAMS (23.6.5) modeler and CPLEX (12.2.0.1) solver to form the base scenario. Then, various alternative scenarios are generated by changing some of the key assumptions and the related parameters and constraints.

This chapter consists of two subsections. The first subsection presents the base scenario and its results. The second subsection describes the alternative scenarios and compare the obtained results.

5.1. The Base Scenario

The base scenario is the scenario in which the proposed model is solved using the compiled data and the assumed parameter and system settings as explained in Section 3.3 and Chapter 4. In this section, the obtained results of the base scenario are presented and analyzed.

The transportation cost is 3,795,724 ₺ , the CO_2 emission cost is 134,158 ₺ , and the total cost is calculated as 3,929,882 ₺ . Accordingly, the transportation cost is 97% and the CO_2 emission cost is 3% of the total cost. The results are displayed in Tables 5.1-5.5. In these tables, the distribution of vehicle types according to time intervals, the freight flow with respect to each vehicle type and time interval, the freight flow activities of the TCs, and the capacity utilization rates of the TCs (in terms of number of vehicles) are presented. Table 5.1 provides detailed information about the total number of vehicles.

Table 5.1. The total number of vehicles in all zones in each time interval in the base scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	520	926		409	1,855
Truck	2,244	3,589	1,597	85,608	93,038
Panel van				660	660
Electric van	50,000	50,000	50,000	50,000	200,000

As can be inferred from Table 5.1, since electric vans are highly preferred, their deployment reaches the maximum limit of 50,000 in all periods. Panel van usage is very low. Non-electric vehicles cause serious air pollution by emitting environmentally harmful gases such as NO_x and CO. The amounts of NO_x and CO emitted from these vehicles is 8,014,673 g and 6,948,190 g respectively in all periods.

Table 5.2 illustrates the freight flow of each vehicle type, in each time interval. The overall freight flow consists of the following flow classes:

- from TCs on the European Side to CCs (X_{ik}^{pvt})
- from TCs on the Asian Side to CCs (X_{jk}^{pvt})
- from PCs to TCs on the European Side (W_{si}^{pvt})
- from PCs to TCs on the Asian Side (W_{sj}^{pvt})
- from PCs to CCs (Z_{sk}^{pvt})
- from TCs on the European side to TCs on the Asian side (U_{ij}^{pvt})
- from TCs on the Asian side to TCs on the European side (ϑ_{ji}^{pvt})
- from the external zone to TCs on the European side (Y_i^{pt})
- from the external zone to TCs on the Asian side (Y_j^{pt}).

As can be seen in Table 5.2, the majority of products are transported during the evening off-peak time interval (73.9%), while the least amount is transported during in the evening peak time interval (6.8%), 8.5% of the products are distributed in the noon peak time interval, and the remaining 10.8% is distributed in the noon off-peak time interval. This result is primarily due to the low unit operating cost of vehicles (except for electric vans) in the evening off-peak time interval. Regarding freight flow

classes, trucks, panel vans and electric vans are used in incoming/outgoing operations to/from TCs, while most of the electric vans are used in direct shipments from PCs to CCs. The great majority of flows are direct shipments from PCs to CCs (94.0%) for products outgoing from PCs. While a total of 51,027 tonnes of products come from PCs to TCs, a total of 36,187 tonnes of products come from the external zones to the TCs (see Table 5.2). 98% of the products coming from the external zones are shipped through the TCs on the Asian side and 2% of them are shipped through the TCs on the European side.

Table 5.2. Freight flow of each vehicle type, in each time interval in the base scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	7,616	8,268	2,863	20,080	38,827	41,193
	Panel van						
	Electric van	340	866	500	660	2,366	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	465	8,638	7,875	25,883	42,861	46,021
	Panel van						
	Electric van	340	1,000	500	1,320	3,160	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	7,984	14,078	5,225	9,346	36,634	39,737
	Panel van				2,310	2,310	
	Electric van		134		660	794	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	6,379	4,906	4		11,289	11,289
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				600,575	600,575	794,255
	Panel van						
	Electric van	49,320	48,000	49,000	47,360	193,680	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		908			908	908
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				547	547	547
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	10,400	17,605		7,635	35,640	35,640
Total		82,844	104,403	65,967	716,376	969,591	
Rate		8.5%	10.8%	6.8%	73.9%	100%	

Table 5.3. Total freight flow activities outgoing from PCs to CCs and TCs in the base scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	794,255	94.0%			
From PCs to TCs on the European Side (W_{si}^{pvt})	39,737	4.7%	Zone 10	Zone 12	Zone 38
			11,551	15,106	13,081
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,289	1.3%	Zone 64	Zone 69	Zone 97
			4,073		7,216
Total	845,281				

The active usage rates of TCs and the amount of freight arrivals and departures at each TC are reported in Tables 5.3 and 5.4. The TC usage for incoming products from PCs is 6%, and for outgoing products to CCs is 9.9%. The difference is mainly due to the incoming flow to TCs from external nodes (which, by system settings, cannot be sent directly to the CCs).

Table 5.4. Total freight flow activities incoming to CCs from PCs and TCs in the base scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	794,255	90.1%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	41,193	4.7%	Zone 10	Zone 12	Zone 38
			12,098	15,106	13,989
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	46,021	5.2%	Zone 64	Zone 69	Zone 97
			10,800	20,583	14,637
Total	881,469				

Table 5.5. Capacities and deployments of the TCs in each time interval for different vehicle types in the base scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	164	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	6	436	366		618	170
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity		340			340	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	500	500	500		500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity					500	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	660	660		660	660

Table 5.5 shows the current capacities of the TCs and how much of these capacities are occupied in each time interval. Regarding heavy trucks and trucks; all TCs are used at full capacity in the noon off-peak and evening off-peak time intervals. In the noon peak time interval, except for the one in the 64^{th} zone, all TCs are fully utilized. In the evening peak time interval, all TCs, except for the one in the 64^{th} zone, are used but not deployed at full capacity.

Regarding panel vans and electric vans; in the noon peak time interval, the TCs in the 12^{th} and the 69^{th} zones are fully utilized. All the others are fully utilized in the noon off-peak time interval except for the TC in the 64^{th} zone. In the evening peak time interval, only the TCs in the 69^{th} zone is fully utilized. In the evening off-peak time interval, except for the TC in the 64^{th} zone, all other TCs are deployed at full capacity.

In summary, in the base scenario,

(i) heavy reliance on electric vehicles;

(ii) low deployment of panel vans;

(iii) very low usage of TCs;

(iv) heavy activity in evening off-peak time intervals;

(v) very limited/insufficent truck/heavy truck capacity in most TCs (despite their low usage) are observed.

5.2. Alternative Scenarios

In order to explore the possible outcomes of various "what-if" queries, different scenarios are developed by changing some key assumptions and the related parameters and system settings (such as cost and capacity parameters, boundaries (i.e. for the flows of freights and the number of electric vans), and rates (i.e. different truck utilization rates), excluding some constraints or including some new constraints. These alternative scenarios are divided into seven groups, which are, (i) TC capacity scenarios, (ii) truck utilization rate scenarios, (iii) product flow based scenarios, (iv) vehicle based scenarios, (v) deadheading scenarios, (vi) emission scenarios, and (vii) combination scenarios. The details and comparative results of these scenarios are explained in the following subsections.

5.2.1. Transshipment Center Capacity Scenarios

The results of the base scenario highlight the minimal usage of the TCs (while frequently reaching their maximum capacities) during the shipment of the products to CCs. The alternative scenarios in this subsection are developed with the aim of enhancing the TC usage rate. Accordingly, in this set of scenarios, the capacities of all TCs are increased by 50%, 100% and 200% as listed below:

(i) 50% increase in TC capacities (TC50)

(ii) 100% increase in TC capacities (TC100)

(iii) 200% increase in TC capacities (TC200).

5.2.1.1. 50% Increase in Transshipment Center Capacities (TC50). In this scenario, the capacities of all TCs are increased by 50%. So, the capacities of the TCs are as follows:

Table 5.6. Capacities of TCs in the TC50 scenario (in number of vehicles).

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Truck and Heavy Truck	780	1,140	1,140	1,485
Panel van and Electric van	510	750	750	990

The obtained results of the TC50 scenario are presented in Tables 5.7-5.13. The transportation cost is 3,729,637 ₺ , the CO_2 emission cost is 132,455 ₺ and the total cost is calculated as 3,862,091 ₺ . As can be seen in Table 5.7, both the transportation and CO_2 emission costs (and accordingly the total cost) decrease when the capacities of TCs are enlarged. Compared to the base scenario, the transportation cost decreases 2%, the CO_2 emission cost decreases 1%, and accordingly, the total cost decreases 2%. It is less costly to distribute products to CCs through TCs, instead of sending them directly from PCs to CCs, primarily because trucks usually cannot be fully loaded in direct shipments.

Table 5.7. The transportation, CO_2 emission, and total costs in the base and TC50 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
TC50	3,729,637	132,455	3,862,091

Table 5.8. The total number of vehicles in all zones in each time interval in the TC50 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	780	1,024		539	2,343
Truck	3,120	5,698	1,097	84,198	94,113
Panel van				1,319	1,319
Electric van	50,000	50,000	50,000	50,000	200,000

The total number of vehicles in all zones, in each time interval is presented in Table 5.8 for the TC50 scenario. Additionally, Table 5.9 is created to compare the total number of vehicles in the base and TC50 scenarios. Compared to the base scenario, there is a 1% increase in the total number of vehicles (2,222 vehicles). The number of heavy trucks increases 26% (488 heavy trucks) and the number of trucks slightly increases 1% (1,075 trucks). Moreover, the number of panel vans increases almost 100% (659 panel vans) and the number of electric vans is still at the upper bound value of 200,000 which are mostly used in direct shipments from PCs to CCs.

As the capacities of TCs increase, more vehicles can visit them. Since vehicles are used both on the way to the TC and returning from the TC (rather than the single trip associated with a direct shipment), this two-tiered transportation leads to more vehicle deployment but lesser costs.

Table 5.9. The total number of vehicles in all zones in the base and TC50 scenarios.

	Base	TC50
Heavy Truck	1,855	2,343
Truck	93,038	94,113
Panel van	660	1,319
Electric van	200,000	200,000
Total	295,553	297,775

On the other hand, the amount of NO_x emissions from non-electric vehicles is 7,684,750 g, and it decreases 4% compared to the base scenario. Similarly, the amount of CO emissions from these vehicles decreases 6% and reaches to 6,561,353 g. As the capacities of TCs are increased, the numbers of trucks and heavy trucks rise, too. The total amounts of NO_x and CO decline in spite of the increase in the number of vehicles. The reason for this may be related to the decrease in the total distance traveled due to shorter trips per vehicle.

Table 5.10. Freight flow of each vehicle type, in each time interval in the TC50 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	16,226	7,513		30,625	54,364	56,259
	Panel van						
	Electric van	510		750	635	1,895	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck		9,880	8,803	39,691	58,374	62,944
	Panel van				1,131	1,131	
	Electric van	510	1,189	750	990	3,439	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	7,174	25,505	2,167	13,391	48,237	52,827
	Panel van				3,485	3,485	
	Electric van		750		355	1,105	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	7,800	14,084			21,884	21,884
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				568,705	568,705	762,266
	Panel van						
	Electric van	48,980	48,061	48,500	48,020	193,561	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		2,365			2,365	2,365
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				1,068	1,068	1,068
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	15,600	18,107		9,718	43,425	43,425
Total		96,800	12,7454	60,970	717,814	1,003,038	
Rate		9.7%	12.7%	6.0%	71.6%	100%	

The freight flow of each vehicle type in each time interval in the TC50 scenario is displayed in Table 5.10. When the freight flows are examined, it can be seen that the majority of flows are still direct shipments from PCs to CCs although their amount decreases 4% (31,989 tonnes) compared to the base scenario. The amount of products transported between two TCs increases from 908 tonnes to 2,365 tonnes and the external zone shipments also increase 23% (reaching to 44,493). The expansion in the capacities of the TCs leads to an increase in the utilization of the TCs. This also leads to an increase in the amount of products coming from the external zones because these products firstly come to TCs, and then they are shipped to CCs from there. As in the base scenario, the most intense time of the freight flow is the evening

off-peak time interval (71.6%). The reason for that is the vast majority of the products are distributed by trucks, and the cheapest time interval to transport by trucks is the evening off-peak. The least intense time is the evening peak time interval (6.0%).

Table 5.11. Total freight flow activities outgoing from PCs to CCs and TCs in the TC50 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	762,266	91.1%			
From PCs to TCs on the European Side (W_{si}^{pvt})	52,827	6.3%	Zone 10	Zone 12	Zone 38
			17,094	20,471	15,261
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	21,884	2.6%	Zone 64	Zone 69	Zone 97
			6,428		15,456
Total	836,977				

Table 5.12. Total freight flow activities incoming to CCs from PCs and TCs in the TC50 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	762,266	86.5%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	56,259	6.4%	Zone 10	Zone 12	Zone 38
			18,162	20,471	17,626
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	62,944	7.1%	Zone 64	Zone 69	Zone 97
			13,781	30,569	18,594
Total	881,469				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are presented in Table 5.11 and 5.12. Compared to the base scenario, the TC usage for incoming products from PCs increases from 6% to 8.9% (see Table 5.3 and

5.11) and for outgoing products to the CCs increases from 9.9% to 13.5% (see Table 5.4 and 5.12) primarily because of the expanded capacities of TCs. The difference is mainly due to the incoming flow to TCs from the external zones. Regarding incoming products from PCs, the TC in zone 69 is still unused (as can be seen in Table 5.11).

Table 5.13. Capacities and deployments of the TCs in each time interval for different vehicle types in the TC50 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	780	780	780	780	780	780
	Noon Peak Occupied Capacity	780	780	780		780	780
	Noon Off-peak Capacity	1140	1140	1140	1140	1140	1140
	Noon Off-peak Occupied Capacity	1140	1140	1140	1140	1140	1140
	Evening Peak Capacity	1140	1140	1140	1140	1140	1140
	Evening Peak Occupied Capacity		217			880	
	Evening Off-peak Capacity	1485	1485	1485	1485	1485	1485
	Evening Off-peak Occupied Capacity	1485	1485	1485	1485	1485	1485
Panel vans and Electric vans	Noon Peak Capacity	510	510	510	510	510	510
	Noon Peak Occupied Capacity		510			510	
	Noon Off-peak Capacity	750	750	750	750	750	750
	Noon Off-peak Occupied Capacity	750				750	439
	Evening Peak Capacity	750	750	750	750	750	750
	Evening Peak Occupied Capacity		750			750	
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	6		990	323

Table 5.13 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the TC50 scenario. Compared to the base scenario, although the number of TCs utilized is varied in the TC50 scenario, more vehicles use the TCs. The reason for that is the capacities of TCs are larger than those in the base scenario. Regarding heavy trucks and trucks; in the noon peak time interval, except for the TC in the zone 64, all TCs are fully utilized. As for the base scenario, all TCs are deployed, and except for the one in the 64^{th} zone, all the others are fully utilized. In the TC50 scenario, in the noon off-peak and evening off-peak time intervals, all TCs are fully utilized as in the base scenario. In the evening peak time interval, the TCs in the 12^{th} and the 69^{th} zones are used but not fully utilized in the TC50 scenario. However, except for the TC in the 64^{th} zone, all the others are used in the base scenario.

Regarding panel vans and electric vans in the TC50 scenario, in the noon peak time interval, the TCs in the 12^{th} and the 69^{th} zones are deployed at full capacity as in the base scenario. In the noon off-peak time interval, the TCs in the 10^{th}, the 69^{th}, and the 97^{th} zones are utilized in the TC50 scenario, with the 10^{th} and the 69^{th} reaching full capacity. As for the base scenario, except for the one in the 64^{th} zone, all TCs are deployed at full capacity. In the evening peak time interval, in the TC50 scenario, the TCs in the 12^{th} and the 69^{th} zones are fully utilized. In the base scenario, only the TC in the 69^{th} zone is fully utilized. In the evening off-peak time interval, in the TC50 scenario, the TCs in the 10^{th}, the 12^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones are utilized, with the 10^{th}, the 12^{th}, and the 69^{th} reaching full capacity. As for the base scenario, except for the one in the 64^{th} zone, all the others are fully utilized.

5.2.1.2. 100% Increase in Transshipment Center Capacities (TC100). In this scenario, the capacities of all TCs are increased by 100%. So, the capacities of the TCs are as follows:

Table 5.14. Capacities of TCs in the TC100 scenario (in number of vehicles).

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Truck and Heavy Truck	1,040	1,520	1,520	1,980
Panel van and Electric van	680	1,000	1,000	1,320

The obtained results of the TC100 scenario are presented in Tables 5.15-5.21. The transportation cost is 3,671,340 ₺ , the CO_2 emission cost is 130,710 ₺ , and the total cost is calculated as 3,802,051 ₺ . As can be seen in Table 5.15, both the cost of transportation and CO_2 emissions (and accordingly the total cost) are lower, compared to the results of the base and TC50 scenarios. The transportation cost decreases 3% compared to the base scenario and 2% compared to the TC50 scenario. The CO_2 emission cost decreases 3% compared to the base scenario and 1% compared to the TC50 scenario. Accordingly, the total cost is 3% lower than that of the base scenario and 2% lower than that of the TC50 scenario. As discussed before, primarily because of the assumption that trucks usually cannot be fully loaded in direct shipments, generally,

it is less costly to transport products through TCs, rather than sending them directly from PCs to CCs. Accordingly, higher TC capacities enable their higher usage.

Table 5.15. The transportation, CO_2 emission, and total costs in the base, TC50, and TC100 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
TC50	3,729,637	132,455	3,862,091
TC100	3,671,340	130,710	3,802,051

Table 5.16. The total number of vehicles in all zones in each time interval in the TC100 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	697	1,509		731	2,937
Truck	4,503	7,331	552	82,753	95,139
Panel van				1,192	1,192
Electric van	50,000	50,000	50,000	50,000	200,000

The total number of vehicles in all zones, in each time interval in the TC100 scenario is displayed in Table 5.16. Additionally, Table 5.17 provides for the comparison of the number of vehicles in the base, TC50, and TC100 scenarios. As can be seen, the number of heavy trucks increases 58% (1,083 heavy trucks) compared to the base scenario and 25% (594 heavy trucks) compared to the TC50 scenario. The number of trucks also increases 2% (2,101 trucks) compared to the base scenario and 1% (1,026 trucks) compared to the TC50 scenario. Furthermore, the number of panel vans increases 81% (532 panel vans) compared to the base scenario and decreases 10% (126 panel vans) compared to the TC50 scenario. Because of the upper bound, the number of electric vans is at the same value of 200,000. As the capacities of TCs increase, more vehicles can use TCs. Since vehicles are used both on the way (inbound) to TCs and outbound from TCs (rather than the single trip associated with a direct shipment), this two-tiered transportation leads to more vehicle deployment.

Table 5.17. The total number of vehicles in the base, TC50, and TC100 scenarios.

	Base	TC50	TC100
Heavy Truck	1,855	2,343	2,937
Truck	93,038	94,113	95,139
Panel van	660	1,319	1,192
Electric van	200,000	200,000	200,000
Total	295,553	297,775	299,268

There is a decrease in the amount of NO_x and CO emissions. The amount of NO_x emitted from non-electric vehicles decreases 6% compared to the base scenario, 2% compared to the TC50 scenario and reaches to 7,495,863 g. Similarly, the amount of CO emitted from these vehicles is 6,282,092 g which is 10% lower than the CO amount in the base scenario and 4% lower than that of the TC50 scenario. As the capacities of TCs are increased, the numbers of trucks and heavy trucks rise; nevertheless, since the total distance traveled is decreasing, the total amounts of NO_x and CO emissions are declining.

The freight flow of each vehicle type, in each time interval in the TC100 scenario is displayed in Table 5.18. It can be seen that the majority of flows are still direct shipments from PCs to CCs. Nevertheless, compared to the base scenario, the total amount of products shipped directly from PCs to CCs decreases 8% (61,022 tonnes). This decline is 4% (29,033 tonnes) compared to the TC50 scenario. The amount of products transported between two TCs increases from 908 tonnes to 5,598 tonnes compared to the base scenario, and it increases from 2,365 to 5,598 tonnes compared to the TC50 scenario. An additional noteworthy change is the 47% increase (from 36,187 to 53,147 tonnes) in the external zone shipments, compared to the base scenario and 19% increase (from 44,493 to 53,147 tonnes) compared to the TC50 scenario. This is because increased TC capacities enable more product flows from external zones to nearby CCs via the TCs. As in the base and TC50 scenarios, few electric vans are used to transport products from TCs to CCs, while most of them are used in direct shipments from PCs to CCs. The most intense time of freight flow is the evening

off-peak time interval (69.3%), and the least intense time is the evening peak time interval (5.4%) similar to the base and TC50 scenarios.

Table 5.18. Freight flow of each vehicle type, in each time interval in the TC100 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	18,010	13,513		39,597	71,120	71,120
	Panel van						
	Electric van						
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	3,432	10,321	5,520	52,596	71,870	77,115
	Panel van				1,443	1,443	
	Electric van	680	1,352	451	1,320	3,803	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	13,190	29,288		19,293	61,770	64,502
	Panel van				2,731	2,731	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	10,400	20,187			30,587	30,587
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				537,036	537,036	733,233
	Panel van						
	Electric van	49,320	48,648	49,549	48,680	196,197	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		5,598			5,598	5,598
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				1,020	1,020	1,020
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	13,935	24,584		13,607	52,127	52,126
Total		108,967	153,491	55,520	717,323	1,035,302	
Rate		10.5%	14.8%	5.4%	69.3%	100%	

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are presented in Tables 5.19 and 5.20. Compared to the base scenario, the TC usage for incoming products from PCs increases from 6% to 11.5% (see Table 5.3 and 5.19) and for outgoing products to CCs increases from 9.9% to 16.8% (see Table 5.4 and 5.20) because of the expanded capacities of TCs. Similarly, the TC usage for incoming products from PCs is 2.6% higher and for outgoing products to CCs is 3.3% higher than those in the TC50 scenario. For incoming products from PCs, the TC in zone 69 is still unused (see Table 5.19).

Table 5.19. Total freight flow activities outgoing from PCs to CCs and TCs in the TC100 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	733,233	88.5%			
From PCs to TCs on the European Side (W_{si}^{pvt})	64,502	7.8%	Zone 10	Zone 12	Zone 38
			21,935	24,066	18,501
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	30,587	3.7%	Zone 64	Zone 69	Zone 97
			8,694		21,893
Total	828,322				

Table 5.20. Total freight flow activities incoming to CCs from PCs and TCs in the TC100 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	733,233	83.2%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	71,120	8.1%	Zone 10	Zone 12	Zone 38
			22,955	24,066	24,100
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	77,115	8.7%	Zone 64	Zone 69	Zone 97
			16,703	36,247	24,165
Total	881,468				

Table 5.21 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the TC100 scenario. As the capacities of TCs are expanded, the number of vehicles using them increases, too. However, some TCs are no longer used in certain time intervals. If the capacity of a TC is available, then vehicles visit that center in the cheapest time interval. Regarding heavy trucks and trucks; in the TC100 scenario, in the noon peak time interval, except for the TC in the 64^{th} zone, all the other TCs are fully utilized as in the TC50 scenario. In that time

interval, the TC in the 64th zone is used but not fully utilized in the base scenario. In the TC100 scenario, in the noon off-peak and evening off-peak time intervals, all TCs are deployed at full capacity as in the base and TC50 scenarios. However, in the TC100 scenario, in the evening peak time interval, only the TC in the 69th zone is deployed while, in that time interval, the TCs in the 12th and the 69th zones are utilized in the TC50 scenario, and except for the one in the 64th zone, all the others are deployed in the base scenario.

Table 5.21. Capacities and deployments of the TCs in each time interval for different vehicle types in the TC100 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	1,040	1,040	1,040	1,040	1,040	1,040
	Noon Peak Occupied Capacity	1,040	1,040	1,040		1,040	1,040
	Noon Off-peak Capacity	1,520	1,520	1,520	1,520	1,520	1,520
	Noon Off-peak Occupied Capacity	1,520	1,520	1,520	1,520	1,520	1,520
	Evening Peak Capacity	1,520	1,520	1,520	1,520	1,520	1,520
	Evening Peak Occupied Capacity					552	
	Evening Off-peak Capacity	1,980	1,980	1,980	1,980	1,980	1,980
	Evening Off-peak Occupied Capacity	1,980	1,980	1,980	1,980	1,980	1,980
Panel vans and Electric vans	Noon Peak Capacity	680	680	680	680	680	680
	Noon Peak Occupied Capacity					680	
	Noon Off-peak Capacity	1,000	1,000	1,000	1,000	1,000	1,000
	Noon Off-peak Occupied Capacity					1,000	352
	Evening Peak Capacity	1,000	1,000	1,000	1,000	1,000	1,000
	Evening Peak Occupied Capacity					451	
	Evening Off-peak Capacity	1,320	1,320	1,320	1,320	1,320	1,320
	Evening Off-peak Occupied Capacity		780			1,320	412

Regarding panel vans and electric vans; in the TC100 scenario, in the noon peak time interval, only the TC in the 69th zone is fully utilized (while, in that time interval, those in the 12th and 69th zones are deployed at full capacity in the base and TC50 scenarios). In the TC100 scenario, in the noon off-peak time interval, the TCs in the 69th and the 97th zones are deployed, with the 69th reaching full capacity (while, in that time interval, those in the 10th, the 69th, and the 97th zones are utilized, with the 10th and the 69th reaching full capacity in the TC50 scenario, and except for the TC in the 64th zone, all the others are fully utilized in the base scenario). In the TC100 scenario, in the evening peak time interval, the TC in the 69th zone is deployed but

not fully utilized (while, in that time interval, those in the 12^{th} and 69^{th} zones are fully utilized in the TC50 scenario and only the one in the 69^{th} zone is fully utilized in the base scenario). In the TC100 scenario, in the evening off-peak time interval, the TCs in the 12^{th}, the 69^{th} and the 97^{th} zones are deployed, with the 69^{th} reaching full capacity (while those in the 10^{th}, the 12^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones are utilized, with the 10^{th}, the 12^{th}, and the 69^{th} reaching full capacity in the TC50 scenario and except for the TC in the 64^{th} zone, all the others are fully utilized in the base scenario).

5.2.1.3. 200% Increase in Transshipment Center Capacities (TC200). In this scenario, the capacities of all TCs are increased by 200%. So, the capacities of the TCs are as follows:

Table 5.22. Capacities of TCs in the TC200 scenario (in number of vehicles).

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Truck and Heavy Truck	1,560	2,280	2,280	2,970
Panel van and Electric van	1,020	1,500	1,500	1,980

The obtained results of the TC200 scenario are presented in Tables 5.23-5.29. The transportation cost is 3,581,155 ₺ , the CO_2 emission cost is 127,769 ₺ , and the total cost is calculated as 3,708,924 ₺ . The transportation cost decreases 6% compared to the base scenario, 4% compared to the TC50 scenario, and 2% compared to the TC100 scenario. The CO_2 emission cost decreases 5% compared to the base scenario, 4% compared to the TC50 scenario, and 2% compared to the TC100 scenario. Accordingly, the total cost is 6% lower than that of the base scenario, 4% lower than that of the TC50 scenario, and 2% lower than that of the TC100 scenario. As can be seen in Table 5.23, both the transportation and CO_2 emission costs (and accordingly the total cost) still decrease when the capacities of TCs are extended. It is still more expensive to distribute products directly from PCs to CCs. The primary reason being the assumption that trucks usually cannot be fully loaded in direct shipments. So, it is less costly to distribute products through TCs rather than sending them directly.

Table 5.23. The transportation, CO_2 emission, and total costs in the base, TC50, TC100, and TC200 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
TC50	3,729,637	132,455	3,862,091
TC100	3,671,340	130,710	3,802,051
TC200	3,581,155	127,769	3,708,924

The total number of vehicles in all zones in each time interval in the TC200 scenario is displayed in Table 5.24. Additionally, Table 5.25 provides for the comparison of the total number of vehicles in the base, TC50, TC100, and TC200 scenarios. The number of heavy trucks increases 72% (1,336 heavy trucks) compared to the base scenario, 36% (848 heavy trucks) compared to the TC50 scenario, and 9% (253 heavy trucks) compared to the TC100 scenario. Similarly, the number of trucks increases 6% (5,220 trucks) compared to the base scenario, 4% (4,144 trucks) compared to the TC50 scenario, and 3% (3,118 trucks) compared to the TC100 scenario. The number of panel vans decreases 87% (577 panel vans) compared to the base scenario, 94% (1,235 panel vans) compared to the TC50 scenario and 93% (1,109 panel vans) compared to the TC100 scenario. Due to the relatively high unit cost and high unit emission of panel vans, the enlarged capacities of TCs lead to a notable reduction in this mode of transportation. The number of electric vans is still at the upper bound value of 200,000. As the capacities of TCs increase, more vehicles can visit the TCs. Since vehicles are used both on the way (inbound) to TCs and outbound from TCs (rather than the single trip associated with a direct shipment), this two-tiered transportation leads to more vehicle deployment.

The amount of NO_x released from non-electric vehicles decreases 10% compared to the base scenario, 6% compared to the TC50 scenario, 4% compared to the TC100 scenario and reaches to 7,200,975 g. Similarly, the amount of CO emitted from these vehicles is 5,913,882 g and it is 15% lower than the CO amount in the base scenario, 10% lower than that of the TC50 scenario, and 6% lower than that of the TC100 scenario. As the capacities of TCs are increased, the numbers of trucks and heavy trucks rise,

too. The total amounts of NO_x and CO decline in spite of this increment in the number of vehicles. The reason for that may be related to the decrease in the total distance traveled and to the lower unit emission rates of fully loaded trucks (compared to panel vans and partially loaded trucks).

Table 5.24. The total number of vehicles in all zones in each time interval in the TC200 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	488	2,122		581	3,191
Truck	6,976	9,535		81,746	98,257
Panel van				83	83
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.25. The total number of vehicles in the base, TC50, TC100, and TC200 scenarios.

	Base	TC50	TC100	TC200
Heavy Truck	1,855	2,343	2,937	3,191
Truck	93,038	94,113	95,139	98,257
Panel van	660	1,319	1,192	83
Electric van	200,000	200,000	200,000	200,000
Total	295,553	297,775	299,268	301,531

The freight flow of each vehicle type, in each time interval in the TC200 scenario is displayed in Table 5.26. The majority of flows are still in direct shipments from PCs to CCs. Nevertheless, compared to the base scenario, the total amount of products shipped directly from PCs to CCs decreases 14% (112,293 tonnes). This decline is 11% (80,304 tonnes) compared to the TC50 scenario and 7% (51,271 tonnes) compared to the TC100 scenario. The amount of products transported between two TCs increases more than four times (from 908 to 4,432 tonnes) considering the base scenario. It increases 87% (2,067 tonnes) compared to the TC50 scenario and decreases 11% (1,166 tonnes) compared to the TC100 scenario. As the capacities of the TCs are expanded, the freight flow between the two TCs increases. It also causes an increase in the amount

of products coming from the external zones. It is observed that the trend to rely more on the external zones continues: 64% increase (23,192 tonnes) from the external zone shipments compared to the base scenario (due to increased TC capacities). The increase from external zone shipments is 33% (14,886 tonnes) compared to the TC50 scenario and 12% (6,232 tonnes) compared to the TC100 scenario. It seems that after a certain rise in the capacities of TCs, TCs need fewer products from other TCs, due to the increase in the external zone shipments. As in the base, TC50, and TC100 scenarios, few electric vans are used to transport products from TCs to CCs, while most of them are used in direct shipments from PCs to CCs.

Table 5.26. Freight flow of each vehicle type, in each time interval in the TC200 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	21,304	20,878		59,397	101,578	101,579
	Panel van						
	Electric van						
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	14,138	6,701		75,248	96,087	97,928
	Panel van						
	Electric van		1,500		341	1,841	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	22,135	45,306		29,701	97,141	97,142
	Panel van						
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	12,186	22,462		8,048	42,695	42,987
	Panel van				291	291	
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				483,803	483,803	681,962
	Panel van						
	Electric van	50,000	48,500	50,000	49,659	198,159	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		4,432			4,432	4,432
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				5	5	5
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	9,753	38,014		11,608	59,374	59,375
Total		129,516	187,793	50,000	718,101	1,085,406	
Rate		11.9%	17.3%	4.6%	66.2%	100%	

Similar to the base scenario, the most intense time of the freight flow is the evening off-peak time interval (66.2%). The reason being that the vast majority of the products are distributed by trucks, and the cheapest time interval to transport by trucks is the evening off-peak. The least intense time is still the evening peak time interval (4.6%).

Table 5.27. Total freight flow activities outgoing from PCs to CCs and TCs in the TC200 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	681,962	83.0%			
From PCs to TCs on the European Side (W_{si}^{pvt})	97,142	11.8%	Zone 10	Zone 12	Zone 38
			34,046	34,050	29,045
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	42,987	5.2%	Zone 64	Zone 69	Zone 97
			10,152		32,835
Total	822,091				

Table 5.28. Total freight flow activities incoming to CCs from PCs and TCs in the TC200 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	681,962	77.4%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	101,579	11.5%	Zone 10	Zone 12	Zone 38
			34,051	34,050	33,477
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	97,928	11.1%	Zone 64	Zone 69	Zone 97
			16,652	46,627	34,649
Total	881,469				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are presented in Tables 5.27 and 5.28. Compared to the base scenario, the TC usage for incoming products from PCs increases from 6% to 17% (see Tables 5.3 and 5.27) and for outgoing products to CCs increases from 9.9% to 22.6% (see Tables 5.4 and 5.28) because of the expanded capacities of TCs. The difference between these flows is still due to the incoming flows from the external zones. The TC usage for incoming products from PCs is 8.1% higher than that in the TC50 scenario and 5.5% higher than that in the TC100 scenario. Similarly, the TC usage for outgoing products to CCs is 9.1% higher than that in the TC50 scenario and 5.8% higher than that in the TC100 scenario. For incoming products from PCs, the TC in zone 69 is still unused (see Table 5.27).

Table 5.29. Capacities and deployments of the TCs in each time interval for different vehicle types in the TC200 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	1,560	1,560	1,560	1,560	1,560	1,560
	Noon Peak Occupied Capacity	1,560	1,560	1,224		1,560	1,560
	Noon Off-peak Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Noon Off-peak Occupied Capacity	2,280	2,280	2,280	479	2,280	2,280
	Evening Peak Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Evening Peak Occupied Capacity						
	Evening Off-peak Capacity	2,970	2,970	2,970	2,970	2,970	2,970
	Evening Off-peak Occupied Capacity	2,970	2,970	2,970	2,970	2,970	2,970
Panel vans and Electric vans	Noon Peak Capacity	1,020	1,020	1,020	1,020	1,020	1,020
	Noon Peak Occupied Capacity						
	Noon Off-peak Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Noon Off-peak Occupied Capacity					1,500	
	Evening Peak Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Evening Peak Occupied Capacity						
	Evening Off-peak Capacity	1,980	1,980	1,980	1,980	1,980	1,980
	Evening Off-peak Occupied Capacity					341	83

Table 5.29 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the TC200 scenario. As the capacities of TCs increase, the number of vehicles using them increases, too. On the other hand, in various time intervals, the number of TCs operating at full capacity decreases compared to the base, TC50, and TC100 scenarios.

Regarding heavy trucks and trucks; in the noon peak time interval, except for the TC in the 64^{th} zone, all TCs are fully utilized as in the TC50 and TC100 scenarios (in the base scenario, all TCs are utilized). In the noon off-peak time interval, in the TC200 scenario, all TCs are used, and except for the one in the 64^{th} zone, all TCs are fully utilized while, in that time interval all TCs are fully utilized in the base, TC50, and TC100 scenarios. In the evening peak time interval, in the TC200 scenario, no TC is utilized while, in that time interval, those in the 12^{th}, 69^{th}, and 97^{th} zones are deployed in the TC50 scenario, and the one in the 69^{th} zone is deployed in the TC100 scenario. As for the base scenario, except for the TC in the 64^{th} zone, all are utilized. In the evening off-peak time interval, in the TC200 scenario, all TCs are fully utilized as in the base, TC50 and TC100 scenarios.

Regarding panel vans and electric vans; in the noon peak time interval, no TC is deployed at all in the TC200 scenario while, in that time interval, the TCs in the 12^{th} and the 69^{th} zones in the base and TC50 scenarios, and only the one in the 69^{th} zone in the TC100 scenario are deployed at full capacity. In the noon off-peak time interval, in the TC200 scenario, only the TC in the 69^{th} zone is utilized, with reaching full capacity (while in that time interval, the TCs in the 10^{th}, 12^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones in the base scenario, those in the 10^{th}, the 69^{th}, and the 97^{th} zones in the TC50 scenario, and those in the 69^{th}, and the 97^{th} zones in the TC100 scenario are used). In the evening peak time interval, in the TC200 scenario, no TC is deployed at all while in that time interval, the TC in the 69^{th} zone in the base and TC100 scenarios and those in the 12^{th} and the 69^{th} zones in the TC50 scenario are used. In the evening off-peak time interval, in the TC200 scenario, the TCs in the 69^{th} and the 97^{th} zones are utilized but not fully utilized while, in that time interval, the TCs in the 10^{th}, the 12^{th}, the 38^{th}, the 69^{th} and the 97^{th} zones in the base and TC50 scenarios, and those in the 12^{th}, the 69^{th} and the 97^{th} zones in the TC100 scenario are deployed.

In summary, as the capacities of TCs increase,

(i) transportation and CO_2 emission costs (accordingly the total cost) decrease;

(ii) NO_x and CO emissions decrease;

(iii) total number of vehicles deployed increases;

(iv) the usage rate of TCs regarding total freight flow increases;

(v) transshipment capacities become sufficient for freight flow;

(vi) the density in the noon peak and noon off-peak time intervals increase, and the density in the evening peak time interval (which is the least intense) and evening off-peak time interval (which is the most intense) decrease;

(vii) these results imply that while capacity increase of TCs is highly desirable, more of the increased capacity should be allocated to trucks and heavy trucks.

5.2.2. Truck Utilization Rate Scenarios

In the base scenario, the trucks traveling between PCs and CCs are assumed to be loaded at 75% capacity, since it is regarded likely to have a daily shipment from one specific PC to one specific CC at less than truck capacity. Since this utilization rate assumption cannot be easily validated, we thought it would be prudent to investigate the effects of considering different utilization rates. Accordingly, in this set of scenarios, the utilization rate of trucks are reduced to 60% and 40% as listed below:

(i) When the trucks traveling between PCs and CCs are loaded at 60% capacity (TUR60)

(ii) When the trucks traveling between PCs and CCs are loaded at 40% capacity (TUR40)

5.2.2.1. When Truck Utilization Rate is 60% (TUR60). In this scenario, trucks traveling between PCs and CCs are assumed to be loaded at 60% capacity.

The obtained results of the TUR60 scenario are presented in Tables 5.30-5.36. The transportation cost is 4,345,173 ₺ , the CO_2 emission cost is 149,833 ₺ , and the total cost is calculated as 4,495,006 ₺ . As depicted in Table 5.30, the transportation, the CO_2 emission (and hence the total) costs increase in the TUR60 scenario. The transportation cost increases 14%, the CO_2 emission cost increases 12%, and accordingly, the total cost increases 14% compared to the base scenario. As the truck utilization rate

decreases in direct shipments from PCs to CCs, more vehicles are needed to transport the same amount of load. This leads to increased costs.

Table 5.30. The transportation, CO_2 emission, and total costs in the base and TUR60 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
TUR60	4,345,173	149,833	4,495,006

The total number of vehicles in all zones in each time interval in the TUR60 scenario is presented in Table 5.31. Additionally, Table 5.32 is provided in order to compare the number of vehicles in the base and TUR60 scenarios. There is an 8% increase in the total number of vehicles (22,759 vehicles). The increase is 40% (749) in the number of heavy trucks, while it is 9% (17,313) in the number of trucks. There is also more than 7 fold increase in the number of panel vans (4,698). On the other hand, the number of electric vans is still at the upper bound value of 200,000. The amount of NO_x released from these vehicles is 10,337,406 g, and it increases 29% compared to the base scenario. Similarly, the amount of CO emitted from these vehicles increases 38% and reaches to 9,558,922 g.

Table 5.31. The total number of vehicles in all zones in each time interval in the TUR60 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	966	782	472	384	2,604
Truck	2,084	4,228	3,310	100,728	110,350
Panel van		1,688		3,670	5,358
Electric van	50,000	50,000	50,000	50,000	200,000

As distributing products directly from PCs to CCs becomes more expensive, shipment through TCs becomes more attractive. Since, vehicles are used both on the way to the TC and returning from the TC (rather than the single trip associated with

a direct shipment), this two-tiered transportation leads to more vehicle deployment (318,312 vehicles in total as can be seen in Table 5.32). This leads to a further increase in costs because of operating more vehicles (in addition to less efficient usage of truck capacities). Accordingly, more vehicles on the road network emit more pollutants, which causes a rise in the amount of NO_x and CO emissions.

Table 5.32. The total number of vehicles in all zones in the base and TUR60 scenarios.

	Base	TUR60
Heavy Truck	1,855	2,604
Truck	93,038	110,350
Panel van	660	5,358
Electric van	200,000	200,000
Total	295,553	318,312

The freight flow of each vehicle type, in each time interval in the TUR60 scenario is displayed in Table 5.33. When the freight flows are examined, it can be seen that the majority of flows are still direct shipments from PCs to CCs although it decreases 3% (21,741 tonnes) compared to the base scenario. The amount of products transported between TCs increases from 908 to 1,414 tonnes. Since the truck utilization rate in direct shipments decreases from 75% to 60%, more vehicles are needed to ship the same amount of products. The increase in costs here also causes a decrease in the amount of product sent directly from PCs to CCs, and an increase in the amount of product sent via the TCs. It should be also noted that shipments from the external zone increase 40% (to 50,657 tonnes) because of increase unit transportation cost between PCs and CCs. These increases in the usage of TCs result in more product transfer between two TCs. Electric vans, which are still deployed at upper bound levels in all time intervals, are mostly used in direct shipments from PCs to CCs.

As can be seen in Table 5.33, the most intense time of freight flow is still the evening off-peak time interval (70.3%), while the least intense time is the noon peak

time interval (9.1%). In this scenario, some shipments shift to other intervals, compared to the base scenario, because most TCs reach their capacity in the most intense time interval. As a result, the intensity in the other intervals rises, and the intensity in the evening off-peak time interval decreases, although it is still the most intense time interval.

Table 5.33. Freight flow of each vehicle type, in each time interval in the TUR60 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	2,524	12,655	10,310	23,093	48,582	51,533
	Panel van				2,111	2,111	
	Electric van	340		500		840	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	5,794	14,978	2,880	27,317	50,968	57,424
	Panel van		2,871		3,205	6,076	
	Electric van	379				379	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	12,369	10,145	12,314	5,153	39,980	47,209
	Panel van		2,409		4,819	7,229	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	151		7,600		7,751	11,089
	Panel van		629		2,709	3,338	
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck		2,703		571,030	573,733	772,514
	Panel van						
	Electric van	49,281	50,000	49,500	50,000	198,781	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck	1,414				1,414	1,414
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				2,909	2,909	2,909
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	17,896	15,645	9,440	4,767	47,748	47,748
Total		90,148	112,035	92,544	697,113	991,839	
Rate		9.1%	11.3%	9.3%	70.3%	100%	

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.34 and 5.35. Compared to the base scenario, the TC usage for incoming products from PCs increases from 6% to 7% (see Tables 5.3 and 5.34) and for outgoing products to CCs increases from 9.9% to 12.4% (see Tables 5.4

and 5.35), as a result of more shipments through TCs. The difference between these flows is again due to the inflows from the external zone. For incoming products from PCs, the TC in zone 69 is still unused (as can be seen in Table 5.34).

Table 5.34. Total freight flow activities outgoing from PCs to CCs and TCs in the TUR60 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	772,514	93.0%			
From PCs to TCs on the European Side (W_{si}^{pvt})	47,209	5.7%	Zone 10	Zone 12	Zone 38
			15,237	16,398	15,574
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,089	1.3%	Zone 64	Zone 69	Zone 97
			980		10,110
Total	830,812				

Table 5.35. Total freight flow activities incoming to CCs from PCs and TCs in the TUR60 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	772,514	87.6%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	51,533	5.8%	Zone 10	Zone 12	Zone 38
			16,543	18,001	16,988
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	57,424	6.5%	Zone 64	Zone 69	Zone 97
			14,727	23,133	19,563
Total	881,471				

Table 5.36 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the TUR60 scenario. Compared to the base scenario, more vehicles use TCs since direct shipments from PCs to CCs become more

expensive. Regarding heavy trucks and trucks; in the noon peak, noon off-peak, and evening off-peak time intervals, all TCs are fully utilized, similar to the base scenario. In the TUR60 scenario, in the evening peak time interval, except for the one in the 64th zone, all TCs are deployed, with the 12th, the 38th, the 69th, and the 97th reaching full capacity. In that time interval, except for the one in the 64th zone, all TCs are utilized but not fully utilized in the base scenario.

Table 5.36. Capacities and deployments of the TCs in each time interval for different vehicle types in the TUR60 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	520	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	742	760	760		760	760
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity		340			340	39
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity		500	188		500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity		500				
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	660	660	370	660	660

Regarding panel vans and electric vans; in the TUR60 scenario, in the noon peak time interval, the TCs in the 12th, the 69th and the 97th zones are deployed, with the 12th and the 69th reaching full capacity while, in that time interval, TCs in the 12th and the 69th zones are fully utilized in the base scenario. In the TUR60 scenario, in the noon off-peak time interval, the TCs in the 12th, the 38th, the 69th and the 97th zones are deployed, with the 12th, the 69th, and the 97th reaching full capacity, while in that time interval, except for the TC in the 64th zone, all the others are fully utilized in the base scenario. In the TUR60 scenario, in the evening peak time interval, only the TC in the 12th zone is deployed at full capacity while, in that time interval, only the one in the 69th zone is fully utilized in the base scenario. In the TUR60 scenario,

in the evening off-peak time interval, all TCs are used, and except for the one in the 64^{th} zone, all the others are deployed at full capacity while, in that time interval, the one in the 64^{th} zone is not deployed, although all the others are fully utilized in the base scenario.

5.2.2.2. When Truck Utilization Rate is 40% (TUR40). In this scenario, trucks traveling between PCs and CCs are assumed to be loaded at 40% capacity.

The obtained results of the TUR40 scenario are presented in Tables 5.37-5.43. The transportation cost is 4,907,881 ₺ , the CO_2 emission cost is 146,592 ₺ , and the total cost is calculated as 5,054,473 ₺ . The transportation cost increases 29% compared to the base scenario and 13% compared to the TUR60 scenario. Although the CO_2 emission cost increases 9% compared to the base scenario, it decreases 2% compared to the TUR60 scenario. Accordingly, the total cost is 29% higher than that of the base scenario and 12% higher than that of the TUR60 scenario. Though the CO_2 emission cost is higher than that of the base scenario, it is lower than that of the TUR60 scenario. The main reason for the decrease in the amount of CO_2 emissions in the TUR40 scenario can be explained as follows: Compared to the TUR60 scenario, there is a decrease in the number of trucks and an increase in the number of panel vans in the TUR40 scenario. The unit transportation cost of trucks is lower than that of panel vans. On the other hand, the unit CO_2 emission of trucks is higher than that of panel vans. This result in an increase in transportation cost and a decrease in CO_2 emission cost.

Table 5.37. The transportation, CO_2 emission, and total costs in the base, TUR60, and TUR40 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
TUR60	4,345,173	149,833	4,495,006
TUR40	4,907,881	146,592	5,054,473

The total number of vehicles in all zones in each time interval in the TUR40 scenario is presented in Table 5.38. Additionally, in order to compare the number of vehicles in the base, TUR60, and TUR40 scenarios, Table 5.39 is provided. As the utilization rate of trucks traveling between PCs and CCs decreases, distributing products directly from PCs to CCs becomes more expensive. Hence, the distribution of products through TCs becomes more advantageous. Vehicles are used both on the way to the TC and returning from the TC (rather than the single trip associated with a direct shipment). Therefore, this two-tiered transportation leads to more vehicle deployment. There is about 31% increase in the total number of vehicles compared to the base scenario. As the truck utilization rate decreases, the number of heavy trucks increases. It increases 64% (1,187 heavy trucks) compared to the base scenario and 17% (430 heavy trucks) compared to the TUR60 scenario. However, the number of trucks decreases 84% (78,460 trucks) compared to the base scenario and 87% (95,773 trucks) compared to the TUR60 scenario. The most significant change is observed in the number of panel vans. It increases from 660 to 170,240 in the TUR40 scenario while there are 5,358 panel vans in the TUR60 scenario. As trucks become more expensive at direct shipments between PCs and CCs (because of reduced utilization rates), panel vans become more attractive. The number of electric vans is still at the upper bound value of 200,000.

Table 5.38. The total number of vehicles in all zones in each time interval in the TUR40 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	1,135	782	792	333	3,042
Truck	1,985	3,778	3,208	5,607	14,578
Panel van	1,700	2,500	1,499	164,541	170,240
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.39. The total number of vehicles in all zones in the base, TUR60, and TUR40 scenarios.

	Base	TUR60	TUR40
Heavy Truck	1,855	2,604	3,042
Truck	93,038	110,350	14,578
Panel van	660	5,358	170,240
Electric van	200,000	200,000	200,000
Total	295,553	318,312	387,860

The amount of NO_x emitted from all vehicles is 2,388,635 g, and it decreases 70% compared to the base scenario and 77% compared to the TUR60 scenario. The reason for the decrease in the NO_x emissions can be explained as follows: Since the amount of NO_x emission emitted by a panel van is lower than that of a truck, the decrease in the number of trucks and the increase in the number of panel vans cause a decrease in the total NO_x amount. The amount of CO emitted from these vehicles increases 11% compared to the base scenario and decreases 19% compared to the TUR60 scenario, and reaches to 7,720,655 g. There is a significant increase in the number of panel vans in the evening off-peak time interval. Since the CO emissions of a panel van is more than that of a truck only in the evening off-peak time interval, the drastic increase in the number of panel vans in that time interval explains the reason for the CO increase in the TUR40 scenario (compared to the base scenario). Compared to the TUR60 scenario, the amount of CO decreases due to the significant decrease in the number of trucks. Also, since the utilization of TCs increases, this may reduce CO emissions.

The freight flow of each vehicle type, in each time interval in the TUR40 scenario is displayed in Table 5.40. The majority of flows are observed in direct shipments from PCs to CCs. Compared to the base scenario, the total amount of products shipped directly from PCs to CCs decreases 4% (32,222 tonnes). This decline is 1% (10,481 tonnes) compared to the TUR60 scenario. The amount of products transported between two TCs increases 72% (from 908 to 1,564 tonnes) compared to the base scenario and 11% (from 1,414 to 1,564 tonnes) compared to the TUR60 scenario. The external zone shipments increase 64% compared to the base scenario and 17% compared

to the TUR60 scenario (to 59,290 tonnes). Electric vans, which are still deployed at upper bound values in all time intervals, are only used in direct shipments from PCs to CCs. In this scenario, a significant increase in the number of vehicles (especially in panel vans) is observed. All these observations are in line with the implemented capacity reduction regarding direct shipments from PCs to CCs.

Table 5.40. Freight flow of each vehicle type, in each time interval in the TUR40 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	9,089	9,750	7,754	24,714	51,307	56,937
	Panel van	1,190	3,500	940		5,630	
	Electric van						
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	4,245	14,984	1,792	29,312	50,333	62,499
	Panel van	2,262	1,750	1,750	6,404	12,166	
	Electric van						
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	6,511	13,050	14,264	2,039	35,864	49,479
	Panel van	2,380	1,750	2,555	6,930	13,615	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck			8,271		8,271	10,665
	Panel van	118	1,750		526	2,394	
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck						762,033
	Panel van				562,033	562,033	
	Electric van	50,000	50,000	50,000	50,000	200,000	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck			1,564		1,564	1,564
FromExternal Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				5,893	5,893	5,893
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	22,709	15,631	14,280	777	53,397	53,397
Total		98,504	112,165	103,170	688,628	1,002,467	
Rate		9.8%	11.2%	10.3%	68.7%	100%	

Owing to the rise in the number of visiting vehicles, the usage rate of TCs also increases compared to the base scenario. As can be observed from Table 5.5, in the base scenario, the most intense time is the evening off-peak time interval (73.9%) due to low unit costs and emissions. In the TUR40 scenario, some vehicles shift to the

other time intervals since most of the TCs reach their full capacity in that busy time interval. As a result, the intensity in the other intervals rises, and the intensity in the evening off-peak time interval decreases, although it is still the most intense time interval (68.7%) in the TUR40 scenario. The least intense time interval is the noon peak time interval (9.8%).

Table 5.41. Total freight flow activities outgoing from PCs to CCs and TCs in the TUR40 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	762,033	92.7%			
From PCs to TCs on the European Side (W_{si}^{pvt})	49,479	6.0%	Zone 10	Zone 12	Zone 38
			16,094	15,911	17,475
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	10,665	1.3%	Zone 64	Zone 69	Zone 97
			671		9,994
Total	822,177				

Table 5.42. Total freight flow activities incoming to CCs from PCs and TCs in the TUR40 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	762,033	86.5%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	56,937	6.5%	Zone 10	Zone 12	Zone 38
			18,335	19,563	19,039
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	62,499	7.1%	Zone 64	Zone 69	Zone 97
			17,264	24,867	20,369
Total	881,469				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are presented in Tables 5.41 and 5.42. Compared to the base scenario, the

TC usage for incoming products from PCs increases from 6% to 7.3% (see Tables 5.3 and 5.41) and for outgoing products to CCs increases from 9.9% to 13.5% (see Tables 5.4 and 5.42). The TC usage for incoming products from PCs to TCs is 0.3% higher, and the TC usage for outgoing products from TCs to CCs is 1.1% higher than those in the TUR60 scenario. It should also be noted that, since the capacity limitation of the TCs become more pronounced in this scenario (as explained in the next paragraph), their utilization rate increase is less than what is observed in the previous scenario (TUR60). The difference between the usage rates is mainly due to the incoming flow to TCs from the external node. For incoming products from PCs, the TC in zone 69 is still unused (as can be seen in Table 5.41).

Table 5.43. Capacities and deployments of the TCs in each time interval for different vehicle types in the TUR40 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	520	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	760	760	760	279	760	760
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity	340	340	340		340	340
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	500	500	500		500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity		500	499		500	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	660	660	660	660	660

Table 5.43 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the TUR40 scenario. Compared to the base and TUR60 scenarios, more vehicles use TCs as direct shipments become more expensive in this scenario. Regarding heavy trucks and trucks, in the TUR40 scenario, in the noon peak, noon off-peak and evening off-peak time intervals, all TCs are fully

utilized, as in the TUR60 scenario. In the evening peak time interval, in the TUR40 scenario, all TCs are utilized, and except for the TC in the 64^{th} zone, all the others are deployed at full capacity. In the base and TUR60 scenarios, except for the TC in the 64^{th} zone, all the others are utilized.

Regarding panel vans and electric vans; in the TUR40 scenario, in the noon peak time interval, except for the TC in zone 64, all other TCs are fully utilized, whereas only those in the 12^{th} and the 69^{th} zones are fully utilized in the base scenario. In that time interval, those in the 12^{th}, the 69^{th}, and the 97^{th} zones are utilized, with the 12^{th} and the 69^{th} reaching full capacity in the TUR60 scenario. In the TUR40 scenario, in the noon off-peak time interval, except for the one in the 64^{th} zone, all the others are fully utilized while, in that time interval, except for the TCs in the 10^{th} and 64^{th} zones, all the others are utilized, with the 12^{th}, the 69^{th}, and 97^{th} reaching full capacity in the TUR60 scenario, and except for the one in the 64^{th} zone, all the others are used at full capacity in the base scenario. In the TUR40 scenario, in the evening peak time interval, the TCs in the 12^{th}, the 38^{th}, and the 69^{th} zones are deployed, with the 12^{th} and the 69^{th} reaching full capacity. However, in that time interval, only one TC is fully utilized in the base and TUR60 scenarios. In the TUR40 scenario, in the evening off-peak time interval, all TCs are deployed at full capacity while, in that time interval, all TCs are utilized, and except for the one in the 64^{th} zone, all the others are fully utilized in the TUR60 scenario, and except for the one in the 64^{th} zone, all the others are fully utilized in the base scenario.

In summary, as the rate of truck utilization decreases in direct shipments;

(i) the transportation and the total costs increase;
(ii) the total number of panel vans increases;
(iii) the amount of shipments from external zones increases;
(iv) the usage of TCs slightly increases since almost all TCs have reached their limited capacities in most time intervals;
(v) the intensity in the evening off-peak time interval decreases. Some vehicles shift to other time intervals, so the intensity in other time intervals increase.

5.2.3. Product Flow Based Scenarios

In this group of scenarios, the effects of limitations to product flows are investigated. As explained in Section 4.5, due to product aggregation, it may be problematic to have a CC's demand for a specific product category met by the PC in the same zone with it. Similarly, flows of products to and from a TC originating from a PC and ending at a CC located in the same zone with it, may be problematic. Accordingly, via constraint sets 4.14, 4.15, 4.16, upper bounds are installed on such flows. On the other hand, realistic upper bounds on intra-zone direct shipments of a specific product category and upper bounds on incoming and outgoing flows between a particular zone and a TC, regarding a specific product category, are difficult to set. Therefore, it is prudent to try different upper bound values and study their effects on freight flows, vehicle assignments and time periods.

Furthermore, in this set of scenarios, an additional scenario about shipping products to the external zones is also investigated. This set of product flow based scenarios is listed below:

(i) The percentage of intra-zone flow of individual (aggregate) product categories (i.e. being produced and consumed in the same zone) to be at most 10% of zone's supply (SZPC10)

(ii) The percentage of incoming and outgoing flows between a particular zone and a TC, to be at most 20% of all incoming and outgoing product flows at that TC (SZTC20)

(iii) The percentage of incoming and outgoing flows between a particular zone and a TC, to be at most 40% of all incoming and outgoing product flows at that TC (SZTC40)

(iv) Full capacities of PCs to be deployed to satisfy CCs demands, while surplus capacity of PCs to be shipped to external zones (to satisfy possible external demand) (EXT)

5.2.3.1. 10% Upper Bound for Intra-Zone Supply/Demand Satisfaction (SZPC10) . As mentioned before, PCs often meet the demands of CCs at their own zones because of lower costs and PCs usually have sufficient supply due to product aggregation. However, as explained in Section 4.5, excess intra zone demand satisfaction from self supply is not realistic. So, constraint set 4.14 is set up, according to which, PCs can send up to 4% of the products to CCs in the same zone with them, while the remainder is sent to CCs in other zones. Unfortunately, the set upper bound value is based on incomplete data; accordingly, this scenario is developed to revise the right hand side in the constraint set 4.14 to 10% as follows:

$$\sum_{p}\sum_{v}\sum_{t} Z_{ss}^{pvt} \leq \sum_{p}\sum_{v}\sum_{t}\sum_{k} 0.1\ Z_{sk}^{pvt} \qquad \forall s. \tag{5.1}$$

The obtained results of the SZPC10 scenario are presented in Tables 5.44-5.50. These results are quite similar to the results of the base scenario. The transportation cost is 3,636,225 ₺ , the CO_2 emission cost is 129,552 ₺ , and the total cost is calculated as 3,765,777 ₺ . As can be observed from Table 5.44, the transportation cost decreases 4%, the CO_2 emission cost decreases 3%, and accordingly, the total cost decreases 4% compared to the base scenario.

Table 5.44. The transportation, CO_2 emission, and total costs in the base and SZPC10 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
SZPC10	3,636,225	129,552	3,765,777

The total number of vehicles in all zones in each time interval in the SZPC10 scenario is presented in Table 5.45. In order to compare the number of vehicles in the base and SZPC10 scenarios, Table 5.46 is provided. The numbers of vehicles deployed in the SZPC10 scenario are very close to those in the base scenario (there are only 161 more vehicles than in the base scenario). The number of heavy trucks decreases 15% (282 heavy trucks), and the number of trucks slightly decreases (398 trucks). The

number of panel vans increases 79% (519 panel vans) compared to the base scenario. The number of electric vans is still at the upper bound value of 200,000. In this scenario, since PCs are able to send a higher proportion of products to CCs in their zones compared to the base scenario, the amount of intra-zone shipments increases. This increase in intra-zone shipments directly causes an increase in the number of trucks and a decrease in the number of heavy trucks. The reason is that the increase in the intra-zone shipments leads to a decrease in the amount of external zone shipments and thus a decrease in the usage of heavy trucks, which is the transportation mode in this flow. Furthermore, the increase in intra-zone shipments also leads to an increase in the number of trucks and electric vans utilized while shipping products directly from PCs to CCs. Since the upper bound of electric vans that can be used is 200,000, the utilization of electric vans in other flows (i.e. from TCs to CCs, from PCs to TCs) decreases. Therefore, the utilization of panel vans increases in these flows between PCs and TCs.

The amount of NO_x emitted from these vehicles is 7,637,443 g, and it decreases 5% compared to the base scenario. Similarly, the amount of CO emitted from these vehicles decreases 5% (to 6,608,240 g). The increase in the number of panel vans and the decrease in the number of heavy trucks can be explained as the cause of the drop in NO_x and CO emissions.

Table 5.45. The total number of vehicles in all zones in each time interval in the SZPC10 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	47	1,051		475	1,573
Truck	2,621	3,447		86,572	92,640
Panel van				1,179	1,179
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.46. The total number of vehicles in all zones in the base and SZPC10 scenarios.

	Base	SZPC10
Heavy Truck	1,855	1,573
Truck	93,038	92,640
Panel van	660	1,179
Electric van	200,000	200,000
Total	295,553	295,392

The freight flow of each vehicle type in each time interval in the SZPC10 scenario is displayed in Table 5.47. In this scenario, as PCs have the opportunity to ship more products to CCs in their own zones, the total amount of products shipped directly from PCs to CCs increases 1% (from 794,255 to 804,963 tonnes) compared to the base scenario. The amount of products transported between two TCs increases 36% (324 tonnes) and the external zone shipments decrease 16% (5,968 tonnes) compared to the base scenario. As the amount of products sent directly from PCs to CCs increases, the amount of products distributed from PCs to TCs on the European side decreases considerably (from 39,738 to 34,452 tonnes). Therefore, the amount of products sent from TCs on the Asian side to TCs on the European side increases. Furthermore, there is a slight increase in the amount of products coming to TCs on the European side from the external zones (from 547 to 946 tonnes) although the total amount of the external shipments decreases. Due to the increase in the intra-zone demand satisfaction, the need for external zone shipments decreases. Similar to the base scenario, the most intense time of the freight flow is the evening off-peak time interval (75.7%), and the least intense time is the evening peak time interval (5.2%). Electric vans, which are still deployed at upper bound value in all time intervals, are mostly used in direct shipments from PCs to CCs.

Table 5.47. Freight flow of each vehicle type, in each time interval in the SZPC10 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	9,507	6,005		20,607	36,118	36,631
	Panel van						
	Electric van		273		239	511	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	6,112	6,164		25,427	37,704	39,876
	Panel van						
	Electric van	340	1,000		833	2,173	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	6,093	16,180		8,620	30,893	34,452
	Panel van				2,911	2,911	
	Electric van		227		421	649	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	4,498	6,122			10,621	11,834
	Panel van				1,214	1,214	
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				608,296	608,296	804,963
	Panel van						
	Electric van	49,660	48,500	50,000	48,507	196,667	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		1,232			1,232	1,232
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				946	946	946
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	933	19,795		8,545	29,273	29,273
Total		77,143	105,498	50,000	726,566	959,208	
Rate		8.1%	11.0%	5.2%	75.7%	100%	

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.48 and 5.49. Compared to the base scenario, the TC usage for incoming products from PCs decreases from 6% to 5.4%(as can be seen in Tables 5.3 and 5.48) and for outgoing products to CCs decreases from 9.9% to 8.7% (as can be seen in Tables 5.4 and 5.49), because of fewer freight flows from TCs to CCs and fewer "out of zone" flows. For incoming products from PCs, the TC in zone 69 is still unused (see Table 5.48).

Table 5.48. Total freight flow activities outgoing from PCs to CCs and TCs in the SZPC10 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	804,963	94.6%			
From PCs to TCs on the European Side (W_{si}^{pvt})	34,452	4.0%	Zone 10	Zone 12	Zone 38
			11,221	12,500	10,731
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,834	1.4%	Zone 64	Zone 69	Zone 97
			2,988		8,847
Total	851,249				

Table 5.49. Total freight flow activities incoming to CCs from PCs and TCs in the SZPC10 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	804,963	91.3%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	36,631	4.2%	Zone 10	Zone 12	Zone 38
			12,166	12,500	11,963
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	39,876	4.5%	Zone 64	Zone 69	Zone 97
			10,301	16,133	13,443
Total	881,470				

Table 5.50 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the SZPC10 scenario. In this scenario, PCs are able to send a higher proportion of products to CCs directly in their zones compared to the base scenario. The increase in intra-zone shipments leads to a decrease in the utilization of TCs. This decrease in the usage of TCs also leads to a decrease in the number of vehicles since more vehicles are required both inbound to TCs and outbound from TCs (rather than the single trip associated with a direct shipment). Even though

the number of trucks and heavy trucks using TCs decreases, the number of panel vans slightly increases in the SZPC10 scenario. In addition, a reduction in transportation and CO_2 costs and CO and NO_x emissions is also observed in this scenario. Regarding heavy trucks and trucks; in the SZPC10 scenario, in the noon peak time interval, all TCs are utilized as in the base scenario. In the SZPC10 scenario, in the noon off-peak and evening off-peak time intervals, all TCs are deployed at full capacity as in the base scenario. In the evening peak time interval, although the TCs in the 10^{th}, the 12^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones are utilized in the base scenario, none of the TCs is utilized in the SZPC10 scenario.

Table 5.50. Capacities and deployments of the TCs in each time interval for different vehicle types in the SZPC10 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	68	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity						
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity					340	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	500				500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity						
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	657	175		660	520

Regarding panel vans and electric vans; in the SZPC10 scenario, in the noon peak time interval, only the TC in the 69^{th} zone is utilized (while, in that time interval, the TCs in the 12^{th} and 69^{th} zones are fully utilized in the base scenario). In the SZPC10 scenario, in the noon off-peak time interval, the TCs in the 10^{th}, the 12^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones are fully utilized while, in that time interval, those in the 10^{th}, the 69^{th}, and the 97^{th} zones are deployed at full capacity in the base scenario. In the SZPC10 scenario, in the evening peak time interval, none of the TCs is used while, in

that time interval, only the one in the 69^{th} zone is deployed in the base scenario. In the SZPC10 scenario, in the evening off-peak time interval, except for the one in the 64^{th} zone, all TCs are utilized, with the 10^{th} and the 69^{th} reaching full capacity (while, in that time interval, except for the one in the 64^{th} zone, all the others are fully utilized in the base scenario).

In summary, in the SZPC10 scenario,

(i) the amount of intra-zone shipments increase since PCs are able to send a higher proportion of products to CCs in their zones;
(ii) the utilization of TCs decreases;
(iii) the transportation and CO_2 costs decrease;
(iv) CO and NO_x emissions decrease;
(v) the number of panel vans slightly increases;
(vi) the number of trucks and heavy trucks decreases due to the decrease in the usage of TCs compared to the base scenario.

5.2.3.2. 20% Upper Bound on the Inflow to and Outflow from a Transshipment Center to the Same Zone (SZTC20). As mentioned before, for any specific aggregate product category, TCs usually receive products from PCs at their own zones. It is also observed that these TCs usually send their products to the CCs in the same zone with them. However, as explained in Section 4.5, excess intra zone shipment is not realistic. So, constraint sets (4.15) and (4.16) are set up, according to which, the percentage of incoming and outgoing products to the TC in the same zone should be less than 30% of all incoming and outgoing products from all zones. Unfortunately, the upper bound value is based on incomplete data; accordingly, this scenario is developed to revise the right-hand side in the constraint set to 20% (constraint being tightened) as follows:

$$\sum_t \sum_v W_{ii}^{pvt} + \sum_t \sum_v X_{ii}^{pvt} \leq 0.2 \left(\sum_v \sum_t \sum_k X_{ik}^{pvt} + \sum_v \sum_t \sum_s W_{si}^{pvt} \right) \qquad \forall i,\ p \tag{5.2}$$

$$\sum_t \sum_v W_{jj}^{pvt} + \sum_t \sum_v X_{jj}^{pvt} \leq 0.2 \left(\sum_v \sum_t \sum_k X_{jk}^{pvt} + \sum_v \sum_t \sum_s W_{sj}^{pvt} \right) \qquad \forall j,\ p. \tag{5.3}$$

The obtained results of the SZTC20 scenario are presented in Tables 5.51-5.57. These results are very similar to the results of the base scenario. The transportation cost is 3,812,073 ₺ , the CO_2 emission cost is 134,537 ₺ , and the total cost is calculated as 3,946,610 ₺ . Compared to the results of the base scenario, both the transportation and CO_2 emission costs (and hence the total cost) slightly increase (about 0.4%) as can be observed from Table 5.51. As the products incoming to and outgoing from TCs to other zones increase, the costs increase because longer trips are required to ship to other zones.

Table 5.51. The transportation, CO_2 emission, and total costs in the base and SZTC20 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
SZTC20	3,812,073	134,537	3,946,610

The total number of vehicles in all zones in each time interval in the SZTC20 scenario is presented in Table 5.52. In order to compare the number of vehicles in the base and SZTC20 scenarios, Table 5.53 is provided. There is a decrease in the total number of vehicles (455 vehicles) compared to the base scenario. The number of heavy trucks decreases 5% (90 heavy trucks). There is also a small decrease in the number of trucks (283 trucks). Compared to the base scenario, the number of panel vans decreases from 660 to 578 (12%). The number of electric vans is still at the upper bound value of 200,000.

As the percentage of incoming and outgoing flows from/to a TC in the same zone decreases, the preference of TCs slightly decreases. The decrease in the utilization of TCs is also the main reason for the decline in the number of trucks since most of the products incoming and outgoing from/to TCs are transported by trucks. Moreover, two-tiered transportation leads to more vehicle deployment since vehicles are used both on the way (inbound) to TCs and outbound from TCs (rather than the single trip associated with a direct shipment). Therefore, as the usage of TCs decreases, a

decrease in the total number of panel vans and trucks is observed. Furthermore, due to the decrease in the external zone shipments, the number of heavy trucks drops. The underlying reason is that only heavy trucks can be used for external zone shipments. Although the number of vehicles decreases, the transportation and CO_2 emission costs increase since "cost saving" TCs are used less.

The amount of NO_x emitted from these vehicles is 8,100,269 g, and the amount of CO emitted is 7,021,342 g. There is only a 1% increase in the amounts of NO_x and CO emissions compared to the base scenario.

Table 5.52. The total number of vehicles in all zones in each time interval in the SZTC20 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	583	722		459	1,764
Truck	2182	3,838	550	86,185	92,755
Panel van				578	578
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.53. The total number of vehicles in all zones in the base and SZTC20 scenarios.

	Base	SZTC20
Heavy Truck	1,855	1,764
Truck	93,038	92,755
Panel van	660	578
Electric van	200,000	200,000
Total	295,553	295,097

The freight flow of each vehicle type, in each time interval in the SZTC20 scenario is displayed in Table 5.54. As TCs can receive and distribute less products from(/to) their own zone, the utilization of TCs decreases. This decrease causes a 1% (6,844 tonnes) increase in the total amount of products shipped directly from PCs to CCs, compared to the base scenario. This reduction in the use of TCs also leads to a

decrease in the need for the products coming from the external zones, since the external zone shipments are distributed through TCs. Therefore, the external zone shipments decrease 6% (2,160 tonnes). The amount of products transported between two TCs increases 39% (352 tonnes). This is probably due to the limitation on TCs to supply CCs in their own zone, thereby being encouraged to send flows to other TCs. Similar to the base scenario, the most intense time of the freight flow is the evening off-peak time interval (74.9%), and the least intense time is the evening peak time interval (5.8%). Electric vans, which are still deployed at upper bound value in all time intervals, are mostly used in direct shipments from PCs to CCs.

Table 5.54. Freight flow of each vehicle type, in each time interval in the SZTC20 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	6,767	6,031	1,724	21,432	35,954	37,114
	Panel van						
	Electric van		500		660	1,160	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	465	10,581	3,146	25,554	39,746	43,255
	Panel van				489	489	
	Electric van	340	1,000	500	1,180	3,020	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	8,203	16,769	632	7,821	33,424	34,960
	Panel van				1,535	1,535	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	6,384	4,999			11,383	11,383
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				605,280	605,280	801,100
	Panel van						
	Electric van	49,660	48,500	49,500	48,160	195,820	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck	1,260				1,260	1,260
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				895	895	895
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	10,400	14,440		8,292	33,132	33,132
Total		83,479	102,820	55,502	721,298	963,098	
Rate		8.6%	10.7%	5.8%	74.9%	100%	

Table 5.55. Total freight flow activities outgoing from PCs to CCs and TCs in the SZTC20 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	801,100	94.5%			
From PCs to TCs on the European Side (W_{si}^{pvt})	34,960	4.1%	Zone 10	Zone 12	Zone 38
			11,103	11,693	12,163
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,383	1.3%	Zone 64	Zone 69	Zone 97
			3,986		7,397
Total	847,443				

Table 5.56. Total freight flow activities incoming to CCs from PCs and TCs in the SZTC20 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	801,100	90.9%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	37,114	4.2%	Zone 10	Zone 12	Zone 38
			11,432	12,259	13,423
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	43,255	4.9%	Zone 64	Zone 69	Zone 97
			11,018	18,295	13,943
Total	881,469				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.55 and 5.56. Compared to the base scenario, the TC usage for incoming products from PCs decreases from 6% to 5.5% (see Tables 5.3 and 5.55) and for the TC usage outgoing products to CCs decreases from 9.9% to 9.1% (see Tables 5.4 and 5.56). As the percentage of incoming and outgoing flows to/from TCs regarding the zones where they are located is decreased, the direct shipments between PCs and CCs increase. This increase causes TCs to be less preferred. The difference is

due to the incoming flow to TCs from the external node. For incoming products from PCs, the TC in zone 69 is still unused (as can be inferred from Table 5.55).

Table 5.57 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the SZTC20 scenario. In this scenario, since the percentage of incoming and outgoing flows from/to a TC in the same zone is decreased, the utilization of TCs slightly decreases compared to the base scenario. Regarding heavy trucks and trucks; in the noon peak, noon off-peak and evening off-peak time intervals, all TCs are deployed as in the base scenario. In the SZTC20 scenario, in the evening peak time interval, the TCs in the 12^{th}, the 69^{th}, and the 97^{th} zones are utilized (while, in that time interval, except for the TC in the 64^{th} zone, all the others are utilized in the base scenario).

Table 5.57. Capacities and deployments of the TCs in each time interval for different vehicle types in the SZTC20 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	228	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity			236		274	40
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity					340	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity			500		500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity					500	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity		439	660		660	660

Regarding panel vans and electric vans; in the SZTC20 scenario, in the noon peak time interval, only the TC in the 69^{th} zone is fully utilized while, in that time interval, those in the 12^{th} and the 69^{th} zones are deployed at full capacity in the base scenario. In the SZTC20 scenario, in the noon off-peak interval, the TCs in the 38^{th},

the 69th, and the 97th zones are deployed at full capacity (while, in that time interval, in addition to these TCs deployed in the SZTC20 scenario, those in the 10th and the 12th zones are also fully utilized in the base scenario). In the SZTC20 scenario, in the evening peak time interval, only the TC in the 69th zone is deployed at full capacity as in the base scenario. In the SZTC20 scenario, in the evening off-peak time interval, the TCs in the 12th, the 38th, the 69th, and the 97th zones are deployed (while, in that time interval, in addition to those used in the SZTC20 scenario, the TC in the 10th zone is also fully utilized in the base scenario).

5.2.3.3. 40% Upper Bound on the Inflow to and Outflow from a Transshipment Center to the Same Zone (SZTC40). In this scenario, in contrast to the SZTC20 scenario, constraint sets (4.15) and (4.16) are relaxed (with respect to the base scenario) to 40%, as follows:

$$\sum_t \sum_v W_{ii}^{pvt} + \sum_t \sum_v X_{ii}^{pvt} \leq 0.4 \left(\sum_v \sum_t \sum_k X_{ik}^{pvt} + \sum_v \sum_t \sum_s W_{si}^{pvt} \right) \qquad \forall i,\ p \tag{5.4}$$

$$\sum_t \sum_v W_{jj}^{pvt} + \sum_t \sum_v X_{jj}^{pvt} \leq 0.4 \left(\sum_v \sum_t \sum_k X_{jk}^{pvt} + \sum_v \sum_t \sum_s W_{sj}^{pvt} \right) \qquad \forall j,\ p \tag{5.5}$$

The obtained results of the SZTC40 scenario are presented in Tables 5.58-5.64. These results are still very similar to the results of the base scenario. The transportation cost is 3,777,591 ₺ , the CO_2 emission cost is 133,717 ₺ , and the total cost is calculated as 3,911,308 ₺ . Compared to the results of the base scenario, both the transportation and CO_2 emission costs (and hence the total cost) slightly decrease as displayed in Table 5.58. As the products incoming to and outgoing from TCs to other zones decrease, the costs decrease, too. The main reason for that is shipping products from/to a TC in the same zone is cheaper due to shorter distance.

Table 5.58. The transportation, CO_2 emission, and total costs in the base, SZTC20, and SZTC40 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
SZTC20	3,812,073	134,537	3,946,610
SZTC40	3,777,591	133,717	3,911,308

The total number of vehicles in all zones in each time interval in the SZTC40 scenario is presented in Table 5.59. Furthermore, Table 5.60 is prepared to compare the total number of vehicles in the base and SZTC40 scenarios. There is an increase in the total number of vehicles (521 vehicles) compared to the base scenario. The number of heavy trucks increases 5% (89 heavy trucks). There is a small decrease in the number of trucks (47 trucks). However, the number of panel vans increases 73% (479 panel vans). The number of electric vans is still at the upper bound value of 200,000. As the percentage of incoming and outgoing flows from/to a TC in the same zone increases, the preference of TCs slightly increases. This increase in the usage of TCs leads to more vehicle deployment since more vehicles are used both inbound to TCs and outbound from TCs (rather than the single trip associated with a direct shipment) in this two-tiered transportation. This is the main reason for the increase in the number of panel vans. Additionally, due to the increase in the shipments between two TCs and shipments coming from the external zones, the number of heavy trucks increases since only heavy trucks are utilized in these shipments in this scenario. Although the number of trucks is expected to increase due to the increase in the usage of TCs, the total number of trucks decreases because of the decrease in direct shipments. The underlying reason is that the vast majority of direct shipments from PCs to CCs are transported by trucks. Furthermore, this increase in the number of panel vans occurs mainly in the evening off-peak time interval. The fact that the slots of TCs for heavy trucks and trucks are full in this time interval may contribute to the increase in panel vans usage.

The amount of NO_x emitted from these vehicles is 7,937,232 g, and the amount of CO emitted is 6,896,099 g. There is a 1% decrease in the amounts of NO_x and

CO emissions compared to the base scenario which may be explained by the heavier reliance on panel vans.

Table 5.59. The total number of vehicles in all zones in each time interval in the SZTC40 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	520	1,016		408	1,944
Truck	2,244	3,508	2,195	85,044	92,991
Panel van				1,139	1,139
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.60. The total number of vehicles in all zones in the base and SZTC40 scenarios.

	Base	SZTC40
Heavy Truck	1,855	1,944
Truck	93,038	92,991
Panel van	660	1,139
Electric van	200,000	200,000
Total	295,553	296,074

The freight flow of each vehicle type, in each time interval in the SZTC40 scenario is displayed in Table 5.61. As TCs can receive (send) more products from(to) their own zone, the total amount of products shipped directly from PCs to CCs decreases 1% (4,596 tonnes) compared to the base scenario. The fact that TCs can receive more products from PCs and ship more products to CCs in their own zones leads to higher usage of TCs. Additionally, with the shipping of more products through TCs, the direct shipments from PCs to CCs decrease in this scenario, while external zone shipments increase by 5% (1,968 tonnes). At the same time, the amount of products transported between two TCs decreases 21% (192 tonnes). All of these flow changes can be traced to the relaxation of flows from TCs to the CCs in their own zones. Similar to the base scenario, the most intense time of the freight flow is the evening off-peak time interval (73.3%), and the least intense time is the evening peak time interval (7.4%). Electric

vans, which are still deployed at upper bound value in all time intervals, are mostly used in direct shipments from PCs to CCs as in the base scenario.

Table 5.61. Freight flow of each vehicle type, in each time interval in the SZTC40 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	9,194	10,412	3,667	17,823	41,096	43,737
	Panel van						
	Electric van	377	1,000	500	764	2,641	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	465	7,839	9258	25,895	43,457	48,074
	Panel van				2,039	2,039	
	Electric van	340	1,000	500	738	2,578	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	6,406	12,030	9,024	11,603	39,062	42,473
	Panel van				1,947	1,947	
	Electric van	303	500		660	1,463	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	6,373	4,804	6		11,183	11,183
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				596,340	596,340	789,659
	Panel van						
	Electric van	48,980	47,500	49,000	47,839	193,319	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		716			716	716
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				548	548	548
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	10,400	19,597		7,609	37,607	37,606
Total		82,838	105,398	71,955	713,805	973,996	
Rate		8.5%	10.8%	7.4%	73.3%	100%	

The active usage rates of TCs and the amount of freight arrivals/departures from each TC are reported in Tables 5.62 and 5.63. The TC usage for incoming products from PCs increases from 6% to 6.4% (as can be seen in Tables 5.3 and 5.62). Furthermore, this usage for outgoing products to CCs increases from 9.9% to 10.4% (as can be seen in Tables 5.4 and 5.63) compared to the base scenario. This TC usage for incoming products from PCs is 5.5% (see Table 5.55) and for outgoing products to CCs is 9.1% (see Table 5.56) in the SZTC20 scenario. As can be seen, TC usage

for incoming and outgoing products increase in the SZTC40 scenario compared to the base scenario, whereas it decreases in the SZTC20 scenario. This is because, in the SZTC40 scenario, TCs can receive more products from PCs and ship more products to CCs in their own zones (40%) compared to the base scenario. However, in the SZTC20 scenario, fewer intra-zone shipments are allowed between TCs and PCs/CCs in their own zones. This explains the reason for the decrease in the active usage rate of TCs in this scenario. The difference between the incoming and outgoing flow of TCs is mainly due to incoming flows from the external zone. For incoming products from PCs, the TC in zone 69 is still unused (see Table 5.62).

Table 5.62. Total freight flow activities outgoing from PCs to CCs and TCs in the SZTC40 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	789,659	93.6%			
From PCs to TCs on the European Side (W_{si}^{pvt})	42,473	5.0%	Zone 10	Zone 12	Zone 38
			11,773	16,845	13,854
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,183	1.3%	Zone 64	Zone 69	Zone 97
			4,041		7,142
Total	843,315				

Table 5.63. Total freight flow activities incoming to CCs from PCs and TCs in the SZTC40 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	789,659	89.6%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	43,737	5.0%	Zone 10	Zone 12	Zone 38
			12,322	16,845	14,570
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	48,074	5.5%	Zone 64	Zone 69	Zone 97
			10,934	22,129	15,010
Total	881,470				

Table 5.64 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the SZTC40 scenario. In this scenario, since the percentage of incoming and outgoing flows from/to a TC in the same zone is increased, the usage of TCs slightly increases compared to the base scenario. Regarding heavy trucks and trucks; in the SZTC40 scenario, in the noon peak, noon off-peak, and evening off-peak time intervals, all TCs are utilized as in the base and SZTC20 scenarios. In the SZTC40 scenario, in the evening peak time interval, except for the TC in the 64^{th} zone, all the others are utilized, with the 12^{th} and the 69^{th} reaching full capacity (while, in that time interval, only the TCs in the 38^{th}, the 69^{th}, and the 97^{th} zones are utilized in the SZTC20 scenario, and except for the TC in the 64^{th} zone, all the others are utilized in the base scenario).

Table 5.64. Capacities and deployments of the TCs in each time interval for different vehicle types in the SZTC40 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	164	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	17	760	492		760	166
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity	340	340			340	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	500	500	500		500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity		500			500	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	660	660		660	660

Regarding panel vans and electric vans; in the SZTC40 scenario, in the noon peak time interval, the TCs in the 10^{th}, the 12^{th}, and the 69^{th} zones are fully utilized (while, in that time interval, only the TCs in the 12^{th} and the 69^{th} zones are fully utilized in the base scenario, and only the one in the 69^{th} zone is fully utilized in the SZTC20

scenario). In the SZTC40 scenario, in the noon off-peak time interval, the TCs in the 10^{th}, the 12^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones are deployed at full capacity as in the base scenario while, in that time interval, TCs in the 38^{th}, the 69^{th}, and the 97^{th} zones are fully utilized in the SZTC20 scenario. In the SZTC40 scenario, in the evening peak time interval, the TCs in the 12^{th} and the 69^{th} zones are deployed at full capacity while, in that time interval, only the one in the 69^{th} zone is fully utilized in the base and SZTC20 scenarios. In the SZTC40 scenario, in the evening off-peak time interval, except for the TC in the 64^{th} zone, all the others are fully utilized as in the base scenario (while, in that time interval, except for the TCs in the 10^{th} and the 64^{th} zones, all the others are utilized in the SZTC20 scenario).

In summary, in the SZTC40 scenario,

(i) both the transportation and CO_2 emission costs (and hence the total cost) slightly decrease;
(ii) the amount of NO_x and CO emissions slightly decreases;
(iii) while the number of heavy trucks and panel vans increases, the number of trucks decreases;
(iv) the usage of TCs increases;
(v) the amount of direct shipments from PCs to CCs decreases;
(vi) the external zone shipments increase

compared to the base scenario.

In summary, in the SZTC20 scenario,

(i) both the transportation and CO_2 emission costs (and hence the total cost) slightly increase;
(ii) the amount of NO_x and CO emissions slightly increases;
(iii) the number of heavy trucks, trucks, and panel vans decreases;
(iv) the usage of TCs decreases;
(v) the amount of direct shipments from PCs to CCs increases;
(vi) the external zone shipments decrease

compared to the base scenario. All of these changes can be linked to the tightening or relaxation of flows from TCs to the CC in their own zones.

5.2.3.4. Forcing Full Capacities of Production Centers to be Deployed (EXT). In the EXT scenario, in contrast with the base scenario, surplus capacities of PCs are shipped to the external zones, to be sent to other regions of the Nation or to be exported. Two decision variables are added to determine how many products to send to the external zones. One is to determine how much is to be shipped from the TCs on the European side, and the other is to determine how much is to be shipped from the TCs on the Asian side. These decision variables are as follows:

ψ_i^{pt} : Amount of product p transported from TC i on the European Side to external zone in time interval t (tonne)

ψ_j^{pt} : Amount of product p transported from TC j on the Asian Side to external zone in time interval t (tonne).

These variables are embedded to the model constraints and to the objective function as follows:

$$
\begin{aligned}
min\ \Omega = \xi & \left(\sum_{p}\sum_{v}\sum_{t}\sum_{i}\sum_{k} m_{ik}\eta^{vt}X_{ik}^{pvt} + \sum_{p}\sum_{v}\sum_{t}\sum_{j}\sum_{k} m_{jk}\eta^{vt}X_{jk}^{pvt} \right) \\
& + \left(\sum_{p}\sum_{v}\sum_{t}\sum_{i}\sum_{j} m_{ij}\eta^{vt}U_{ij}^{pvt} + \sum_{p}\sum_{v}\sum_{t}\sum_{j}\sum_{i} m_{ji}\eta^{vt}\vartheta_{ji}^{pvt} \right) \\
& + \left(\sum_{p}\sum_{v}\sum_{t}\sum_{s}\sum_{i} m_{si}\eta^{vt}W_{si}^{pvt} + \sum_{p}\sum_{v}\sum_{t}\sum_{s}\sum_{j} m_{sj}\eta^{vt}W_{sj}^{pvt} \right) \\
& + \left(\sum_{p}\sum_{t}\sum_{i} m_{i}^{'}n^{\text{“HT”}\ t}Y_{i}^{pt} + \sum_{p}\sum_{t}\sum_{j} m_{j}^{'}n^{\text{“HT”}\ t}Y_{j}^{pt} \right) \\
& + \left(\sum_{p}\sum_{t}\sum_{i} m_{i}^{'}n^{\text{“HT”}\ t}\psi_{i}^{pt} + \sum_{p}\sum_{t}\sum_{j} m_{j}^{'}n^{\text{“HT”}\ t}\psi_{j}^{pt} \right) \\
& + \xi \left(\sum_{p}\sum_{v}\sum_{t}\sum_{s}\sum_{k} m_{sk}\eta^{vt}Z_{sk}^{pvt} + (\frac{1}{3}) \left[\sum_{p}\sum_{t}\sum_{s}\sum_{k} m_{sk}\eta^{\text{“TR”}t}\ Z_{sk}^{p\text{“TR”}t} \right] \right) \\
& + \kappa\ \beta \left(\sum_{t}\sum_{i}\sum_{k} \left\{ \sum_{v} \left[\frac{\sum_{p} X_{ik}^{pvt}}{c^{v}} oe^{vt} \right] \right\} m_{ik} \right) \\
& + \kappa\ \beta \left(\sum_{t}\sum_{j}\sum_{k} \left\{ \sum_{v} \left[\frac{\sum_{p} X_{jk}^{pvt}}{c^{v}} oe^{vt} \right] \right\} m_{jk} \right) \\
& + \beta \left(\sum_{t}\sum_{i}\sum_{j} \left\{ \sum_{v} \left[\frac{\sum_{p}(U_{ij}^{pvt} + \sum_{p}\vartheta_{ji}^{pvt})}{c^{v}} oe^{vt} \right] \right\} m_{ij} \right) \\
& + \beta \left(\sum_{s}\sum_{i}\sum_{t} \left\{ \sum_{v} \left[\frac{\sum_{p} W_{si}^{pvt}}{c^{v}} oe^{vt} \right] \right\} m_{si} \right) \\
& + \beta \left(\sum_{s}\sum_{j}\sum_{t} \left\{ \sum_{v} \left[\frac{\sum_{p} W_{sj}^{pvt}}{c^{v}} oe^{vt} \right] \right\} m_{sj} \right) \\
& + \beta \left(\sum_{i}\sum_{t} \left[\frac{\sum_{p} Y_{i}^{pt}}{c^{\text{“HT”}}} oe^{\text{“HT”}\ t} \right] m_{i}^{'} \right) + \beta \left(\sum_{j}\sum_{t} \left[\frac{\sum_{p} Y_{j}^{pt}}{c^{\text{“HT”}}} oe^{\text{“HT”}\ t} \right] m_{j}^{'} \right) \\
& + \beta \left(\sum_{i}\sum_{t} \left[\frac{\sum_{p} \psi_{i}^{pt}}{c^{\text{“HT”}}} oe^{\text{“HT”}\ t} \right] m_{i}^{'} \right) + \beta \left(\sum_{j}\sum_{t} \left[\frac{\sum_{p} \psi_{j}^{pt}}{c^{\text{“HT”}}} oe^{\text{“HT”}\ t} \right] m_{j}^{'} \right) \\
& + \kappa\ \beta \left(\sum_{t}\sum_{s}\sum_{k} \left\{ \sum_{v} \left[\frac{\sum_{p} Z_{sk}^{pvt}}{c^{v}} oe^{vt} \right] \right\} m_{sk} \right. \\
& \qquad \left. + \left(\frac{1}{3}\right) \sum_{t}\sum_{s}\sum_{k} \left[\frac{\sum_{p} Z_{sk}^{p\ \text{“TR”}\ t}}{c^{\text{“TR”}}} oe^{\text{“TR”}\ t} \right] m_{sk} \right).
\end{aligned}
\tag{5.6}
$$

Constraint set (4.9) is revised as follows:

$$\sum_{t}\sum_{v}\sum_{i} W_{si}^{pvt} + \sum_{t}\sum_{v}\sum_{j} W_{sj}^{pvt} + \sum_{v}\sum_{t}\sum_{k} Z_{sk}^{pvt} = f_{s}^{p} \qquad \forall s,\ p. \tag{5.7}$$

Constraint set (5.7) ensures that all products produced in PCs are to be shipped to either TCs or to CCs. Since CCs can only receive products up to their demand, the surplus capacity of PCs flowing into TCs will be shipped to external zones.

Furthermore, the demands of CCs will be met. In this case, constraint set (4.2) is updated as follows:

$$\sum_{v}\sum_{t}\sum_{i} X_{ik}^{pvt} + \sum_{v}\sum_{t}\sum_{j} X_{jk}^{pvt} + \sum_{t}\sum_{v}\sum_{s} Z_{sk}^{pvt} = d_{k}^{p} \qquad \forall k,\ p. \tag{5.8}$$

Similar to the shipment of products from an external zone to a TC, products shipped from a TC to an external zone are transported by heavy trucks. Therefore, constraint sets (4.3) and (4.5) that ensure TC capacity restrictions are updated as follows:

$$\sum_{v\in\{\text{HT, TR}\}} \left(\frac{\sum_p \sum_k X_{ik}^{pvt} + \sum_p \sum_j U_{ij}^{pvt} + \sum_p \sum_j \vartheta_{ji}^{pvt} + \sum_p \sum_s W_{si}^{pvt}}{c^{v}} \right) + \frac{\sum_p Y_{i}^{pt}}{c^{\text{“}HT\text{”}}} + \frac{\sum_p \psi_{i}^{pt}}{c^{\text{“}HT\text{”}}} \leq g_{i}^{t} \qquad \forall t,\ i \tag{5.9}$$

$$\sum_{v\in\{\text{HT, TR}\}} \left(\frac{\sum_p \sum_k X_{jk}^{pvt} + \sum_p \sum_i U_{ij}^{pvt} + \sum_p \sum_i V_{ji}^{pvt} + \sum_p \sum_s W_{sj}^{pvt}}{c^{v}} \right) + \frac{\sum_p Y_{j}^{pt}}{c^{\text{“}HT\text{”}}} + \frac{\sum_p \psi_{j}^{pt}}{c^{\text{“}HT\text{”}}} \leq g_{j}^{t} \qquad \forall t,\ j. \tag{5.10}$$

Constraint sets (4.7) and (4.8), which ensure that the amount of each product category incoming to each TC is equal to the amount of each product category outgoing, are also revised. Accordingly, the products shipped from TCs to external zones are revised as follows:

$$\sum_t Y_i^{pt} + \sum_v \sum_t \sum_s W_{si}^{pvt} + \sum_t \sum_v \sum_j \vartheta_{ji}^{pvt} = \sum_v \sum_t \sum_k X_{ik}^{pvt} + \sum_t \sum_v \sum_j U_{ij}^{pvt} + \sum_t \psi_i^{pt} \qquad \forall p,\ i \tag{5.11}$$

$$\sum_t Y_j^{pt} + \sum_v \sum_t \sum_s W_{sj}^{pvt} + \sum_t \sum_v \sum_i U_{ij}^{pvt} = \sum_v \sum_t \sum_k X_{jk}^{pvt} + \sum_t \sum_v \sum_i \vartheta_{ji}^{pvt} + \sum_t \psi_j^{pt} \qquad \forall p,\ j. \tag{5.12}$$

Additionally, constraint sets (4.10) and (4.11) are revised as below by taking into consideration the NO_x/CO emissions emitted by the vehicles traveling between TCs and external zones. Moreover, constraint set (4.12), which limits the number of vehicles in each zone, is also revised in order to include the vehicles, traveling between TCs and external zones, to the model.

$$\sum_v \left\{ \left[\frac{\sum_p \sum_s \sum_i a_{sir} W_{si}^{pvt}}{c^v} + \frac{\sum_p \sum_s \sum_j a_{sjr} W_{sj}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_k a_{ikr} X_{ik}^{pvt} \varepsilon}{c^v} + \frac{\sum_p \sum_j \sum_k a_{jkr} X_{jk}^{pvt} \varepsilon}{c^v} + \frac{\sum_p \sum_s \sum_k a_{skr} Z_{sk}^{pvt} \varepsilon}{c^v} + (\frac{1}{3}) \frac{\sum_p \sum_s \sum_k a_{skr} Z_{sk}^{p\text{“}TR\text{”}t} \varepsilon}{c^{\text{“}TR\text{”}}} + \frac{\sum_p \sum_i \sum_j a_{ijr} U_{ij}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_i a_{jir} \vartheta_{ji}^{pvt}}{c^v} + \frac{\sum_p \sum_i \alpha_{ir} Y_i^{pt}}{c^v} + \frac{\sum_p \sum_j \alpha_{jr} Y_j^{pt}}{c^v} \right] ne^v\ o_r \right\} \leq nb_{rt} \qquad \forall r,\ t \tag{5.13}$$

$$\sum_v \left[\left(\frac{\sum_p \sum_s \sum_i a_{sir} W_{si}^{pvt}}{c^v} + \frac{\sum_p \sum_s \sum_j a_{sjr} W_{sj}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_k a_{ikr} X_{ik}^{pvt} \varepsilon}{c^v} + \frac{\sum_p \sum_j \sum_k a_{jkr} X_{jk}^{pvt} \varepsilon}{c^v} + \frac{\sum_p \sum_s \sum_k a_{skr} Z_{sk}^{pvt} \varepsilon}{c^v} + (\frac{1}{3}) \frac{\sum_p \sum_s \sum_k a_{skr} Z_{sk}^{p\text{“}TR\text{”}t} \varepsilon}{c^{\text{“}TR\text{”}}} + \frac{\sum_p \sum_i \sum_j a_{ijr} U_{ij}^{pvt}}{c^v} + \frac{\sum_p \sum_j \sum_i a_{jir} \vartheta_{ji}^{pvt}}{c^v} + \frac{\sum_p \sum_i \alpha_{ir} Y_i^{pt}}{c^v} + \frac{\sum_p \sum_j \alpha_{jr} Y_j^{pt}}{c^v} \right) ce^v\ o_r \right] \leq cb_{rt} \qquad \forall r,\ t \tag{5.14}$$

$$\sum_{v}\left(\frac{\sum_{p}\sum_{s}\sum_{i}\bar{a}_{sir}h^{v}W_{si}^{pvt}}{c^{v}}+\frac{\sum_{p}\sum_{s}\sum_{j}\bar{a}_{sjr}h^{v}W_{sj}^{pvt}}{c^{v}}+\frac{\sum_{p}\sum_{j}\sum_{k}\bar{a}_{ikr}h^{v}X_{ik}^{pvt}\tau}{c^{v}}\right.$$
$$+\frac{\sum_{p}\sum_{j}\sum_{k}\bar{a}_{jkr}h^{v}X_{jk}^{pvt}\tau}{c^{v}}+\frac{\sum_{p}\sum_{s}\sum_{k}\bar{a}_{skr}h^{v}Z_{sk}^{pvt}\tau}{c^{v}}+(\frac{1}{3})\frac{\sum_{p}\sum_{s}\sum_{k}\bar{a}_{skr}h^{v}Z_{sk}^{p\text{“}TR\text{”}t}\tau}{c^{\text{“}TR\text{”}}}$$
$$+\frac{\sum_{p}\sum_{i}\sum_{j}\bar{a}_{ijr}h^{v}U_{ij}^{pvt}}{c^{v}}+\frac{\sum_{p}\sum_{j}\sum_{i}\bar{a}_{jir}h^{v}\vartheta_{ji}^{pvt}}{c^{v}}+\frac{\sum_{p}\sum_{i}\alpha_{ir}h^{v}Y_{i}^{pt}}{c^{v}}$$
$$\left.+\frac{\sum_{p}\sum_{j}\alpha_{jr}h^{v}Y_{j}^{pt}}{c^{v}}\right)/\gamma_{r}\ \leq\theta_{r}^{t}\qquad\forall r,\ t. \tag{5.15}$$

The obtained results of the EXT scenario are presented in Tables 5.66-5.72. The transportation cost is 3,861,766 ₺ , the CO_2 emission cost is 136,209 ₺ , and the total cost is calculated as 3,997,975 ₺ . As displayed in Table 5.66, compared to the base scenario, the transportation cost increases 2%, the CO_2 emission cost increases 2%, and accordingly, the total cost increases 2%. The reason for this increase in costs is due to forcing the satisfaction of all demand of CCs first through the productions of PCs (instead of the supplies from external zones, which may be less costly).

Table 5.66. The transportation, CO_2 emission, and total costs in the base and EXT scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
EXT	3,861,766	136,209	3,997,975

The total number of vehicles in all zones in each time interval in the EXT scenario is presented in Table 5.67. Additionally, in order to compare the number of vehicles in the base and EXT scenarios, Table 5.61 is provided. There is an increase in the total number of vehicles (1,199 vehicles) compared to the base scenario. The number of heavy trucks decreases 97% (from 1,855 to 55 heavy trucks). As PCs have to send all the products they produce to either CCs or to TCs, they try to meet all demands of CCs. Therefore, as can be seen in Table 5.69, fewer products come from the external

zones, and also fewer products are distributed to the external zones. Since heavy trucks are the primary transportation mode in these flows, the decrease in these (incoming and outgoing) external zone shipments is the most significant factor in the decrease in the number of heavy trucks in this scenario. The number of trucks increases 3% (2,629 trucks). The rise in shipments from PCs to TCs and to CCs is one of the most important reasons for the increase in the number of trucks because the vast majority of these shipments are transported by trucks. Furthermore, the number of panel vans increases 56% (370 panel vans). The most significant increase in the number of panel vans is observed in the flow from TCs to CCs. The number of electric vans is still at the upper bound value of 200,000.

The amount of NO_x emission emitted from non-electric vehicles is 8,175,194 g, and it increases 2% compared to the base scenario. The amount of CO released from these vehicles increases 1% and reaches to 7,051,752 g. The reason for higher emissions are due to the increase in the total number of vehicles.

Table 5.67. The total number of vehicles in all zones in each time interval in the EXT scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck		2		53	55
Truck	3,120	4,584	583	87,379	95,667
Panel van				1,030	1,030
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.68. The total number of vehicles in all zones in the base and EXT scenarios.

	Base	EXT
Heavy Truck	1,855	55
Truck	93,038	95,667
Panel van	660	1,030
Electric van	200,000	200,000
Total	295,553	296,751

Table 5.69. Freight flow of each vehicle type, in each time interval in the EXT scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	9,010	8,902	2,544	16,982	37,437	39,937
	Panel van						
	Electric van	340	500	1,000	660	2,500	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	5,581	4,593		22,331	32,505	34,063
	Panel van				1,294	1,294	
	Electric van		264			264	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	6,590	13,898	3,289	12,709	36,486	39,956
	Panel van				2,310	2,310	
	Electric van		500		660	1,160	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	10,019	18,190		6,840	35,049	35,049
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck		193		611,200	611,393	807,469
	Panel van						
	Electric van	49,660	48,736	49,000	48,680	196,076	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck				19	19	19
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck						
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck						
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck		34			34	34
From TCs on the European Side to External Zone (EX1)	Heavy Truck						
From TCs on the Asian Side to External Zone (EX2)	Heavy Truck				1,039		1,039
Total		81,200	95,810	55,833	724,724	956,527	
Rate		8.5%	10.0%	5.8%	75.7%	100%	

The freight flow of each vehicle type, in each time interval in the EXT scenario is displayed in Table 5.69. The total amount of products shipped directly from PCs to CCs increases 2% (13,214 tonnes) compared to the base scenario as PCs have to send all the products that they produce to either CCs or TCs while satisfying the demand of CCs. Moreover, a small amount of products are transported between two TCs (only 19 tonnes). The amount of products shipped from the external zones to transshipment centers decreases from 36,187 tonnes to 34 tonnes. The amount of products shipped

from TCs to external zones is 1,039 tonnes. In this scenario, PCs have to send their products either to CCs or to the external zones through TCs, while in the base scenario, PCs do not have to ship the excess products to the external zones. This leads to an increase in the amount of products that CCs receive from PCs and a decrease in the amount of products supplied from the external zones. Similar to the base scenario, the most intense time of the freight flow is the evening off-peak time interval (75.7%). The reason for that is the vast majority of the products are distributed by trucks, and the cheapest time interval to transport by trucks is the evening off-peak. The least intense time is the evening peak time interval (5.8%).

Table 5.70. Total freight flow activities outgoing from PCs to CCs and TCs in the EXT scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	807,469	91.5%			
From PCs to TCs on the European Side (W_{si}^{pvt})	39,956	4.5%	Zone 10	Zone 12	Zone 38
			11,948	14,497	13,511
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	35,049	4.0%	Zone 64	Zone 69	Zone 97
			11,350	11,570	12,129
Total	882,474				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are presented in Tables 5.70 and 5.71. Compared to the base scenario, the TC usage for incoming products from PCs increases from 6% to 8.5% (see Tables 5.3 and 5.70) since PCs have to send the products they produce either directly to CCs or to TCs (and thus, to the external zones through TCs) in this scenario. The TC usage for outgoing products to CCs decreases from 9.9% to 8.4% (see Tables 5.4 and 5.71). In addition, with the increase in direct shipments from PCs to CCs, CCs need fewer products through TCs. Furthermore, the decrease in the amount of products coming from the external zones affects the amount of products coming to CCs from

TCs. Another difference from the base scenario is that, for incoming products from PCs, the TC in 69th zone is started to be used, as can be seen in Table 5.70. The reason for this can be explained as follows: PCs send their surplus capacities to the external zones via TCs. This leads to an increase in the shipment from PCs to TCs. Thus, more usage of TCs (hence the 69th zone) is observed.

Table 5.71. Total freight flow activities incoming to CCs from PCs and TCs in the EXT scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	807,469	91.6%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	39,937	4.5%	Zone 10	Zone 12	Zone 38
			11,948	14,478	13,511
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	34,063	3.9%	Zone 64	Zone 69	Zone 97
			11,350	10,584	12,129
Total	881,469				

Table 5.72 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the EXT scenario. PCs meet the demand of CCs directly or through TCs. After satisfaction of demand, surplus capacities of PCs are shipped to the external zones through TCs. Since PCs send more products to TCs, the deployments of TCs increase in this scenario. Regarding heavy trucks and trucks; in the EXT scenario, in the noon peak, noon off-peak, and evening off-peak time intervals, all TCs are used at full capacity, similar to the base scenario. In the EXT scenario, in the evening peak time interval, the TCs in the 10th, the 12th, and the 38th zones are utilized while, in that time interval, all TCs except for the one in the 64th zone are utilized in the base scenario.

Regarding panel vans and electric vans; in the EXT scenario, in the noon peak time interval, the TC in the 12th zone is deployed at full capacity while, in that time

interval, the TCs in the 12^{th} and the 69^{th} zones are fully utilized in the base scenario. In the EXT scenario, in the noon off-peak time interval, the TCs in the 10^{th}, the 38^{th}, and the 97^{th} zones are utilized, with the 10^{th} and the 38^{th} reaching full capacity (while, in that time interval, the TCs in the 10^{th}, the 12^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones are fully utilized in the base scenario). In the EXT scenario, in the evening peak time interval, the TCs in the 12^{th} and the 69^{th} zones are deployed at full capacity while, in that time interval, only the TC in the 69^{th} zone is utilized in the base scenario. In the EXT scenario, in the evening off-peak time interval, the TCs in the 10^{th}, the 12^{th}, the 38^{th}, and the 97^{th} zones are deployed, with the 10^{th}, the 12^{th}, and the 38^{th} reaching full capacity (while, in that time interval, except for the TC in the 64^{th} zone, all the others are fully utilized in the base scenario).

Table 5.72. Capacities and deployments of the TCs in each time interval for different vehicle types in the EXT scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	520	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	4	313	266			
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity		340				
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	500		500			264
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity		500	500			
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	660	660			370

It is a more cost-effective approach to satisfy all demands of CCs from PCs and minimize the shipment of surplus products to external zones since fulfilling demand of CCs from the external zones incurs higher costs. Therefore, in summary, in the EXT scenario,

(i) the amount of direct shipments from PCs to CCs increases;
(ii) the external zone shipments decrease;
(iii) the usage of TCs increases;
(iv) both the transportation and CO_2 emission costs (and hence the total cost) slightly increase due to more direct shipments;
(v) while the TC usage for incoming products from PCs increases, the TC usage for outgoing products to CCs decreases;
(vi) the amount of NO_x and CO emissions slightly increases;
(vii) while the number of heavy trucks decreases, the number of trucks and panel vans increases compared to the base scenario.

5.2.4. Vehicle Based Scenarios

In the base scenario, as can be observed from the constraint set (4.13), in each time interval at most 50,000 electric vans are allowed for freight transportation. While setting this upper bound value, expected future availabilities of electric vans in İstanbul is taken into consideration, which is clearly uncertain. Additionally, maximum range of individual electric van shipments is taken as 30 km, which is also not so definite. Therefore, in this section, some alternative scenarios are developed by revising or removing the constraints/conditions related to the number and usage of electric vans. Furthermore, in order to observe the effect of vehicle densities in zones, two more scenarios are created. Accordingly, the following scenarios are developed:

(i) Number of electric vans available in each time interval to be limited to 100,000 (EVL)
(ii) Number of electric vans available in each time interval to be unlimited (EVU)
(iii) Maximum range of individual trips (shipments) of electric vans to be 100 km (EVR)
(iv) Electric vans and panel vans to be allowed to ship products between TCs (EVP)
(v) Medium level limitation on the number of vehicles per covered area (density level) (VNM)
(vi) Low level limitation on the number of vehicles per covered area (30% lower density

level) (VNL)

5.2.4.1. Number of Electric Vans Available in Each Time Interval to be Limited to 100,000 (EVL). According to constraint set (4.13) in the base scenario, up to 50,000 electric vans are available for each time interval. In this scenario, this upper bound of 50,000 is increased to 100,000.

The obtained results of the EVL scenario are presented in Tables 5.73-5.79. The transportation cost is 3,523,135 ₺ , the CO_2 emission cost is 148,123 ₺ , and the total cost is calculated as 3,671,258 ₺ . The transportation cost is 96% and the CO_2 emission cost is 4% of the total cost. The transportation cost (and the total cost) decreases 7%, and the CO_2 emission cost increases 10% compared to the base scenario (see Table 5.73). Except for the evening off-peak time interval, the unit transportation cost of trucks is higher than that of electric vans. Hence, the decrease in the number of trucks and increase in the number of electric vans lead to such a decrease in the transportation cost. Although unit CO_2 emissions per km are lower for electric vans than other vehicle types, the significant increase in the number of electric vans causes the rise in the CO_2 emission cost.

Table 5.73. The transportation, CO_2 emission, and total costs in the base and EVL scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
EVL	3,523,135	148,123	3,671,258

The total number of vehicles in all zones in each time interval in the EVL scenario is presented in Table 5.74. Additionally, Table 5.75 is provided to compare the number of vehicles in the base and EVL scenarios. As shown in Table 5.74, the deployment of electric vans reaches the maximum limit of 100,000 in all time intervals. Transportation by heavy trucks and electric vans is cheaper than the other vehicle types. Since heavy trucks can only carry products between two TCs and from external zones to TCs,

electric vans are preferred in the shipment of products between other center pairs (from PCs to TCs, TCs to CCs, and PCs to CCs) up to the upper bounds on electric vans. Compared to the base scenario, there is also a 10% decrease (176 heavy trucks) in the number of heavy trucks. The number of trucks also decreases 28% (26,195 trucks) and no panel van is used. The increase in the number of electric vans leads to a decrease in the need for other vehicle types. 193,680 electric vans are used in the flow from PCs to CCs in the base scenario, while 390,839 electric vans are used in the EVL scenario. The significant increase in the number of electric vans in this flow drastically reduces the need for trucks and panel vans.

Table 5.74. The total number of vehicles in all zones in each time interval in the EVL scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	131	1,076		471	1,678
Truck	2,510	3,416	1,156	59,761	66,843
Panel van					
Electric van	100,000	100,000	100,000	100,000	400,000

Table 5.75. The total number of vehicles in all zones in the base and EVL scenarios.

	Base	EVL
Heavy Truck	1,855	1,678
Truck	93,038	66,843
Panel van	660	
Electric van	200,000	400,000
Total	295,553	468,521

The NO_x and CO emissions are also lower in this scenario. The amount of NO_x released from non-electric vehicles is 5,515,553 g, and it decreases 31% compared to the base scenario. Similarly, the amount of CO emitted from these vehicles decreases 32% and it is 4,697,713 g. These emission reductions can be explained by the corresponding decreases in the number of heavy trucks, trucks and panel vans.

Table 5.76. Freight flow of each vehicle type, in each time interval in the EVL scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	8,773	7,106	279	21,298	37,456	41,456
	Panel van						
	Electric van	680	1,000	1,000	1,320	4,000	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	3,889	6,485	2,944	25,001	38,319	41,980
	Panel van						
	Electric van	680	1,000	661	1,320	3,661	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	6,827	15,011	8,336	8,389	38,563	40,063
	Panel van						
	Electric van	340	500		660	1,500	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	5,612	5,553	4		11,169	11,169
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				407,194	407,194	798,033
	Panel van						
	Electric van	98,300	97,500	98,339	96,700	390,839	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		1,366			1,366	1,366
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				27	27	27
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	2,621	20,157		9,399	32,177	32,177
Total		127,722	155,678	111,563	571,308	966,271	
Rate		13.2%	16.1%	11.6%	59.1%	100%	

The freight flow of each vehicle type, in each time interval in the EVL scenario is displayed in Table 5.76. When the freight flows are examined, it is seen that majority of flows are still direct shipments from PCs to CCs. Compared to the base scenario, the increase in the amount of direct shipments is 3,778 tonnes. Electric vans are more advantageous than trucks in terms of cost, except for the evening off-peak time interval. Moreover, the fact that the trucks are not fully loaded on direct flows from PCs to CCs makes electric vans more attractive. Therefore, the increase in the number of electric vans in this scenario is mostly seen in direct flows. With the increase in the amount of direct shipments, fewer products are needed from the external zone. Thus, the external zone shipments decrease 11% (3,983 tonnes). The amount of products

transported between two TCs also increases 51% (458 tonnes). Since the maximum range that electric vans can travel is 30 km, electric vans have become more preferred for short-distance shipments. In order to benefit from these advantages of electric vans, the model prefers electric vans not only for short-distance direct shipments but also for short-distance PCs-TCs and TCs-CCs flows. Hence, with the aim of sending products from PCs to CCs in remote zones, products are first transported from PCs to nearby TCs via electric vans. Next, heavy trucks can be used to transport the products over longer distances between TCs. Then, they are transported from TCs to nearby CCs using electric vans. This may be the reason for the increase in the amount of products transported between two TCs. Electric vans are still deployed at the upper bound value in all time intervals. Similar to the base scenario, the most intense time of the freight flow is the evening off-peak time interval (59.1%). The reason is that the vast majority of products are distributed by trucks, and the cheapest time interval to transport by trucks is the evening off-peak. The least intense time is the evening peak time interval (11.6%).

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.77 and 5.78. Compared to the base scenario, TC usage for incoming products from PCs is almost the same (see Tables 5.3 and 5.77). For outgoing products to CCs, the TC usage decreases from 9.9% to 9.5% (see Tables 5.4 and 5.78). This is because, electric van deployment in direct shipments increases and thus the amount of products shipped through TCs is reduced. Additionally, more products are shipped directly from PCs to CCs, and thus fewer products are received from external zones. Similar to the base scenario, the difference between the incoming and outgoing flow of TCs is mainly due to the incoming flow to TCs from the external node. For incoming products from PCs, the TC in zone 69 is still unused (as can be seen in Table 5.77).

Table 5.77. Total freight flow activities outgoing from PCs to CCs and TCs in the EVL scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	798,033	94.0%			
From PCs to TCs on the European Side (W_{si}^{pvt})	40,063	4.7%	Zone 10	Zone 12	Zone 38
			12,111	16,150	11,802
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,169	1.3%	Zone 64	Zone 69	Zone 97
			2,248		8,921
Total	849,265				

Table 5.78. Total freight flow activities incoming to CCs from PCs and TCs in the EVL scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	798,033	90.5%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	41,456	4.7%	Zone 10	Zone 12	Zone 38
			12,138	16,150	13,168
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	41,980	4.8%	Zone 64	Zone 69	Zone 97
			10,281	17,342	14,357
Total	881,469				

Table 5.79 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the EVL scenario. Compared to the base scenario, although the usage of heavy trucks and trucks decreases, the usage of electric vans increases in TCs. Regarding heavy trucks and trucks; in the EVL scenario, in the noon peak time interval, all TCs are deployed similar to those in the base scenario. In the EVL scenario, in the noon off-peak and evening off-peak time intervals, all TCs are deployed at full capacity as in the base scenario. In the EVL scenario, in the evening

peak time interval, except for the TC in the 64th zone, all TCs are utilized as in the base scenario, with the 12th reaching full capacity.

Table 5.79. Capacities and deployments of the TCs in each time interval for different vehicle types in the EVL scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	41	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	6	760	95		131	163
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity	340	340	340		340	340
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	500	500	500		500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity		500	500		500	161
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	660	660		660	660

In the EVL scenario, although more electric vans use the TCs, no panel van is utilized compared to the base scenario. Regarding electric vans, in the EVL scenario, in the noon peak, noon off-peak, and evening off-peak time intervals, except for the TC in the 64th zone, all the other TCs are fully utilized. This utilization is the same as in the base scenario for the noon off-peak and evening off-peak time intervals. In the EVL scenario, in the evening peak time interval, the TCs in the 12th, the 38th, the 69th, and the 97th are deployed, with the 12th, the 38th, and the 69th reaching full capacity while, in that time interval, only the TC in the 69th zone is fully utilized in the base scenario.

5.2.4.2. Number of Electric Vans Available in Each Time Interval to be Unlimited (EVU). According to constraint set (4.13) in the base scenario, up to 50,000 electric vans are available in each time interval. In this scenario, this constraint is removed so that as many electric vans as the model deems necessary may be deployed.

It should be pointed out that this scenario is fictitious and unrealistic (an unlimited number of electric vans cannot be possible). Its main purpose is to show the "attractiveness" of electric vans and the potential impacts of their "abundant" availability.

The obtained results of the EVU scenario are presented in Tables 5.80-5.86. The transportation cost is 2,912,709 ₺ , the CO_2 emission cost is 146,560 ₺ , and the total cost is calculated as 3,059,269 ₺ . The transportation cost is 95% and the CO_2 emission cost is 5% of the total cost. As depicted in Table 5.80, the transportation cost decreases 23% compared to the base scenario, and 17% compared to the EVL scenario. The CO_2 emission cost increases 9% compared to the base scenario, although it decreases 1% compared to the EVL scenario. Accordingly, the total cost is 22% lower than that of the base scenario, and 17% lower than that of the EVL scenario. Compared to the EVL scenario, the number of heavy trucks and trucks decreases and the number of electric vans drastically increases. Thus, transportation cost decreases can be explained by the fact that unit transportation costs of electric vans are lower than those of trucks and panel vans. The CO_2 emission cost decreases compared to the EVL scenario. The reason is that the unit CO_2 cost of each vehicle is different in each time interval, which differentiates the effects of the changes in the number of vehicles. The increase in the number of electric vans, which is equal in all intervals, leads to increased CO_2 costs (as in the EVL scenario). However, in the EVU scenario, a huge increase in the number of electric vans is observed, especially in the evening peak time interval. In other words, most of the electric vans in different time intervals shift to the evening peak time interval. Therefore, since the unit CO_2 emitted by electric vans in the evening peak time interval is less than that of the other time intervals, the CO_2 emission cost decreases. In addition, the decrease in the number of heavy trucks and trucks also leads to a decrease in CO_2 emission cost.

Table 5.80. The transportation, CO_2 emission, and total costs in the base, EVL, and EVU scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
EVL	3,523,135	148,123	3,671,258
EVU	2,912,709	146,560	3,059,269

The total number of vehicles in all zones in each time interval in the EVU scenario is presented in Table 5.81. Furthermore, in order to compare the number of vehicles in the base, EVL, and EVU scenarios, Table 5.82 is presented. When the upper bound on the deployment of electric vans is removed, the total number of electric vans increases from 200,000 to 773,039. Due to the low unit CO_2 emissions and unit transportation costs of electric vans, a huge rise in the number of electric vans is observed. The number of heavy trucks decreases 16% (306 heavy trucks) compared to the base scenario and 8% (129 heavy trucks) compared to the EVL scenario. Moreover, the number of trucks drastically decreases 81% (75,560 trucks) compared to the base scenario and 74% (49,365 trucks) compared to the EVL scenario due to the sharp increase in the number of electric vans. Panel vans are not used at all in this scenario, as in the EVL scenario. Accordingly, the total number of vehicles increases from 295,553 to 792,066 compared to the base scenario.

There is a decrease in the amount of NO_x and CO emissions. The amount of NO_x released from these vehicles is 2,684,713 g, and it decreases 67% compared to the base scenario and 51% compared to the EVL scenario. Similarly, the amount of CO emitted from these vehicles is 2,129,946 g and decreases 69% compared to the base scenario, and 55% compared to the EVL scenario. These drastic changes in CO and NO_x emissions can easily be explained by the decrease in the number of heavy trucks, trucks, and panel vans and the increase in the number of electric vans.

Table 5.81. The total number of vehicles in all zones in each time interval in the EVU scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	110	1,028		411	1,549
Truck	2,490	3,295	596	11,097	17,478
Panel van					
Electric van	19,136	3,000	746,943	3,960	773,039

Table 5.82. The total number of vehicles in all zones in the base, EVL, and EVU scenarios.

	Base	EVL	EVU
Heavy Truck	1,855	1,678	1,549
Truck	93,038	66,843	17,478
Panel van	660		
Electric van	200,000	400,000	773,039
Total	295,553	468,521	792,066

The freight flow of each vehicle type, in each time interval in the EVU scenario is displayed in Table 5.83. The vast majority of flows are observed in direct shipments from PCs to CCs. The total amount of products shipped directly from PCs to CCs increases 1% (8,544 tonnes) compared to the base scenario and 1% (4,766 tonnes) compared to the EVL scenario. The external zone shipments decrease 28% (9,958 tonnes) compared to the base scenario and 19% (5,975 tonnes) compared to the EVL scenario. Electric vans are more advantageous in terms of both unit cost and CO_2 emission. In addition, the fact that trucks are not fully loaded in direct shipments from PCs to CCs makes electric vans further attractive in these shipments. Due to this low cost delivery alternative via electric vans, fewer products come from external zones. In summary, regarding the direct flows from PCs to CCs, the deployment of electric vans increases from 193,680 to 761,039. Furthermore, since the maximum range that electric vans can travel is 30 km, electric vans have become more preferred for short-distance shipments. In order to benefit from these advantages of electric vans, the model prefers electric vans not only for short-distance direct shipments but

also for short-distance PCs-TCs and TCs-CCs flows. Hence, with the aim of sending products from PCs to CCs in remote zones, products are first transported from PCs to nearby TCs via electric vans. Next, they are shipped between TCs (with long-distance between them) via heavy trucks. Then, they are transported from TCs to nearby CCs via electric vans. For these reasons, the amount of products transported between two TCs increases more than fourfold compared to the base scenario and more than twofold compared to the EVL scenario.

Table 5.83. Freight flow of each vehicle type, in each time interval in the EVU scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	6,934	8,170		22,109	37,213	41,213
	Panel van						
	Electric van	680	1,000	1,000	1,320	4,000	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	4,569	3,187		25,594	33,351	37,456
	Panel van						
	Electric van	1,020	926	1,500	660	4,106	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	8,666	12,263	5,958	7,591	34,479	36,478
	Panel van						
	Electric van	340	500	500	660	2,000	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	4,735	9,333			14,068	15,962
	Panel van						
	Electric van		574		1,320	1,894	
From PCs to CCs (Z_{sk}^{pvt})	Truck				41,760	41,760	802,799
	Panel van						
	Electric van	17,096		743,943		761,039	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		4,734			4,734	4,734
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck						
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	2,191	15,825		8,212	26,229	26,228
Total		46,231	56,512	752,901	109,226	964,873	
Rate		4.8%	5.9%	78.0%	11.3%	100%	

One peculiar feature of this scenario is that 746,943 of 773,039 electric vans are deployed in the evening-peak time interval, since the unit transportation cost and

unit CO_2 emission for electric vans are the lowest in this time interval. So, while the most intense time of the freight flow is the evening off-peak time interval in the base scenario, it is the evening-peak time interval (78.0%) in this scenario. On the other hand, assigning this huge number of vehicles to the already dense evening peak time interval may be quite unrealistic. The least intense time is the noon off-peak time interval (4.8%) in the EVU scenario, while it is the evening-peak time interval in the base and EVL scenarios. Furthermore, although it seems unrealistic to utilize 773,039 electric vans, this number represents the number of trips made by electric vans. Some vehicles can also make more than one trip. Therefore, the required number of registered electric vans is lower in real life. Moreover, in various countries, there is a significant increase in the utilization of electric vans due to environmental considerations, and most governments aim to achieve these figures in a few years.

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.84 and 5.85. Compared to the base scenario, the TC usage for incoming products from PCs increases from 6% to 6.1% (as can be seen in Tables 5.3 and 5.84). The effect of the increase in the number of electric vans is mostly seen in direct shipments. For outgoing products to CCs, the TC usage decreases from 9.9% to 8.9% (as can be seen in Table 5.4 and 5.85). Since more products are shipped from PCs, fewer products are received from external zones. Another reason is that most of the trucks and panel vans are replaced by electric vans, and transporting the same load with electric vans rather than trucks and panel vans requires more vehicles. However, the low capacities of TCs for electric vans prevent the increase in the utilization rate of TCs. Note that the TC usage for incoming products from PCs is 6% and for outgoing products to CCs is 9.5% in the EVL scenario. As the amount of products coming from external zones decreases, the difference between the incoming and outgoing flow of TCs decreases. For incoming products from PCs, the TC in zone 69 is still unused (see Table 5.84).

Table 5.84. Total freight flow activities outgoing from PCs to CCs and TCs in the EVU scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	802,799	93.9%			
From PCs to TCs on the European Side (W_{si}^{pvt})	36,478	4.3%	Zone 10	Zone 12	Zone 38
			12,370	15,309	8,800
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	15,962	1.9%	Zone 64	Zone 69	Zone 97
			4,774		11,187
Total	855,239				

Table 5.85. Total freight flow activities incoming to CCs from PCs and TCs in the EVU scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	802,799	91.1%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	41,213	4.7%	Zone 10	Zone 12	Zone 38
			12,370	15,309	13,533
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	37,456	4.2%	Zone 64	Zone 69	Zone 97
			8,253	16,467	12,738
Total	881,468				

Table 5.86 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the EVU scenario. When the limit on the number of electric vans is removed, the usage of electric vans increases, and the usage of heavy trucks and trucks decreases compared to the base scenario. This decrease in the number of heavy trucks and trucks is also observed in the deployment of TCs. Regarding heavy trucks and trucks; in the EVU scenario, in the noon peak time interval, except for the TC in the 64^{th} zone, all TCs are fully utilized while, in that time interval, all TCs are utilized in the base and EVL scenarios. In the EVU scenario, in the noon

off-peak and evening off-peak time intervals, all TCs are deployed at full capacity as in the base and EVL scenarios. In the EVU scenario, in the evening peak time interval, the TCs in the 10^{th} and the 12^{th} zones are utilized while, in that time interval, except for the TC in the 64^{th} zone, all the others are deployed in the base scenario.

Table 5.86. Capacities and deployments of the TCs in each time interval for different vehicle types in the EVU scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520		520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	4	592				
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity	340	340	340	340	340	340
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	500	500	500	500	500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity	500	500	500	500	500	500
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	660	660	660	660	660

In the EVU scenario, panel vans are not deployed, and there is a considerable increase in the number of electric vans. The number of electric vans using TCs reaches full capacity in all time intervals. This result shows that the current capacities of TCs prevent the utilization of more electric vans in the usage of TCs. In the base scenario, except for the TC in the 64^{th} zone, all TCs are fully utilized only in the noon off-peak and evening off-peak time intervals.

5.2.4.3. Maximum Range of Individual Trips of Electric Vans to be 100 km (EVR).

In the base scenario, the range of electric vans is set to be 30 km. It is obvious that the range of electric vans is normally greater, and the problems associated with charging electric vans are not addressed in this thesis. If the range of electric vans is taken higher, it will not be possible to charge an electric van within the same time interval

since it will take longer to charge, and thus, multiple trips by the same vehicle in the same interval would not be possible. Even so, this scenario is created in order to analyze the outcomes obtained when the range is set as 100 km.

The obtained results of the EVR scenario are presented in Tables 5.87-5.93. As can be seen in Table 5.87, the transportation cost is 3,606,361 ₺ , the CO_2 emission cost is 141,900 ₺ , and the total cost is calculated as 3,748,262 ₺ . The transportation cost is 96% and the CO_2 emission cost is 4% of the total cost. Compared to the base scenario, the transportation cost decreases 5%, the CO_2 emission cost increases 6%, and accordingly, the total cost decreases 5%. The slight decrease in the number of heavy trucks and trucks leads to a decrease in the transportation cost. Although there is a slight decrease in the number of heavy trucks and trucks, an increase in the amount of CO_2 emissions is observed due to the fact that electric vans now travel longer distances. Additionally, the increase in the number of panel vans contributes to this cost.

Table 5.87. The transportation, CO_2 emission, and total costs in the base and EVR scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
EVR	3,606,361	141,900	3,748,262

Table 5.88. The total number of vehicles in all zones in each time interval in the EVR scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	520	525		786	1,831
Truck	2,105	3,997	777	85,356	92,235
Panel van				1,522	1,522
Electric van	50,000	50,000	50,000	50,000	200,000

The total number of vehicles in all zones in each time interval in the EVR scenario is presented in Table 5.88. Furthermore, Table 5.89 is provided to compare the number

of vehicles in the base and EVR scenarios. The number of heavy trucks slightly decreases 1% (24 heavy trucks); the number of trucks also decreases 1% (803 trucks). However, the number of panel vans increases 131% (from 660 to 1,522 panel vans). Since shipping with electric vans is a less costly option, they are primarily preferred in direct shipments between PCs and CCs, even for connecting remote zone pairs. Since the number of electric vans that can be used is limited, panel vans or trucks are used in other flows, such as from TCs to CCs, PCs to TCs, and PCs to CCs that are close to each other. For instance, the decrease in the number of electric vans in the flow from TCs to CCs leads to an increase in the usage of panel vans. The number of electric vans is still at the upper bound value of 200,000.

The amount of NO_x released from non-electric vehicles is 6,662,735 g, which decreases by 17% compared to the base scenario. Furthermore, the amount of CO emitted is 5,806,131 g, which drops 16% compared to the base scenario. In this scenario, although the number of electric vans does not increase, the distance they can travel increases. This causes other vehicle types to travel less. This is the main reason for the decrease in the amount of NO_x and CO emissions. Since the unit NO_x and CO emission values of panel vans are quite low compared to those of trucks and heavy trucks, the increase in the number of panel vans still does not cause an increase in the total amount of NO_x and CO emissions.

Table 5.89. The total number of vehicles in all zones in the base and EVR scenarios.

	Base	EVR
Heavy Truck	1,855	1,831
Truck	93,038	92,235
Panel van	660	1,522
Electric van	200,000	200,000
Total	295,553	295,588

Table 5.90. Freight flow of each vehicle type, in each time interval in the EVR scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	10,262	7,139		1,811	35,212	37,514
	Panel van				2,302	2,302	
	Electric van						
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	4,509	10,168	5,883	21,876	42,436	44,029
	Panel van						
	Electric van	242	500	191	660	1,593	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	5,338	15,275	1,883	11,850	34,346	36,664
	Panel van				2,318	2,318	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	943	7,387			8,330	9,038
	Panel van				708	708	
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				601,519	601,519	799,926
	Panel van						
	Electric van	49,758	49,500	49,809	49,340	198,407	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		774			774	774
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				77	77	77
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	10,400	9,717		15,647	35,764	35,764
Total		81,452	100,460	57,766	724,108	963,786	
Rate		8.5%	10.4%	6.0%	75.1%	100%	

The freight flow of each vehicle type, in each time interval in the EVR scenario is displayed in Table 5.90. Compared to the base scenario, the total amount of products shipped directly from PCs to CCs increases 1% (5,671 tonnes) since, in this scenario, electric vans can transport freights for longer distances. Accordingly, the number of electric vans used for direct shipments increases. Since PCs meet the demands of more CCs directly, PCs ship fewer products through TCs and fewer products are needed from the external zones. Thus, the amount of external zone shipments decreases 1% (345 tonnes) and the amount of products transported between two TCs decreases 15% (134 tonnes). Due to the increased range of electric vans, it is more profitable to meet the demands of CCs from remote PCs rather than from external zones with electric

vans. This is also a factor in the decrease in external zone shipments. Since the products coming from the external zones are also shipped through the TCs, there is also a decrease in the utilization of TCs. Similar to the base scenario, the most intense time of the freight flow is the evening off-peak time interval (75.1%). The reason is that the majority of products are distributed by trucks, and the cheapest time interval to transport by trucks is the evening off-peak. The least intense time is the evening peak time interval (6.0%).

Table 5.91. Total freight flow activities outgoing from PCs to CCs and TCs in the EVR scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	799,926	94.6%			
From PCs to TCs on the European Side (W_{si}^{pvt})	36,664	4.3%	Zone 10	Zone 12	Zone 38
			11,350	13,346	11,967
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	9,038	1.1%	Zone 64	Zone 69	Zone 97
			3,692		5,346
Total	845,628				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.91 and 5.92. Compared to the base scenario, the TC usage for incoming products from PCs decreases from 6% to 5.4% (see Tables 5.3 and 5.91) and for outgoing products to CCs, the TC usage decreases from 9.9% to 9.3% (see Tables 5.4 and 5.92). As in the base scenario, the difference is mainly due to the incoming flow to TCs from the external nodes. In this scenario, since the range of electric vans is increased from 30 km to 100 km, the direct shipments by electric vans between remote PCs and CCs increase (as the usage of electric vans is a less costly alternative than trucks and panel vans). The fact that PCs ship more products directly to CCs and fewer products via TCs is the reason for the decrease in their usage. Furthermore, receiving fewer products from external zones to TCs is another

reason for the decline in TC usage.

Table 5.92. Total freight flow activities incoming to CCs from PCs and TCs in the EVR scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	799,926	90.7%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	37,514	4.3%	Zone 10	Zone 12	Zone 38
			11,350	13,423	12,741
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	44,029	5.0%	Zone 64	Zone 69	Zone 97
			10,088	20,117	13,823
Total	881,469				

Table 5.93 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the EVR scenario. Compared to the base scenario, with the increase in the range of electric vans, shipping products directly from PCs to CCs is more favorable than shipping products to CCs through TCs. Furthermore, the external zone shipments decrease, and thus, the utilization of TCs decreases since fewer vehicles visit TCs. Regarding heavy trucks and trucks; in the EVR scenario, in the noon peak time interval, only the TC in the 64^{th} zone is deployed but not fully utilized, and all the others are fully utilized as in the base scenario. In the EVR scenario, in the noon off-peak and evening off-peak time intervals, all TCs are fully utilized as in the base scenario. In the EVR scenario, in the evening peak time interval, the TCs in the 12^{th}, the 38^{th}, and the 69^{th} zones are used but not fully utilized while, in that time interval, except for the TC in the 64^{th} zone, all the others are utilized in the base scenario.

Table 5.93. Capacities and deployments of the TCs in each time interval for different vehicle types in the EVR scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	25	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity		180	8		588	
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity					242	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity					500	
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity					191	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity		660	660		660	202

Regarding panel vans and electric vans; in the EVR scenario, in the noon peak, noon off-peak, and evening peak time intervals, only the TC in the 69^{th} zone is utilized (while, in the base scenario, the TCs in the 12^{th} and the 69^{th} zones are fully utilized in the noon peak time interval). In the base scenario, except for the TC in the 64^{th} zone, all the others are deployed at full capacity in the noon off-peak time interval, and only the TC in the 69^{th} zone is fully utilized in the evening peak time interval. In the EVR scenario, in the evening off-peak time interval, the TCs in the 12^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones are utilized, with the 12^{th}, the 38^{th}, and the 69^{th} reaching full capacity (while, in that time interval, except for the TC in the 64^{th} zone, all the others are deployed at full capacity in the base scenario).

5.2.4.4. Electric Vans and Panel Vans to be Allowed to Ship Products Between Transshipment Centers (EVP). In the base scenario, the utilization of panel vans and electric vans between TCs are not allowed. However, in this scenario, the relevant constraints are removed (constraint sets 4.27 and 4.28) and the utilization of panel vans and electric vans between TCs is allowed.

The obtained results of the EVP scenario are presented in Tables 5.94-5.99. Similar to the base scenario, the transportation cost is 3,795,724 ₺ , the CO_2 emission cost is 134,158 ₺ , and the total cost is calculated as 3,929,882 ₺ . Accordingly, the transportation cost is 97% and the CO_2 emission cost is 3% of the total cost.

As can be inferred from Tables 5.1-5.5 and Tables 5.94-5.99, the results of the EVP and base scenarios are almost the same, except for minor differences of freight flows and the NO_x and CO emission values. This can be explained as follows: Although the utilization of panel vans and electric vans between the TCs is allowed in this scenario, the results demonstrate that there is no usage of panel vans and electric vans between TCs.

Table 5.94 demonstrates the total number of vehicles in all zones in each time interval in the EVP scenario. As shown in Table 5.1, the utilization of the vehicles are the same as in the base scenario. Electric vans are highly preferred, and their deployment reaches the maximum limit of 50,000 in all periods. Panel van usage is very low. The amount of NO_x emitted from these vehicles is 8,014,984 g, and it increases 311 g compared to the base scenario. The amount of CO emitted from these vehicles is 6,948,465 g for all periods, and it increases 275 g. The reason for that is the small differences in freight flows.

Table 5.94. The total number of vehicles in all zones in each time interval in the EVP scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	520	926		409	1,855
Truck	2,244	3,589	1,597	85,608	93,038
Panel van				660	660
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.95. The total number of vehicles in all zones in the base and EVP scenarios.

	Base	EVP
Heavy Truck	1,855	1,855
Truck	93,038	93,038
Panel van	660	660
Electric van	200,000	200,000
Total	295,553	295,553

Table 5.96. Freight flow of each vehicle type, in each time interval in the EVP scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	7,616	8,268	2,863	20,080	38,827	41,193
	Panel van						
	Electric van	340	866	500	660	2,366	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	465	8,638	7,875	25,883	42,861	46,021
	Panel van						
	Electric van	340	1,000	500	1,320	3,160	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	7,984	14,078	5,225	9,346	36,634	39,737
	Panel van				2,310	2,310	
	Electric van		134		660	794	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	6,379	4,906	4		11,289	11,289
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				600,575	600,575	794,255
	Panel van						
	Electric van	49,320	48,000	49,000	47,360	193,680	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		908			908	908
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				547	547	547
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	10,400	17,605		7,635	35,640	35,640
Total		82,844	104,403	65,967	71,6376	969,591	
Rate		8.5%	10.8%	6.8%	73.9%	100%	

As can be seen in Table 5.96, the majority of products are transported during the evening off-peak time interval (73.9%), while the least are transported during in the

evening peak time interval (6.8%). The great majority of flows are direct shipments from PCs to CCs (94.0%) for products outgoing from PCs. While a total of 51,027 tonnes of products come from PCs to TCs, a total of 36,187 tonnes of products come from the external zones to the TCs (see Table 5.2). These results are also the same as in the base scenario.

Table 5.97. Total freight flow activities outgoing from PCs to CCs and TCs in the EVP scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	794,255	94.0%			
From PCs to TCs on the European Side (W_{si}^{pvt})	39,737	4.7%	Zone 10	Zone 12	Zone 38
			11,551	15,106	13,081
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,289	1.3%	Zone 64	Zone 69	Zone 97
			4,073		7,216
Total	845,281				

Table 5.98. Total freight flow activities incoming to CCs from PCs and TCs in the EVP scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	794,255	90.1%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	41,193	4.7%	Zone 10	Zone 12	Zone 38
			12,098	15,106	13,989
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	46,021	5.2%	Zone 64	Zone 69	Zone 97
			10,800	20,583	14,637
Total	881,469				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.97 and 5.98. The TC usage for incoming products from PCs is 6%, and for outgoing products to CCs is 9.9%. These results are the same as in the base scenario (see Tables 5.3 and 5.4).

Table 5.99. Capacities and deployments of the TCs in each time interval for different vehicle types in the EVP scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	164	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	6	436	366		618	170
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity		340			340	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	500	500	500		500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity					500	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	660	660		660	660

Table 5.99 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the EVP scenario. As can be seen in Table 5.5, these results are the same as in the base scenario.

5.2.4.5. Medium Level Limitation on the Number of Vehicles per Covered Area (Density Level) (VNM). In this scenario, the limit on the number of vehicles per km^2 in each zone and in each time interval is reduced (see Appendix A.14). So, the upper bounds of constraint set 4.12 (which is 12,000 in the base scenario) are revised based on the vehicle numbers (densities) obtained in the base scenario, as follows: i) for the values greater than 8,000, the upper bound is revised as 6,000; ii) for the values between 6,000-8,000, the upper bound is revised as 4,500; iii) for the values between 4,000-6,000, the upper bound is revised as 3,000; iv) for the values between 0-4,000, the upper bound is revised as 1,500.

The obtained results of the VNM scenario are presented in Tables 5.100-5.106. The transportation cost is 3,831,976 ₺ , the CO_2 emission cost is 134,910 ₺ , and the total cost is calculated as 3,966,885 ₺ . As can be observed from Table 5.100, both the transportation and CO_2 emission costs (and accordingly the total cost) increase when the maximum number of vehicles per covered area in each zone is restricted as described. Compared to the base scenario, the transportation cost and the CO_2 emission cost increase 1%. This is because as the constraint on the number of vehicles per unit area becomes tighter, vehicles shift to different routes and higher cost time intervals. This situation directly affects the total distance traveled and costs.

Table 5.100. The transportation, CO_2 emission, and total costs in the base and VNM scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
VNM	3,831,976	134,910	3,966,885

The total number of vehicles in all zones in each time interval in the VNM scenario is presented in Table 5.101. In order to compare the number of vehicles in the base and the VNM scenarios, Table 5.102 is provided. Compared to the base scenario, there is a 13% (239 heavy trucks) increase in the number of heavy trucks and an 89% (585 panel vans) increase in the number of panel vans. However, the number of trucks decreases 1% (691 trucks). The number of electric vans is still at the upper bound value of 200,000. In this scenario, due to the limit on the number of vehicles in each time interval in each zone, the usage of some trucks is replaced by panel vans and heavy trucks. The usage of heavy trucks can be advantageous in reducing density in zones since their PCE value is 3.5 and the load-carrying capacity is 20 tonnes. However, heavy trucks are only used in the shipments from external zones to TCs and the shipments between two TCs. On the other hand, the PCE value of a panel van is 1, with a load capacity of 3.5 tonnes, and the PCE value of a truck is 2.5, with a load capacity of 10 tonnes. Furthermore, trucks traveling between PCs and CCs are assumed to be loaded at 75%

capacity. Although trucks are advantageous in terms of costs in the base scenario, they are less preferred in the VNM scenario due to the congestion they create.

The amount of NO_x emitted from non-electric vehicles is 7,962,664 g, and it decreases only 1% compared to the base scenario. Similarly, the amount of CO emitted from these vehicles decreases 2% (to 6,828,118 g). The decrease in the number of trucks can be explained as the cause of the drop in the amount of NO_x and CO emissions.

Table 5.101. The total number of vehicles in all zones in each time interval in the VNM scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	550	985	114	445	2,094
Truck	2,479	10,020	1,471	78,377	92,347
Panel van				1,245	1,245
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.102. The total number of vehicles in all zones in the base and VNM scenarios.

	Base	VNM
Heavy Truck	1,855	2,094
Truck	93,038	92,347
Panel van	660	1,245
Electric van	200,000	200,000
Total	295,553	295,686

The freight flow of each vehicle type, in each time interval in the VNM scenario is displayed in Table 5.103. Compared to the base scenario, the total amount of products shipped directly from PCs to CCs decreases only 0.2% (1,461 tonnes), and the amount of products transported between two TCs decreases 34% (310 tonnes). However, the external zone shipments increase 14% (5,090 tonnes). The usage of TCs provides the opportunity to consolidate loads and enable them to be transported by larger vehicles. For example, heavy trucks with a PCE value of 3.5 and a load-carrying capacity of 20 tonnes provide a great advantage in this respect. This is an important reason that

the external zone shipments (where the primary transportation mode is heavy trucks) increase. Furthermore, since trucks are not loaded at full capacity in direct shipments from PCs to CCs, the share of trucks (with a PCE value of 2.5 and load-carrying capacity of 10 tonnes) in these shipments decreases. Therefore, as the number of trucks decreases, the amount of products transported in this flow also decreases. The most intense time of the freight flow is the evening off-peak time interval (68.5%), and this intensity decreases 5.4% compared to the base scenario. This is because vehicles shift to different time intervals and routes due to the relevant density constraint. The least intense time is the evening peak time interval (6.9%), similar to the base scenario.

Table 5.103. Freight flow of each vehicle type, in each time interval in the VNM scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	8,143	5,885	1,456	20,874	36,357	40,093
	Panel van				2,019	2,019	
	Electric van			1,000	716	1,716	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	788	10,342	7,126	25,667	43,924	48,582
	Panel van				2,310	2,310	
	Electric van	340	849	500	660	2,349	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	7,158	16,915	6,132	8,411	38,617	38,663
	Panel van				28	28	
	Electric van				19	19	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	6,126	2,608			8,734	8,734
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck	1,929	48,336		546,614	596,878	792,795
	Panel van						
	Electric van	49,660	49,151	48,500	48,605	195,916	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (v_{ji}^{pvt})	Heavy Truck	598				598	598
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				831	831	831
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	10,400	19,701	2,280	8,065	40,446	40,446
Total		85,142	153,787	66,994	664,819	970,742	
Percentage		8.8%	15.8%	6.9%	68.5%	100%	

Table 5.104. Total freight flow activities outgoing from PCs to CCs and TCs in the VNM scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	792,795	94.4%			
From PCs to TCs on the European Side (W_{si}^{pvt})	38,663	4.6%	Zone 10	Zone 12	Zone 38
			11,067	14,469	13,127
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	8,734	1.0%	Zone 64	Zone 69	Zone 97
			3.857		4,877
Total	840,192				

Table 5.105. Total freight flow activities incoming to CCs from PCs and TCs in the VNM scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	792,795	89.9%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	40,093	4.5%	Zone 10	Zone 12	Zone 38
			11,898	14,469	13,725
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	48,582	5.5%	Zone 64	Zone 69	Zone 97
			11,325	21,533	15,724
Total	881,470				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.104 and 5.105. The limit on the total number of vehicles in each zone in each time interval (due to the density constraint) affects the freight flows. Due to the increase in external zone shipments, fewer products are shipped from PCs either directly to CCs or through TCs. This (fewer inflows to TCs from PCs) causes a decrease from 6.0% to 5.6% (see Tables 5.3 and 5.104) in the TC usage for incoming products from PCs compared to the base scenario. However, the

TC usage for outgoing products to CCs increases from 9.9% to 10.1% (see Tables 5.4 and 5.105). The increase in the amount of products coming from the external zones to TCs leads to an increase in the amount of products going from TCs to CCs. For incoming products from PCs, the TC in zone 69 is still unused.

Table 5.106. Capacities and deployments of the TCs in each time interval for different vehicle types in the VNM scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	201	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity		574	185		760	67
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity					340	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity					500	349
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity		500	500		500	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660		660		660	660

Table 5.106 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the VNM scenario. Compared to the base scenario, the utilizations of TCs vary among intervals, especially for panel vans and electric vans. Also, there is a decrease in the usage of TCs for these vehicle types. Regarding heavy trucks and trucks; in the VNM scenario, in the noon peak time interval, all TCs are deployed, and except for the one in the 64^{th} zone, all TCs are fully utilized as in the base scenario. In the VNM scenario, in the noon off-peak and evening off-peak time intervals, all TCs are deployed at full capacity as in the base scenario. In the VNM scenario, in the evening peak time interval, the TCs in the 12^{th}, the 38^{th}, the 69^{th} and the 97^{th} zones are deployed, with the 69^{th} reaching full capacity (while, in that time interval, except for the TC in the 64^{th} zone, all the others are utilized but not fully utilized in the base scenario).

Regarding panel vans and electric vans; in the VNM scenario, in the noon peak time interval, only the TC in the 69th zone is deployed at full capacity while, in that time interval, those in the 12th and the 69th zones are fully utilized in the base scenario. In the VNM scenario, in the noon off-peak time interval, the TCs in the 69th and the 97th zones are deployed, with the 69th reaching full capacity (while, in that time interval, except for the one in the 64th zone, all the others are fully utilized in the base scenario). In the VNM scenario, in the evening peak time interval, the TCs in the 12th, the 38th, and the 69th zones are fully utilized while, in that time interval, only the one in the 69th zone is deployed at full capacity in the base scenario. In the VNM scenario, in the evening off-peak time interval, the TCs in the 10th, the 38th, the 69th, and the 97th zones are deployed at full capacity (while, in that time interval, except for the one in the 64th zone, all the others are fully utilized in the base scenario).

5.2.4.6. Low Level Limitation on the Number of Vehicles per Covered Area (30% Lower Density Level) (VNL). In this scenario, the bounds used in the VNM scenario have been further reduced (See Appendix A.15). Therefore, the upper bounds of constraint set 4.12 in each zone and in each time interval (which are 1,500, 3,000, 4,500, and 6,000 in the VNM scenario) are revised by examining the density values obtained in the base scenario as follows: i) for the values greater than 8,000, the upper bound is revised as 4,500; ii) for the values between 6,000-8,000, the upper bound is revised as 3,000; iii) for the values between 4,000-6,000, the upper bound is revised as 2,000; iv) for the values between 0-4,000, the upper bound is revised as 1,000.

The obtained results of the VNL scenario are presented in Tables 5.107-5.113. The transportation cost is 4,057,578 ₺ , the CO_2 emission cost is 140,321 ₺ , and the total cost is calculated as 4,197,900 ₺ . As can be observed from Table 5.107, both the transportation and CO_2 emission costs (and accordingly the total cost) increase when the maximum number of vehicles per covered area in each zone is further restricted as described compared to the base and VNM scenarios. The transportation cost increases 7% compared to the base scenario and 6% compared to the VNM scenario. The CO_2 emission cost increases 5% compared to the base scenario and 4% compared to the

VNM scenario. Since the upper bound values on the number of vehicles per unit area are such reduced (making the relevant constraint tighter), vehicles shift to higher cost routes and higher cost time intervals.

Table 5.107. The transportation, CO_2 emission, and total costs in the base, VNM, and VNL scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
VNM	3,831,976	134,910	3,966,885
VNL	4,057,578	140,321	4,197,900

The total number of vehicles in all zones, in each time interval in the VNL scenario is displayed in Table 5.108. Additionally, Table 5.109 provides for the comparison of the number of vehicles in the base, VNM, and VNL scenarios. As can be seen, the number of heavy trucks increases 36% (662 heavy trucks) compared to the base scenario and 20% (424 heavy trucks) compared to the VNM scenario. However, the number of trucks decreases 6% (5,551 trucks) compared to the base scenario and 5% (4,860 trucks) compared to the VNM scenario. Furthermore, there is a significant increase in the number of panel vans. It increases from 660 to 11,804 panel vans compared to the base scenario, whereas there are 1,245 panel vans in the VNM scenario. The number of electric vans is still at the upper bound value of 200,000. Due to the reduced limit on the number of vehicles in each zone, vehicles are diverted to different routes and different time intervals. In this scenario, the usage of some trucks is replaced by panel vans and heavy trucks. As the relevant constraint becomes tighter, there is an increase in the number of high-capacitated vehicles such as heavy trucks. The usage of heavy trucks can be advantageous in reducing density in zones since their PCE value is 3.5 and the load-carrying capacity is 20 tonnes. In addition, the share of panel vans in direct shipments from PCs to CCs increases and thus, the total number of panel vans as well. So, similar to the VNM scenario, trucks are less preferred in the VNL scenario due to the congestion they create.

The amount of NO_x emitted from non-electric vehicles increases to 8,045,681 g. It is only 0.4% higher than that of the base scenario and 1.0% higher than that of the VNM scenario. Furthermore, the amount of CO emitted from these vehicles is 6,920,919 g. It is 0.4% lower than that of the base scenario and 1.4% higher than that of the VNM scenario. The reason for the increase in the amount of NO_x and CO emissions is due to the additional distance traveled by all vehicles resulting from tighter vehicle density limits. Furthermore, compared to the VNM scenario, the increase in the number of heavy trucks and panel vans also causes an increase in emissions. However, there is a slight decrease in the amount of CO emissions compared to the base scenario. This decrease can be attributed to the decrease in the number of trucks.

Table 5.108. The total number of vehicles in all zones in each time interval in the VNL scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	520	840	338	819	2,517
Truck	10,765	24,174	2,775	49,773	87,487
Panel van		646	269	10,889	11,804
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.109. The total number of vehicles in all zones in the base, VNM, and VNL scenarios.

	Base	VNM	VNL
Heavy Truck	1,855	2,094	2,517
Truck	93,038	92,347	87,487
Panel van	660	1,245	11,804
Electric van	200,000	200,000	200,000
Total	295,553	295,686	301,808

Table 5.110. Freight flow of each vehicle type, in each time interval in the VNL scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	9,055	11,105	1,193	19,011	40,364	44,528
	Panel van		926		2,310	3,236	
	Electric van	128	140		660	928	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	8,738	14,403	7,450	22,768	53,358	57,169
	Panel van				2,310	2,310	
	Electric van	340	500		660	1,500	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	6,545	11,695	14,007	9,431	41,678	42,012
	Panel van		334			334	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	1,662		4,365		6,028	9,339
	Panel van		1,002		2,310	3,312	
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck	61,234	153,402	552	334,890	550,079	779,772
	Panel van			940	31,182	32,121	
	Electric van	49,532	49,360	50,000	48,680	197,572	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck						
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				2,516	2,516	2,516
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	10,400	16,794	6,770	138,65	47,828	47,829
Total		147,634	259,661	85,277	490,593	983,164	
Percentage		15.0%	26.4%	8.7%	49.9%	100%	

The freight flow of each vehicle type, in each time interval in the VNL scenario is displayed in Table 5.110. It can be seen that the majority of flows are still direct shipments from PCs to CCs. Nevertheless, the total amount of products shipped directly from PCs to CCs decreases 2% (14,482 tonnes) compared to the base scenario and 2% (13,021 tonnes) compared to the VNM scenario. There is no product transported between two TCs. Also, a noteworthy increase is observed in the external zone shipments. It increases 39% (14,158 tonnes) compared to the base scenario and 22% (9,068 tonnes) compared to the VNM scenario. In this scenario, due to the fact that the restrictions on the number of vehicles are tighter than in the VNM scenario, the direct shipments from PCs to CCs decrease, and the amount of products coming from the

external zones through TCs increases. This is because the usage of TCs provides the opportunity to consolidate loads and enable them to be transported by larger vehicles, such as heavy trucks. Furthermore, in direct shipments from PCs to CCs, trucks (with a PCE value of 2.5 and a load-carrying capacity of 10 tonnes) are not loaded at full capacity. Thus, in direct shipments, the share of trucks decreases, and the share of panel vans (with a PCE value of 1 and load-carrying capacity of 3.5 tonnes) increases. In other flows, such as from PCs to TCs and from TCs to CCs, trucks can be loaded at full capacity. This is one of the reasons that the amount of products shipped from TCs to CCs increases due to the density constraint. Electric vans are mostly used in direct shipments from PCs to CCs. The most intense time of freight flow is the evening off-peak time interval (49.9%), as in the base and VNM scenarios. The least intense time is the evening peak time interval (8.7%), as in the base and VNM scenarios. Compared to the base and VNM scenarios, the intensity in the evening off-peak time interval decreases (24% and 18.6%, respectively), and the intensity in the evening peak time interval increases (1.9% and 1.8%, respectively) in the VNL scenario.

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.111 and 5.112. Compared to the base scenario, the TC usage for incoming products from PCs increases from 6% to 6.2% (see Tables 5.3 and 5.111), while it is 5.6% in the VNM scenario. The limit on the total number of vehicles in each zone in each time interval (due to the density constraint) affects the freight flows. Compared to the VNM and base scenarios, due to the decrease in direct shipments from PCs to CCs, more products are shipped from PCs to TCs. This results in an increase in TC usage for incoming products from PCs. Compared to the base scenario, the TC usage for outgoing products to CCs increases from 9.9% to 11.5% (see Tables 5.4 and 5.112) in the VNL scenario. Meanwhile, it is 10.1% in the VNM scenario, as shown in Table 5.105. Compared to the base and VNM scenarios, since the amount of products coming from the external zones and from PCs to TCs increases in the VNL scenario, the amount of products shipped through TCs to CCs also increases. This results in an increase in TC usage for outgoing products to CCs. For incoming products from PCs, the TCs in zone 69 is unused, as in the base and VNM scenarios.

Table 5.111. Total freight flow activities outgoing from PCs to CCs and TCs in the VNL scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	779,772	93.8%			
From PCs to TCs on the European Side (W_{si}^{pvt})	42,012	5.1%	Zone 10	Zone 12	Zone 38
			10,627	14,380	17,005
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	9,339	1.1%	Zone 64	Zone 69	Zone 97
			1,662		7,678
Total	831,123				

Table 5.112. Total freight flow activities incoming to CCs from PCs and TCs in the VNL scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	779,772	88.5%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	44,528	5.1%	Zone 10	Zone 12	Zone 38
			12,031	15,492	17,005
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	57,169	6.5%	Zone 64	Zone 69	Zone 97
			15,019	22,300	19,849
Total	881,469				

Table 5.113 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the VNL scenario. As can be seen in this table, most of the TCs are fully utilized regarding heavy trucks and trucks. This occupancy of TCs indicates that the capacities of TCs are not sufficient in the VNL scenario for these vehicles. However, the capacities of TCs seem to be sufficient for panel vans and electric vans.

Table 5.113. Capacities and deployments of the TCs in each time interval for different vehicle types in the VNL scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	520	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity		760	760		760	760
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity		128			340	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity			500		500	286
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity						
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660		660	660	660	660

Regarding heavy trucks and trucks; in the VNL scenario, all TCs are deployed at full capacity in the noon peak time interval, while in that time interval, except for the one in the 64^{th} zone, all TCs are fully utilized in the base and VNM scenarios. In the VNL scenario, in the noon off-peak and evening off-peak time intervals, all TCs are deployed at full capacity as in the base and VNM scenarios. In the VNL scenario, in the evening peak time interval, TCs in the 12^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones are fully utilized (while, in that time interval, four TCs are utilized, with one of them reaching full capacity in the VNM scenario, and five TCs are utilized in the base scenario).

Regarding panel vans and electric vans; in the VNL scenario, in the noon peak time interval, TCs in the 12^{th} and the 69^{th} zones are utilized, with the 69^{th} reaching full capacity (while, in that time interval, these TCs are fully utilized in the base scenario, and only the one in the 69^{th} zone is fully utilized in the VNM scenario). In the VNL scenario, in the noon off-peak time interval, TCs in the 38^{th}, the 69^{th}, and the 97^{th} zones are utilized, with the 38^{th} and the 69^{th} reaching full capacity (while, in that time interval, except for the one in the 64^{th} zone, all TCs are deployed at full capacity in

the base scenario, and TCs in the 69^{th} and the 97^{th} zones are deployed, with the 69^{th} reaching full capacity in the VNM scenario). In the VNL scenario, in the evening peak time interval, none of the TCs is utilized (while, in that time interval, only the one in the 69^{th} zone is fully utilized in the base scenario, and TCs in the 12^{th}, the 38^{th}, and the 69^{th} zones are fully utilized in the VNM scenario). In VNL scenario, in the evening off-peak time interval, except for the one in the 12^{th} zone, all TCs are deployed at full capacity (while, in that time interval, except for the one in the 64^{th} zone, all TCs are fully utilized in the base scenario, and TCs in the 10^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones are fully utilized in the VNM scenario).

In conclusion, as the constraint on the number of vehicles in each zone, in each time interval becomes tighter;

(i) both the transportation and CO_2 emission costs (and hence the total cost) increase;
(ii) the number of heavy trucks and panel vans increases, and the number of trucks decreases;
(iii) the amount of direct shipments from PCs to CCs decreases;
(iv) the external zone shipments increase;
(v) the TC usage for outgoing products to CCs increases.

5.2.5. Deadheading Scenarios

Since there is no definite percentage of deadheading trips for İstanbul, in the base scenario it is assumed that deadheading trips are at the maximum level (one for each supply carrying - live trip). Hence, in this section, different deadheading percentages are considered leading to different levels of transportation and CO_2 emission costs, density levels, amount of NO_x/CO emissions, and related flow structures. The following scenarios are developed:

(i) Deadheading percentages at medium level (DHM)
(ii) Deadheading percentages at low level (DHL)

5.2.5.1. Deadheading Percentages at Medium Level (DHM). In this scenario, the deadheading trip percentage is considered at medium level. At this level, it is assumed that the deadheading trip percentage is 80% of the live trips (density levels), leading to 60% of the transportation cost, 40% of the CO_2 emission cost, and 50% of the amount of NO_x and CO emissions. In other words, while there is a 100% increase in the number of live trips as a result of deadheading in the base scenario, it is assumed that the number of live trips increases by 80% due to the deadheading in the DHM scenario. In addition, it is assumed that deadheading trips cause a 60% increase in transportation cost and a 40% increase in CO_2 emission costs in the DHM scenario, although it is presumed that deadheading trips result in a 79% rise in transportation cost and a 61% rise in CO_2 emission cost in the base scenario. Additionally, in the DHM scenario, it is assumed that deadheading trips lead to an 50% rise in the amount of NO_x and CO emissions, while in the base scenario, it is estimated that they cause a 72% increase in NO_x and CO emissions. Vehicles may not always return with empty trailers and may find loads to transport on the return trip. Therefore, in order to take this into account, these deadheading trip percentages are taken into account as explained.

The obtained results of the DHM scenario are presented in Tables 5.114-5.120. The transportation cost is 3,409,206 ₺ , the CO_2 emission cost is 117,331 ₺ , and the total cost is calculated as 3,526,538 ₺ . As shown in Table 5.114, compared to the base scenario, the transportation cost decreases 10%, the CO_2 emission cost decreases 13%, and accordingly, the total cost decreases 10%. The decrease in these costs is due to the fact that deadheading percentages are lower than those in the base scenario.

Table 5.114. The transportation, CO_2 emission, and total costs in the base and DHM scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
DHM	3,409,206	117,331	3,526,538

Table 5.115. The total number of vehicles in all zones in each time interval in the DHM scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	520	850		405	1,775
Truck	2,105	3,670	778	86,149	92,702
Panel van				373	373
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.116. The total number of vehicles in all zones in the base and DHM scenarios.

	Base	DHM
Heavy Truck	1,855	1,775
Truck	93,038	92,702
Panel van	660	373
Electric van	200,000	200,000
Total	295,553	294,850

The total number of vehicles in all zones in each time interval in the DHM scenario is presented in 5.115. Additionally, in order to compare the number of vehicles in the base and DHM scenarios, Table 5.116 is provided. In this scenario, due to the decreases in the shipments incoming from the external zones and the shipments between two TCs, the number of heavy trucks utilized in the transportation of these flows decreases 4% (80 heavy trucks). There is a slight decrease in the number of trucks (336 trucks). The number of panel vans also decreases 43% (287 panel vans). The number of electric vans is still at the upper bound value of 200,000. They are mostly used in direct shipments from PCs to CCs. In this scenario, the utilization of TCs decreases. Since the usage of TCs requires more trucks (as vehicles are used both on the way to the TC and returning from the TC), the decrease in the usage of TCs results in less vehicle deployment.

The amount of NO_x emitted from non-electric vehicles is 7,046,345 g and decreases 12% compared to the base scenario. Similarly, the amount of CO released from these vehicles decreases 12% and drops to 6,104,311 g. The decrease in deadheading trip emissions (from 72% to 50% compared to the base scenario as explained in Section 3.3.11) leads to the above quoted reduction in the amount of NO_x and CO emissions.

Table 5.117. Freight flow of each vehicle type, in each time interval in the DHM scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	6,675	7,378		20,533	34,587	34,945
	Panel van				359	359	
	Electric van						
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck		8,404	7,777	25,739	41,921	45,080
	Panel van						
	Electric van	340	1,000	500	1,320	3,160	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	8,925	15,023		9,080	33,028	33,975
	Panel van				947	947	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	5,452	5,894	4		11,349	11,350
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				604,602	604,602	801,442
	Panel van						
	Electric van	49,660	49,000	49,500	48,680	196,840	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		798			798	798
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				174	174	174
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	10,400	16,206		7,923	34,529	34,529
Total		81,452	103,703	57,781	719,357	962,294	
Rate		8.5%	10.8%	6.0%	74.7%	100%	

The freight flow of each vehicle type, in each time interval in the DHM scenario is displayed in 5.117. There is a 1% increase in the amount of products shipped directly from PCs to CCs compared to the base scenario (7,187 tonnes). Deadheading trips related to the incoming flows to CCs (from PCs or TCs) are always taken into account in cost and emission computations. Since deadheading percentages are reduced in this scenario, the direct shipments from PCs to CCs become less costly. Therefore, the amount of products shipped directly increases. Due to the increase in these direct shipments, fewer products are needed from the external zones to satisfy CCs. The decrease in external zone shipments is 4% (1,484 tonnes). The amount of products transported between two TCs decreases 12% (110 tonnes). As direct shipments from

PCs to CCs increase, shipping via TCs decreases. In addition, the decrease in external zone shipments results in a decrease in the usage of TCs. This causes the shipments between two TCs to decrease. As can be seen in Table 5.117, the most intense time of freight flow is the evening off-peak time interval (74.7%), and the least intense time is the evening peak time interval (6.0%) similar to the base scenario.

Table 5.118. Total freight flow activities outgoing from PCs to CCs and TCs in the DHM scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	801,442	94.6%			
From PCs to TCs on the European Side (W_{si}^{pvt})	33,975	4.0%	Zone 10	Zone 12	Zone 38
			11,220	11,417	11,338
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,350	1.3%	Zone 64	Zone 69	Zone 97
			3,133		8,216
Total	846,767				

Table 5.119. Total freight flow activities incoming to CCs from PCs and TCs in the DHM scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	801,442	90.9%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	34,945	4.0%	Zone 10	Zone 12	Zone 38
			11,393	11,417	12,136
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	45,080	5.1%	Zone 64	Zone 69	Zone 97
			10,258	20,583	14,239
Total	881,467				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.118 and 5.119. Compared to the base scenario, the TC usage rate for incoming products from PCs decreases from 6% to 5.4% (see Tables 5.3 and 5.118), and the TC usage rate for outgoing products to CCs decreases from 9.9% to 9.1% (see Tables 5.4 and 5.119). As the deadheading rates decrease (in the flows from PCs to CCs and TCs to CCs), the shipments from PCs to CCs become less costly. Therefore, the shipments from PCs to CCs increase, and the shipments from external zones and from PCs to TCs decrease. For these reasons, the usage of TCs decreases. For incoming products from PCs, the TC in zone 69 is still unused (as can be seen in Table 5.118).

Table 5.120. Capacities and deployments of the TCs in each time interval for different vehicle types in the DHM scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	25	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity					618	161
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity					340	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity					500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity					500	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity		38	335		660	660

Table 5.120 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the DHM scenario. The increase in direct shipments results in less need for products coming from PCs or external zone through TCs. Regarding heavy trucks and trucks; in the DHM scenario, in the noon peak time interval, all TCs are deployed, and except for the TC in the 64^{th} zone, all the others are fully utilized as in the base scenario. In the DHM scenario, in the noon off-peak

and evening off-peak time intervals, all TCs are fully utilized as in the base scenario. In the DHM scenario, in the evening peak time interval, the TC in the 69^{th} and the 97^{th} zones are utilized while, in that time interval, except for the TC in the 64^{th} zone, all the others are deployed in the base scenario.

Regarding panel vans and electric vans; in the DHM scenario, in the noon peak time interval, only the TC in the 69^{th} zone is fully utilized while, in that time interval, in addition to the TC in the 69^{th} zone, the one in the 12^{th} zone is also deployed at full capacity in the base scenario. In the DHM scenario, in the noon off-peak time interval, the TCs in the 69^{th} and the 97^{th} zones are fully utilized while, in that time interval, those in the 10^{th}, the 38^{th}, the 69^{th}, and the 97^{th} zones are deployed at full capacity in the base scenario. In the DHM scenario, in the evening peak time interval, only the TC in the 69^{th} zone is deployed at full capacity as in the base scenario. In the DHM scenario, in the evening off-peak time interval, except for the TCs in the 10^{th}, and the 64^{th} zones, all the others are utilized, with the 69^{th} and the 97^{th} reaching full capacity while, in that time interval, except for the TC in the 64^{th} zone, all the others are fully utilized in the base scenario.

5.2.5.2. Deadheading Percentages at Low Level (DHL). In this scenario, the deadheading trip percentage is considered at low level. At this level, it is assumed that the deadheading trip percentage is 60% of the live trips (density levels), leading to 40% of the transportation cost, 20% of the CO_2 emission cost, and 25% of the amount of NO_x and CO emissions. In other words, while there is a 100% increase in the number of live trips as a result of deadheading in the base scenario, it is assumed that the number of live trips increases by 60% due to the deadheading in the DHM scenario. In addition, it is assumed that deadheading trips cause a 40% increase in transportation cost and a 20% increase in CO_2 emission costs in the DHM scenario, although it is presumed that deadheading trips result in a 79% rise in transportation cost and a 61% rise in CO_2 emission cost in the base scenario. Similarly, in the DHM scenario, it is assumed that deadheading trips lead to a 25% rise in the amount of NO_x and CO emissions, while in the base scenario, it is estimated that they cause a 72% increase in NO_x and

CO emissions. Vehicles may not always return with empty trailers and may find loads to transport on the return trip. Therefore, in order to take this into account, these deadheading trip percentages are considered as explained.

The obtained results of the DHL scenario are presented in Tables 5.121-5.127. The transportation cost is 3,000,350 ₺ , the CO_2 emission cost is 101,223 ₺ , and the total cost is calculated as 3,101,572 ₺ . Due to the decreased deadheading percentages, both the transportation and CO_2 emissions (and accordingly the total) costs decrease compared to the results of the base and the DHM scenarios. As presented in Table 5.121, the transportation cost decreases 21% compared to the base scenario and 12% compared to the DHM scenario. The CO_2 emission cost decreases 25% compared to the base scenario and 14% compared to the DHM scenario. Accordingly, the total cost is 21% lower than that of the base scenario and 12% lower than that of the base scenario. These results imply that as the deadheading trip percentages decrease, the transportation and CO_2 emission costs decrease, too.

Table 5.121. The transportation, CO_2 emission, and total costs in the base, DHM, and DHL scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
DHM	3,409,206	117,331	3,526,538
DHL	3,000,350	101,223	3,101,572

The total number of vehicles in all zones in each time interval in the DHL scenario is presented in Table 5.122. Additionally, 5.123 is provided to compare the number of vehicles in the base, DHM, and DHL scenarios. Due to the decrease in the shipments incoming from the external zones and the shipments between two TCs, the number of heavy trucks utilized in the transportation of these flows decreases 20% (367 heavy trucks) compared to the base scenario and 16% (287 heavy trucks) compared to the DHM scenario. There is a slight decrease in the number of trucks compared to the base scenario (62 trucks) but a notable increase of 274 trucks compared to the DHM

scenario. Furthermore, a sharp decrease in the number of panel vans is observed, which is 96% (from 660 to 26 panel vans) compared to the base scenario and 93% (from 373 to 26 panel vans) compared to the DHM scenario. It is the decrease in the flow from PCs to TCs that leads to this decrease in the number of panel vans, because most of the panel vans are deployed in this flow. The increase in direct shipments from PCs to CCs and the decrease in the usage of TCs also cause a reduction in the number of vehicles since direct shipments (related to single trip) require less vehicle deployment rather than two-tiered transportation. The number of electric vans is still at the upper bound value of 200,000.

Table 5.122. The total number of vehicles in all zones in each time interval in the DHL scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	75	990		423	1,488
Truck	2,525	3,538	57	86,856	92,976
Panel van				26	26
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.123. The total number of vehicles in all zones in the base, DHM, and DHL scenarios.

	Base	DHM	DHL
Heavy Truck	1,855	1,775	1,488
Truck	93,038	92,702	92,976
Panel van	660	373	26
Electric van	200,000	200,000	200,000
Total	295,553	294,850	294,490

The amount of NO_x emitted from non-electric vehicles is 5,954,151 g and decreases 26% compared to the base scenario and 16% compared to the DHM scenario. Similarly, the amount of CO emitted from these vehicles decreases 26% compared to the base scenario, 16% compared to the DHM scenario, and drops to 5,152,872 g. The decrease in deadheading trip emissions (from 72% to 25% compared to the base scenario as

explained in Section 3.3.11) leads to the above quoted reduction in the amount of NO_x and CO emissions.

Table 5.124. Freight flow of each vehicle type, in each time interval in the DHL scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	6,987	6,363		20,861	34,211	34,211
	Panel van						
	Electric van						
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	5,543	5,547	566	25,471	37,127	39,937
	Panel van				88	88	
	Electric van	340	1,000	296	1,086	2,721	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	8,613	16,115		8,839	33,567	33,567
	Panel van						
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	4,103	7,357			11,461	11,464
	Panel van				4	4	
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				610,044	610,044	807,322
	Panel van						
	Electric van	49,660	49,000	49,704	48,914	197,279	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		644			644	644
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck						
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	1,508	19,148		8,458	29,115	29,114
Total		76,754	105,174	50,566	723,765	956,261	
Rate		8.0%	11.0%	5.3%	75.7%	100%	

The freight flow of each vehicle type, in each time interval, in the DHL scenario is displayed in Table 5.124. The amount of products shipped directly from PCs to CCs increases 2% (13,067 tonnes) compared to the base scenario and 1% (5,880 tonnes) compared to the DHM scenario. Deadheading trips related to the incoming flows to CCs (from PCs or TCs) are always taken into account in cost and emission computations. As the deadheading percentages decrease, the direct shipments from PCs to CCs increase since these shipments become less costly. The amount of products

transported between two TCs decreases 29% (269 tonnes) compared to the base scenario and 19% (154 tonnes) compared to the DHM scenario. Moreover, the external zone shipments decrease 29% (7,072 tonnes) compared to the base scenario and 16% (5,588 tonnes) compared to the DHM scenario. As the amount of products shipped directly from PCs to CCs increases, fewer products are needed from the external zones. Also, fewer products arrive from PCs to the TCs, as can be seen in Table 5.124. This decrease in the usage of TCs also causes less freight flow between TCs. As in the base and DHM scenarios, the most intense time of freight flow is the evening off-peak time interval (75.7%), and the least intense time is the evening peak time interval (5.3%), as displayed in Table 5.124.

Table 5.125. Total freight flow activities outgoing from PCs to CCs and TCs in the DHL scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	807,322	94.7%			
From PCs to TCs on the European Side (W_{si}^{pvt})	33,567	3.9%	Zone 10	Zone 12	Zone 38
			11,350	11,350	10,867
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,464	1.3%	Zone 64	Zone 69	Zone 97
			2,567		8,898
Total	852,353				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.125 and 5.126. Compared to the base scenario, the TC usage rate for incoming products from PCs decreases from 6% to 5.3% (see Tables 5.3 and 5.125), and the TC usage rate for outgoing products to CCs decreases from 9.9% to 8.4% (see Tables 5.4 and 5.126). Meanwhile, the TC usage for incoming products from PCs is 5.4%, and the TC usage for outgoing products to CCs is 9.1% in the DHM scenario, as shown in Tables 5.118 and 5.119. As the deadheading trip percentages in the flows going directly from PCs and through TCs to CCs decrease, the

direct shipments from PCs to CCs become less costly. Therefore, the shipments from PCs to CCs increase, and thus, the shipments from external zones to TCs decrease. For these reasons, the usage of TCs decreases. For incoming products from PCs, the TC in zone 69 is still unused (as can be interpreted from Table 5.125).

Table 5.126. Total freight flow activities incoming to CCs from PCs and TCs in the DHL scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	807,322	91.6%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	34,211	3.9%	Zone 10	Zone 12	Zone 38
			11,350	11,350	11,511
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	39,937	4.5%	Zone 64	Zone 69	Zone 97
			10,382	16,708	12,846
Total	881,470				

Table 5.127 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the DHL scenario. The increase in direct shipments results in less need for products coming from PCs or external zones through TCs. In the DHL scenario, since the deadheading cost rates are lower than those in the base and the DHM scenarios, the utilization of TCs decreases further. Regarding heavy trucks and trucks; in the DHL scenario, in the noon peak time interval, five TCs are fully utilized (while, in that time interval, all TCs are utilized in the base and DHM scenarios). In the DHL scenario, in the noon off-peak and evening off-peak time intervals, all TCs are deployed at full capacity as in the base and DHM scenarios. In the DHL scenario, in the evening peak time interval, only one TC is utilized, while in that time interval, two TCs are utilized in the DHM scenario, and five TCs are utilized in the base scenario.

Table 5.127. Capacities and deployments of the TCs in each time interval for different vehicle types in the DHL scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520		520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity					57	
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity					340	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity					500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity					296	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity					660	452

Regarding panel vans and electric vans; in the DHL scenario, the utilization of TCs are also lower. In the noon peak time interval, only one TC is fully utilized as in the DHM scenario, while in that time interval, two TCs are fully utilized in the base scenario. In the DHL scenario, in the noon off-peak time interval, two TCs are fully utilized as in the DHM scenario, while in that time interval, five TCs are deployed at full capacity in the base scenario. In the DHL scenario, in the evening peak time interval, only one TC is utilized similar to the base and DHM scenarios. In the DHL scenario, in the evening off-peak time interval, two TCs are utilized, with one of them reaching full capacity while, in that time interval, four TCs are utilized in the DHM scenario, and five TCs are fully utilized in the base scenario.

In summary, reduction in deadheading rates (related with CC flows) leads to transportation cost reductions, increase of direct flows from PCs to CCs, reduction in the usage and utilization of TCs, reduction in the usage of external zone shipments and heavy trucks and a decrease in NO_x and CO emissions.

5.2.6. Emission Scenarios

In order to examine the effects of changes or limitations on CO_2 emissions on the city logistics of İstanbul, the EMCO2 scenario is created. Furthermore, two more scenarios are prepared by lowering the upper bound on the amount of NO_x and CO emissions (the EM15 and EM30 scenarios). This set of emission scenarios is listed below:

(i) Scenario with different CO_2 emission values (EMCO2)
(ii) NO_x and CO emission boundaries are decreased 15% (EM15)
(iii) NO_x and CO emission boundaries are decreased 30% (EM30)

According to the report of the European Environment Agency, the amount of NO_x emitted in Turkey is about 371,232,877 g in a single day by the road-transport sector in 2020. It is stated that about 40% of this, which is 148,493,151 g, is emitted by light-duty and heavy-duty vehicles [81]. According to the results of the base scenario, the amount of NO_x emitted only in İstanbul in a single day is 8,014,673 g. These findings demonstrate that the NO_x levels estimated in our model align with realistic expectations. Therefore, while limiting the amount of NO_x and CO emissions in the EM15 and EM30 scenarios, the values calculated in the base scenario are taken into account.

5.2.6.1. Scenario with Different CO_2 Emission Values (EMCO2). In this scenario, different CO_2 values are applied instead of using the CO_2 values in the base scenario. The rapid change in technology also shows its effect on the vehicle industry. Such a scenario is prepared in order to see the effects of vehicles manufactured with different technologies and having different CO_2 emissions. While designating these new CO_2 emission values, not only different sources are referenced, but also the ratios between the CO_2 values in different time intervals in the base scenario are utilized. These new CO_2 values are displayed in Table 5.128 [57, 79, 82].

Table 5.128. New unit CO_2 emissions used in the EMCO2 scenario (g/km) [57, 79, 82].

	Heavy Truck	Truck	Panel van	Electric van
Noon peak	983.6	515.2	300.0	204.0
Noon off-peak	876.0	459.6	256.6	236.8
Evening peak	1,536.8	803.8	334.0	177.6
Evening off-peak	753.1	395.5	220.7	236.8

The obtained results of the EMCO2 scenario are presented in Tables 5.129-5.135. Since the transportation cost is 96% and the CO_2 emission cost is 4% of the total cost, compared to the results of the base scenario, the transportation and total costs only slightly increase. As for the CO_2 emission cost, this increase is about 26% due to the increase in the unit CO_2 emissions of heavy trucks and electric vans. In this scenario, the unit CO_2 emissions of heavy trucks and electric vans are higher than those in the base scenario, and the unit CO_2 emissions of trucks and panel vans are lower than those in the base scenario.

The amount of emissions is not changed much compared to the base scenario. The amount of NO_x is 8,028,734 g and the amount of CO emitted from these vehicles is 6,957,559 g.

Table 5.129. The transportation, CO_2 emission, and total costs in the base and EMCO2 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
EMCO2	3,796,029	168,522	3,964,551

The total number of vehicles in all zones in each time interval in the EMCO2 scenario is presented in Table 5.130. Additionally, in order to compare the number of vehicles in the base and EMCO2 scenarios, Table 5.131 is provided. The number of heavy trucks slightly decreases (22 heavy trucks) and the number of trucks slightly increases (32 trucks) due to the increase/decrease in their CO_2 emissions in this

scenario. There is no change in the number of panel vans and electric vans. The number of electric vans is still at the upper bound value of 200,000.

Table 5.130. The total number of vehicles in all zones in each time interval in the EMCO2 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	564	894		375	1,833
Truck	2,200	3,666	1,584	85,620	93,070
Panel van				660	660
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.131. The total number of vehicles in all zones in the base and EMCO2 scenarios.

	Base	EMCO2
Heavy Truck	1,855	1,833
Truck	93,038	93,070
Panel van	660	660
Electric van	200,000	200,000
Total	295,553	295,563

The freight flow of each vehicle type, in each time interval in the EMCO2 scenario is displayed in Table 5.132. These results are not significantly different from those in the base scenario. The effect of trucks, which have lower CO_2 emission costs, is seen in direct shipments, since most of the products that are sent directly from PCs to CCs are transported by trucks. Compared to the base scenario, the total amount of products shipped directly from PCs to CCs increases only 21 tonnes. Furthermore, since CO_2 emissions of heavy trucks are higher than those in the base scenario, the amount of products transported between two TCs decreases 4% (35 tonnes) and the external zone shipments decrease 1% (408 tonnes). This is in line with the reduced number of heavy trucks. Similar to the base scenario, the most intense time of the freight flow is the evening off-peak time interval (73.8%), and the least intense time is the evening peak

time interval (6.8%). Electric vans, which are still deployed at upper bound value in all time intervals, are mostly used in direct shipments from PCs to CCs.

Table 5.132. Freight flow of each vehicle type, in each time interval in the EMCO2 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	7,635	7,450	3,066	19,966	38,117	40,777
	Panel van						
	Electric van	340	1,000		1,320	2,660	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	465	8,408	7,954	26,109	42,937	46,415
	Panel van						
	Electric van	659	1,000	500	1,320	3,479	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	7,528	15,350	4,819	9,571	37,268	39,578
	Panel van				2,310	2,310	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	6,375	5,457	4		11,836	11,836
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				600,415	600,415	794,276
	Panel van						
	Electric van	49,001	48,000	49,500	47,360	193,861	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck	873				873	873
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				327	327	327
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	10,400	17,870		7,182	35,452	35,452
Total		83,276	104,535	65,843	715,880	969,535	
Rate		8.6%	10.8%	6.8%	73.8%	100%	

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.133 and 5.134. As expected, the TC usage for incoming flows from PCs and for outgoing flows to CCs are almost the same as in the base scenario (see Tables 5.3 and 5.4).

Table 5.133. Total freight flow activities outgoing from PCs to CCs and TCs in the EMCO2 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	794,276	93.9%			
From PCs to TCs on the European Side (W_{si}^{pvt})	39,578	4.7%	Zone 10	Zone 12	Zone 38
			11,886	14,506	13,186
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,836	1.4%	Zone 64	Zone 69	Zone 97
			4,620		7,216
Total	845,690				

Table 5.134. Total freight flow activities incoming to CCs from PCs and TCs in the EMCO2 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	794,276	90.1%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	40,777	4.6%	Zone 10	Zone 12	Zone 38
			12,213	14,506	14,059
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	46,415	5.3%	Zone 64	Zone 69	Zone 97
			10,929	20,583	14,903
Total	881,468				

Table 5.135 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the EMCO2 scenario. Since trucks and heavy trucks use the same docks in TCs and since their overall numbers are about the same in the EMCO2 scenario, the occupancy rates of TCs in the EMCO2 scenario for heavy trucks and trucks are very similar to those in the base scenario.

Table 5.135. Capacities and deployments of the TCs in each time interval for different vehicle types in the EMCO2 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	208	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	6	400	382		618	178
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity	340				340	319
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	500		500		500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity					500	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	660	660		660	660

Since the numbers of electric vans and panel vans are the same as in the base scenario, there is no significant change in the number of vehicles occupying TCs. In the noon peak time interval, three TCs are used in the EMCO2 scenario, while two TCs are used in the base scenario. In the noon off-peak time interval, four TCs are fully utilized in the EMCO scenario, while five TCs are fully utilized in the base scenario. In other intervals, the utilizations of TCs are the same as in the base scenario.

5.2.6.2. NO_x and CO Emission Boundaries are Decreased %15 (EM15). In this scenario, the upper bound on the amount of NO_x and CO emissions is decreased by 15%. This scenario is prepared to observe the effects of reducing NO_x and CO emissions on city logistics, freight movements and density in İstanbul.

The obtained results of the EM15 scenario are presented in Tables 5.136-5.142. The transportation cost is 4,006,906 ₺ , the CO_2 emission cost is 138,973 ₺ , and the total cost is calculated as 4,145,879 ₺ . Compared to the results of the base scenario, the transportation cost increases 6%, the CO_2 emission cost increases 4%, and accordingly, the total cost increases 5%. The decrease in NO_x and CO emissions by 15% leads to

the distribution of vehicles across different intervals, as well as changes in the number and types of vehicles utilized. As a consequence, there is a rise in costs.

Table 5.136. The transportation, CO_2 emission, and total costs in the base and EM15 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
EM15	4,006,906	138,973	4,145,879

The total number of vehicles in all zones in each time interval in the EM15 scenario is presented in Table 5.137. Furthermore, Table 5.138 is provided to compare the number of vehicles in the base and EM15 scenarios. The number of heavy trucks decreases 35% (649 heavy trucks), and the number of trucks also decreases 6% (5,617 trucks). However, the number of panel vans increases from 660 to 18,293 panel vans. In order to reduce the amount of NO_x and CO emissions, there is a reduction in the number of vehicles with higher unit NO_x and CO emission values (such as trucks and heavy trucks), while the number of vehicles with lower emissions (such as panel vans) increases. Although electric vans do not emit NO_x and CO emissions, the number of electric vans remains unchanged due to the upper bound (200,000 electric vans) on the number of these vehicles.

Table 5.137. The total number of vehicles in all zones in each time interval in the EM15 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	582	250	374		1,206
Truck	2,538	4,310	3,570	77,003	87,421
Panel van	15,270	1,863	500	660	18,293
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.138. The total number of vehicles in all zones in the base and EM15 scenarios.

	Base	EM15
Heavy Truck	1,855	1,206
Truck	93,038	87,421
Panel van	660	18,293
Electric van	200,000	200,000
Total	295,553	306,920

The amount of NO_x released from non-electric vehicles is 6,747,694 g, which decreases by 16% compared to the base scenario. Furthermore, the amount of CO emitted is 5,905,961 g, which drops 15% compared to the base scenario. These decreases are observed since the reduction of the amount of NO_x and CO emissions by 15% is targeted with constraints in this scenario.

The freight flow of each vehicle type, in each time interval in the EM15 scenario is displayed in Table 5.139. When the freight flows are examined, it can be seen that the majority of flows are still direct shipments from PCs to CCs, although it decreases 2% (16,030 tonnes) compared to the base scenario. Due to this decrease in direct shipments, the amount of product sent through TCs increases. Furthermore, since it is aimed to reduce NO_x and CO emissions in this scenario, there is a decrease in the utilization of heavy trucks, which are known for emitting high amounts of these pollutants. Since heavy trucks are primarily used for transportation in external zone shipments and between two TCs, the reduction in the amount of heavy trucks leads to a decrease in these shipments. Therefore, there is no product transported between two TCs, and the amount of external zone shipments decreases 33% (12,053 tonnes) compared to the base scenario. Similar to the base scenario, the most intense time of the freight flow is the evening off-peak time interval (65.5%). The reason is that the majority of products are distributed by trucks, and the cheapest time interval to transport by trucks is the evening off-peak. The least intense time is the evening peak time interval (9.6%).

Table 5.139. Freight flow of each vehicle type, in each time interval in the EM15 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	580	11,901	10,387	22,130	44,998	49,324
	Panel van	2,380	786			3,166	
	Electric van			500	660	1,160	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	3,570	14,289	4,322	27,713	49,893	53,920
	Panel van	1,190	1,750			2,940	
	Electric van			426	660	1,086	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	15,020	10,899	12,413	7,570	45,902	49,325
	Panel van	1,190	2,233			3,423	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	6,206	6,013	8,581	1,987	22,786	29,787
	Panel van	1,190	1,750	1,750	2,310	7,000	
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				532,975	532,975	778,225
	Panel van	47,496				47,496	
	Electric van	50,000	50,000	49,074	48,680	197,754	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck						
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck						
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	11,649	4,996	7,488		24,134	24,133
Total		140,471	104,617	94,941	644,685	984,713	
Rate		14.3%	10.6%	9.6%	65.5%	100%	

Table 5.140. Total freight flow activities outgoing from PCs to CCs and TCs in the EM15 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	778,225	90.8%			
From PCs to TCs on the European Side (W_{si}^{pvt})	49,325	5.8%	Zone 10	Zone 12	Zone 38
			15,927	17,200	16,197
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	29,787	3.5%	Zone 64	Zone 69	Zone 97
			11,136		18,650
Total	857,337				

Table 5.141. Total freight flow activities incoming to CCs from PCs and TCs in the EM15 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	778,225	88.3%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	49,324	5.6%	Zone 10	Zone 12	Zone 38
			15,927	17,200	16,197
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	53,920	6.1%	Zone 64	Zone 69	Zone 97
			12,386	22,884	18,650
Total	881,469				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.140 and 5.141. Compared to the base scenario, the TC usage for incoming products from PCs increases from 6% to 9.2% (see Tables 5.3 and 5.140), and for outgoing products to CCs, the TC usage increases from 9.9% to 11.7% (see Tables 5.4 and 5.141). Due to the decrease in the external zone shipments and shipments from PCs to CCs directly, more products are shipped from PCs to TCs and TCs to CCs, that result in increased usage of TCs.

Table 5.142 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the EM15 scenario. In this scenario, as the decrease in direct shipments from PCs to CCs and external zone shipments, shipments through TCs (from PCs to TCs and from TCs to CCs) increase. Hence, for heavy trucks and trucks, most of TCs are fully utilized. Regarding heavy trucks and trucks, in the EM15 scenario, in the noon peak time interval, all TCs are fully utilized, while in that time interval, except for the TC in the 64^{th} zone, all the others are fully utilized in the base scenario. In the EM15 scenario, in the noon off-peak and evening off-peak time intervals, all TCs are fully utilized as in the base scenario. In the EM15 scenario, in the evening peak time interval, all TCs are utilized, and except for the TC in the 64^{th} zone, all the others are fully utilized, while in that time interval, except for the TC in the 64^{th} zone, all the others are deployed in the base scenario.

Table 5.142. Capacities and deployments of the TCs in each time interval for different vehicle types in the EM15 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	520	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	760	760	760	145	760	760
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity	340	340	340		340	340
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	104	500	259		500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity		500			426	500
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity		660			660	660

Regarding panel vans and electric vans; in the EM15 scenario, in the noon peak time interval, except for the TC in the 64^{th} zone, all the others are fully utilized, while in that time interval, the TCs in the 12^{th} and the 69^{th} zones are fully utilized in the base scenario. In the EM15 scenario, in the noon off-peak time interval, except for the TC in the 64^{th} zone, all the others are utilized, with the 12^{th}, the 69^{th}, and the 97^{th} reaching full capacity (while, in that time interval, except for the TC in the 64^{th} zone, all the others are deployed at full capacity in the base scenario). In the EM15 scenario, in the evening peak time interval, the TCs in the 12^{th}, the 69^{th}, and the 97^{th} zones are utilized, with the 12^{th} and the 97^{th} reaching full capacity (while in that time interval, only the TC in the 69^{th} zone is fully utilized in the evening peak time interval). In the EM15 scenario, in the evening off-peak time interval, the TCs in the 12^{th}, the 69^{th}, and the 97^{th} zones are deployed at full capacity (while, in that time interval, except for the TC in the 64^{th} zone, all the others are deployed at full capacity in the base scenario).

5.2.6.3. NO_x and CO Emission Boundaries are Decreased %30 (EM30). In this scenario, the upper bound on the amount of NO_x and CO emissions is decreased by 30%. This scenario is prepared to observe the effects of reducing NO_x and CO emissions on city logistics, freight movements and density in İstanbul.

The obtained results of the EM30 scenario are presented in Tables 5.143-5.149. The transportation cost is 5,146,792 ₺ , the CO_2 emission cost is 157,077 ₺ , and the total cost is calculated as 5,303,870 ₺ . The transportation cost increases 36% compared to the base scenario and 28% compared to the EM15 scenario. The CO_2 emission cost increases 17% compared to the base scenario and 13% compared to the EM15 scenario. Accordingly, the total cost is 35% higher than that of the base scenario and 28% higher than that of the EM15 scenario. The decrease in NO_x and CO emissions by 30% leads to a distribution of vehicles across different intervals, as well as changes in the number and types of vehicles utilized. As the amount of NO_x and CO emissions are further reduced, the costs get higher.

Table 5.143. The transportation, CO_2 emission, and total costs in the base, EM15, and EM30 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
Base	3,795,724	134,158	3,929,882
EM15	4,006,906	138,973	4,145,879
EM30	5,146,792	157,077	5,303,870

The total number of vehicles in all zones in each time interval in the EM30 scenario is presented in Table 5.144. Furthermore, Table 5.145 is provided to compare the number of vehicles in the base, EM15, and EM30 scenarios. While there is only a decrease of 5 units in the number of heavy trucks compared to the EM15 scenario, there is a 35% (654 heavy trucks) decrease compared to the base scenario. As can be seen, the number of trucks decreases 44% (38,795 trucks) compared to the EM15 scenario and 48% (44,412 trucks) compared to the base scenario. However, there is a significant increase in the number of panel vans. It increases from 660 to 101,338 panel vans compared to the base scenario, while there are 18,293 panel vans in the EM15 scenario. These results indicate a significant shift in vehicle usage patterns with tighter restrictions on NO_x and CO emissions. Specifically, the usage of trucks, which are known to emit higher levels of NO_x and CO, decreases, while the usage of panel vans, which tend to have lower emissions, increases. Although electric vans do not

emit NO_x and CO emissions, the number of electric vans remains unchanged due to the upper bound (200,000 electric vans) on the number of these vehicles.

Table 5.144. The total number of vehicles in all zones in each time interval in the EM30 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	578	250	373		1,201
Truck	2,542	4,310	3,500	38,274	48,626
Panel van	98,419	1,759	500	660	101,338
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.145. The total number of vehicles in all zones in the base, EM15, and EM30 scenarios.

	Base	EM15	EM30
Heavy Truck	1,855	1,206	1,201
Truck	93,038	87,421	48,626
Panel van	660	18,293	101,338
Electric van	200,000	200,000	200,000
Total	295,553	306,920	351,165

The amount of NO_x released from non-electric vehicles is 4,001,421 g, which decreases by 50% compared to the base scenario and 41% compared to the EM15 scenario. Furthermore, the amount of CO emitted is 4,863,733 g, which drops 30% compared to the base scenario and 18% compared to the EM15 scenario. These decreases are observed since the reduction of the amount of NO_x and CO emissions by 30% is targeted with constraints in this scenario. As can be seen, the decrease in the amount of NO_x is more than 30% compared to the base scenario. This decrease can be attributed to the adjustments made in vehicle types and their utilization at various time intervals in order to achieve a 30% reduction in the amount of CO emissions.

Table 5.146. Freight flow of each vehicle type, in each time interval in the EM30 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	581	10,921	11,107	22,830	45,440	49,142
	Panel van	2,380	163			2,543	
	Electric van			500	660	1,160	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	3,145	14,328	4,333	27,716	49,522	53,525
	Panel van	1,190	1,750			2,940	
	Electric van			403	660	1,063	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	15,019	11,879	11,693	6,870	45,460	49,144
	Panel van	1,190	2,493			3,683	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	6,671	5,970	7,864	1,984	22,489	29,489
	Panel van	1,190	1,750	1,750	2,310	7,000	
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				242,508	242,508	778,802
	Panel van	338,517				338,517	
	Electric van	50,000	50,000	49,097	48,680	197,777	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck						
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck						
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	11,567	5,004	7,465		24,036	24,036
Total		431,450	104,258	94,212	354,218	984,138	
Rate		43.8%	10.6%	9.6%	36.0%	100%	

The freight flow of each vehicle type, in each time interval, in the EM30 scenario is displayed in Table 5.146. Compared to the base scenario, the total amount of products shipped directly from PCs to CCs decreases 2% (15,454 tonnes), while it increases only 506 tonnes (0.1%) compared to the EM15 scenario. There is no product transported between two TCs as in the EM15 scenario. The amount of external zone shipments decreases 34% (12,151 tonnes) compared to the base scenario and only 97 tonnes (0.4%) compared to the EM15 scenario. These results reveal that freight flow activities in the EM30 and EM15 scenarios are very similar. Compared to the base scenario, there is a decrease in the utilization of heavy trucks, which are known for emitting high amounts of these pollutants, since it is aimed to reduce NO_x and CO emissions in

this scenario. As heavy trucks are primarily used for external zone shipments and shipments between two TCs, the reduction in the amount of heavy trucks leads to a decrease in these shipments. Although the most intense time of the freight flow is the evening off-peak time interval in the base and EM15 scenarios, it is the noon peak time interval (43.8%) in the EM30 scenario since there is a significant increase in the number of panel vans and the time interval with the lowest unit CO value of the panel vans is the noon peak. The least intense time is the evening peak time interval (9.6%).

Table 5.147. Total freight flow activities outgoing from PCs to CCs and TCs in the EM30 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	778,802	90.8%			
From PCs to TCs on the European Side (W_{si}^{pvt})	49,144	5.7%	Zone 10	Zone 12	Zone 38
			15,994	17,200	15,948
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	29,489	3.4%	Zone 64	Zone 69	Zone 97
			10,839		18,650
Total	857,435				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.147 and 5.148. Compared to the base scenario, the TC usage for incoming products from PCs increases from 6% to 9.2% (see Tables 5.3 and 5.147). Similarly, it is 9.2% in the EM15 scenario. For outgoing products to CCs, the TC usage increases from 9.9% to 11.6% compared to the base scenario (see Tables 5.4 and 5.148), while it is 11.7% in the EM15 scenario. These results demonstrate that TC usages in the EM15 and EM30 scenarios are very close to each other. As a consequence of the decline in external zone shipments and direct shipments from PCs to CCs, there is a shift towards shipping more products from PCs to TCs and from TCs to CCs compared to the base scenario. This change leads to an increased utilization of TCs.

Table 5.148. Total freight flow activities incoming to CCs from PCs and TCs in the EM30 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	778,802	88.4%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	49,142	5.6%	Zone 10	Zone 12	Zone 38
			15,994	17,200	15,948
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	53,525	6.1%	Zone 64	Zone 69	Zone 97
			12,006	22,869	18,650
Total	881,469				

Table 5.149. Capacities and deployments of the TCs in each time interval for different vehicle types in the EM30 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	520	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	760	760	760	73	760	760
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity	340	340	340		340	340
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	143	500	116		500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity		500			403	500
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity		660			660	660

Table 5.149 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the EM30 scenario. In this scenario, with the decrease in direct shipments from PCs to CCs and external zone shipments, shipments through TCs (from PCs to CCs and from TCs to CCs) increase. Hence, for heavy trucks and trucks, most TCs are fully utilized. Regarding heavy trucks and trucks; in the EM30 scenario, all TCs are fully utilized in the noon peak time interval

as in the EM15 scenario, while in that time interval, except for the TC in the 64^{th} zone, all the others are fully utilized in the base scenario. In the EM30 scenario, in the noon off-peak and evening off-peak time intervals, all TCs are fully utilized as in the base and EM15 scenarios. In the EM30 scenario, in the evening peak time interval, all TCs are utilized, and except for the TC in the 64^{th} zone, all the others are fully utilized as in the EM15 scenario, while in that time interval, except for the TC in the 64^{th} zone, all the others are deployed in the base scenario.

Regarding panel vans and electric vans; in the EM30 scenario, in the noon peak time interval, except for the TC in the 64^{th} zone, all the others are fully utilized as in the EM15 scenario, while in that time interval, the TCs in the 12^{th} and the 69^{th} zones are fully utilized in the base scenario. In the EM30 scenario, in the noon off-peak time interval, except for the TC in the 64^{th} zone, all the others are utilized, with the 12^{th}, the 69^{th}, and the 97^{th} reaching full capacity as in the EM15 scenario (while, in that time interval, except for the TC in the 64^{th} zone, all the others are deployed at full capacity in the base scenario). In the EM30 scenario, in the evening peak time interval, the TCs in the 12^{th}, the 69^{th}, and the 97^{th} zones are utilized, with the 12^{th} and the 97^{th} reaching full capacity as in the EM15 scenario (while in that time interval, only the TC in the 69^{th} zone is fully utilized in the evening peak time interval). In the EM30 scenario, in the evening off-peak time interval, the TCs in the 12^{th}, the 69^{th}, and the 97^{th} zones are deployed at full capacity as in the EM15 scenario (while, in that time interval, except for the TC in the 64^{th} zone, all the others are deployed at full capacity in the base scenario). These results show that the occupations of TCs in the EM15 and EM30 scenarios are almost the same.

In summary, as the restrictions on the amount of NO_x and CO emissions become tighter;

(i) transportation and CO_2 emission costs increase;
(ii) the number of trucks decreases, and the number of panel vans increases;
(iii) external zone shipments decrease;
(iv) the intensity on the evening off-peak time interval decreases.

5.2.7. Combination Scenarios

In this scenario group, new scenarios are generated by the combination of some previous scenarios, which are selected due to their key features. These features are related to capacities, utilization rates, and some parameters that may have significant effects on the results. The list of these combination scenarios is as follows:

(i) Combination of the TC100 and TUR40 Scenarios (C-TC100TUR40)
(ii) Combination of the TC200 and TUR40 Scenarios (C-TC200TUR40)
(iii) Combination of the EVR and EVL Scenarios (C-EVREVL)
(iv) Combination of the TC200, EVL, EVP, and EVR Scenarios (C-TC200EVRLP)
(v) Combination of the TC200 and EVU Scenarios (C-TC200EVU)
(vi) Combination of the VNL and TC200 Scenarios (C-VNLTC200)
(vii) Combination of the EVU and VNL Scenarios (C-EVUVNL).

5.2.7.1. Combination of the TC100 and TUR40 Scenarios (C-TC100TUR40). In this scenario, the capacities of all TCs are increased by 100% and trucks traveling between PCs and CCs are assumed to be loaded at 40% capacity. The revised capacities of the TCs are presented in Table 5.150. The number of vehicles used in the TUR40 scenario considerably changes compared to the base scenario. In addition, the usage of TCs also increases. In order to find out how much the utilization of TCs would have changed if the capacities of TCs are increased, such a combined scenario is prepared.

Table 5.150. Capacities of TCs in the C-TC100TUR40 scenario (in number of vehicles).

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Truck and Heavy Truck	1,040	1,520	1,520	1,980
Panel van and Electric van	680	1,000	1,000	1,320

The obtained results of the C-TC100TUR40 scenario are presented in Tables 5.151-5.157. The transportation cost is 4,535,583 ₺ , the CO_2 emission cost is 141,000 ₺ and the total cost is calculated as 4,676,583 ₺ . As shown in Table 5.151, both the transportation and CO_2 emission costs (and accordingly the total cost) are higher than those in the TC100 scenario. However, these costs are lower than those in the TUR40 scenario. The transportation cost increases 24% compared to the TC100 scenario, but it decreases 8% compared to the TUR40 scenario. The CO_2 emission cost increases 8% compared to the TC100 scenario although it decreases 4% compared to the TUR40 scenario. These results can be interpreted as follows: The costs are increased compared to the TC100 scenario since the truck utilization rate is reduced to 40% between PCs and CCs (as in the TUR40 scenario), which requires more vehicles to transport the same amount of load. This leads to increased costs. However, the costs can be reduced by expanding the capacities of TCs (as in the TC100 scenario) since it is a less costly alternative to distribute products to CCs through TCs.

Table 5.151. The transportation, CO_2 emission, and total costs in the TC100, TUR40, and C-TC100TUR40 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
TC100	3,671,340	130,710	3,802,051
TUR40	4,907,881	146,592	5,054,473
C-TC100TUR40	4,535,583	141,000	4,676,583

The total number of vehicles in all zones in each time interval in the C-TC100TUR40 scenario is displayed in Table 5.152. Additionally, Table 5.153 provides for the comparison of the number of vehicles in the TC100, and TUR40 scenarios. The number of heavy trucks increases 73% (2,151 heavy trucks) compared to the TC100 scenario and 67% (2,046 heavy trucks) compared to the TUR40 scenario. The number of trucks decreases 69% (65,387 trucks) compared to the TC100 scenario while it increases 104% (14,578 to 29,752 trucks) compared to the TUR40 scenario. Moreover, there is a significant increase in the number of panel vans considering the TC100 scenario (from 1,192 to 143,848 panel vans). However, it decreases 16% (26,391 panel

vans) compared to the TUR40 scenario. The number of electric vans is still at the upper bound value of 200,000. The increase in the amount of products coming from the external zones leads to an increase in the number of heavy trucks used to transport these products. As in the TUR40 scenario, trucks are not preferred for transportation between PCs and CCs since they are loaded at 40% capacity in this transportation. Accordingly, panel vans are widely used instead of trucks in this direct shipment from PCs to CCs. This results in an increase in the number of panel vans and a decrease in the number of trucks in this scenario.

Table 5.152. The total number of vehicles in all zones in each time interval in the C-TC100TUR40 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	1,436	756	1,430	1,466	5,088
Truck	4,804	8,364	6,170	10,414	29,752
Panel van	2,040	3,651		138,157	143,848
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.153. The total number of vehicles in all zones in the TC100, TUR40, and C-TC100TUR40 scenarios.

	TC100	TUR40	C-TC100TUR40
Heavy Truck	2,937	3,042	5,088
Truck	95,139	14,578	29,752
Panel van	1,192	170,240	143,848
Electric van	200,000	200,000	200,000
Total	299,268	387,860	378,688

The amount of CO released from non-electric vehicles is 6,966,891 g, and this is 11% higher than that of the TC100 scenario, and 10% lower than that of the TUR40 scenario. Only in the evening off-peak time interval, the CO emissions emitted by a panel van is more than a truck emits. Due to the significant increase in the number of panel vans in the evening off-peak time interval, the amount of CO emissions is higher than that of the TC100 scenario. By combining the TC100 and TUR40 scenarios, the

TC capacities increase compared to the TUR40 scenario, which results in a decrease in CO emissions compared to the TUR40 scenario. The amount of NO_x emitted from these vehicles is 3,603,782 g. It decreases 52% compared to the TC100 scenario and increases 51% compared to the TUR40 scenario. The amount of NO_x emission emitted by a panel van is lower than that of a truck. Accordingly, compared to the TC100 scenario, the significant decrease in the number of trucks leads to a decrease in the amount of NO_x emissions. However, since the numbers of heavy trucks and trucks increase compared to the TUR40 scenario, the amount of NO_x emissions increase with respect to that scenario.

Table 5.154. Freight flow of each vehicle type, in each time interval in the C-TC100TUR40 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	9,541	14,129	24,314	51,632	99,616	103,404
	Panel van				3,788	3,788	
	Electric van						
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	14,097	38,045	7,495	47,731	107,367	117,868
	Panel van	2,380	3,500		4,620	10,500	
	Electric van						
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	21,659	31,471	21,286	4,781	79,197	97,428
	Panel van	2,380	5,779		10,072	18,231	
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	2,744		8,605		11,349	22,101
	Panel van	2,380	3,500		4,872	10,752	
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck						660,199
	Panel van				460,199	460,199	
	Electric van	50,000	50,000	50,000	50,000	200,000	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck	1				1	1
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				5,974	5,974	5,974
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	28,718	15,110	28,601	23,339	95,768	95,768
Total		133,900	161,534	140,301	667,008	1,102,742	
Rate		12.2%	14.6%	12.7%	60.5%	100%	

The freight flow of each vehicle type, in each time interval in the C-TC100TUR40 scenario is displayed in Table 5.154. The total amount of products shipped directly from PCs to CCs decreases 10% (73,034 tonnes) compared to the TC100 scenario and 13% (101,834 tonnes) compared to the TUR40 scenario. The amount of products transported between two TCs decreases to 1 tonne in the C-TC100TUR40 scenario. Compared to the TC100 and TUR40 scenarios, one noteworthy change is observed in the external zone shipments due to increased TC capacities (as in the TC100 scenario) and high cost of direct shipments from PCs to CCs (due to low truck utilization rates as in the TUR40 scenario). The increase in the amount of external zone shipments is 91% (48,595 tonnes) compared to the TC100 scenario and 72% (42,451 tonnes) compared to the TUR40 scenario. The vast majority of flows are still observed in direct shipments from PCs to CCs. As in the TUR40 scenario, all electric vans are used in direct shipments from PCs to CCs.

As the capacities of all TCs are increased by 100%, the active usage rates of TCs increase, too. Furthermore, the fact that the trucks between PCs and CCs are loaded at 40% capacity leads to more preference for TCs (the less than truckload shipment results in fewer amount of products directly shipped from PCs to CCs). Due to the decrease in the direct shipments from PCs to CCs, the amount of products coming from the external zones increases. Since it is a cheaper alternative to send products to CCs via TCs, the demands of CCs are often met through TCs from the external zones rather than transporting directly from PCs in the nearby zone of CCs. This reduces the shipments that require the usage of TCs while meeting the demand of remote CCs.

Similar to the TC100, and TUR40 scenarios, the most intense time of the freight flow is the evening off-peak time interval (60.5%). In the TC100 scenario, the evening off-peak time interval density is 69.3%, and all TCs are fully utilized in this time interval for heavy trucks and trucks. Similarly, in this combined scenario, all TCs are deployed at full capacity in the evening off-peak time interval (for heavy trucks and trucks). Since they reach to their full capacity, some vehicles shift to other time intervals with

the increased usage of TCs. Therefore, the intensity in other time intervals increases as in the TC100 scenario.

Table 5.155. Total freight flow activities outgoing from PCs to CCs and TCs in the C-TC100TUR40 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	660,199	84.7%			
From PCs to TCs on the European Side (W_{si}^{pvt})	97,428	12.5%	Zone 10	Zone 12	Zone 38
			29,718	33,961	33,749
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	22,101	2.8%	Zone 64	Zone 69	Zone 97
			2,996		19,105
Total	779,728				

Table 5.156. Total freight flow activities incoming to CCs from PCs and TCs in the C-TC100TUR40 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	660,199	74.9%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	103,404	11.7%	Zone 10	Zone 12	Zone 38
			33,574	36,080	33,750
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	117,868	13.4%	Zone 64	Zone 69	Zone 97
			29,435	47,400	41,032
Total	881,471				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are presented in Tables 5.155 and 5.156. Compared to the TC100 scenario, the TC usage for incoming products from PCs increases from 11.5% to 15.3% (see Tables 5.19 and 5.155), and the TC usage for outgoing products to CCs increases from

16.8% to 25.1% (see Tables 5.20 and 5.156) because of the lower truck utilization rate between PCs and CCs. Since the trucks are loaded at 40% capacity between PCs and CCs, fewer products are sent directly from the PCs to CCs and more products are shipped through the TCs (the TC usage for incoming products from PCs is 7.3% in the TUR40 scenario, and the TC usage for outgoing products to CCs is 13.5% in the TUR40 scenario). For incoming products from PCs, the TC in zone 69 is still unused (as can be inferred from Table 5.155).

Table 5.157. Capacities and deployments of the TCs in each time interval for different vehicle types in the C-TC100TUR40 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	1,040	1,040	1,040	1,040	1,040	1,040
	Noon Peak Occupied Capacity	1,040	1,040	1,040	1,040	1,040	1,040
	Noon Off-peak Capacity	1,520	1,520	1,520	1,520	1,520	1,520
	Noon Off-peak Occupied Capacity	1,520	1,520	1,520	1,520	1,520	1,520
	Evening Peak Capacity	1,520	1,520	1,520	1,520	1,520	1,520
	Evening Peak Occupied Capacity	1,520	1,520	1,520		1,520	1,520
	Evening Off-peak Capacity	1,980	1,980	1,980	1,980	1,980	1,980
	Evening Off-peak Occupied Capacity	1,980	1,980	1,980	1,980	1,980	1,980
Panel vans and Electric vans	Noon Peak Capacity	680	680	680	680	680	680
	Noon Peak Occupied Capacity		680			680	680
	Noon Off-peak Capacity	1,000	1,000	1,000	1,000	1,000	1,000
	Noon Off-peak Occupied Capacity		1,000	651		1,000	1,000
	Evening Peak Capacity	1,000	1,000	1,000	1,000	1,000	1,000
	Evening Peak Occupied Capacity						
	Evening Off-peak Capacity	1,320	1,320	1,320	1,320	1,320	1,320
	Evening Off-peak Occupied Capacity	1,320	1,320	1,320	72	1,320	1,320

Table 5.157 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the C-TC100TUR40 scenario. The low truck utilization rate causes direct shipments from PCs to CCs to become more costly. Thus, fewer products are sent directly from PCs to CCs, and more products are shipped through TCs. With the increase in the capacities of TCs, more vehicles are able to use them. Due to the low truck utilization rate between PCs and CCs and the increased capacities of TCs, the usage of TCs is higher in this combined scenario compared to the TUR40 and TC100 scenarios. Regarding heavy trucks and trucks; in

the C-TC100TUR40 scenario, in the noon peak, noon off-peak, and evening off-peak time intervals, all TCs are fully utilized as in the TUR40 scenario. In the evening peak time interval, except for the TC in the 64^{th} zone, all the others are fully utilized in the C-TC100TUR40 scenario. In the TC100 scenario, in the noon off-peak and evening off-peak time intervals, all TCs are fully utilized. Five of six TCs are used in the noon peak time interval, while only one TC is utilized in the evening peak time interval.

Regarding panel vans and electric vans; in the C-TC100TUR40 scenario, the number of panel vans and electric vans using TCs is higher than those in the TUR40 scenario, although the total number of panel vans and electric vans is higher in the TUR40 scenario. The reason behind that is the increase in the capacities of TCs in the C-TC100TUR40 scenario. In the C-TC100TUR40 scenario, three TCs are fully utilized in the noon peak time interval and four TCs are deployed in the noon off-peak time interval with three of them fully utilized. None of the TCs is utilized in the evening peak time interval, and all of them are deployed in the evening off-peak time interval, with five of them being deployed at full capacity. In the TUR40 scenario, five TCs are fully utilized in the noon peak and noon off-peak time intervals, while three TCs are deployed in the evening peak time interval and all of them being fully utilized in the evening off-peak time interval. In the TC100 scenario, only one TC is utilized in the noon peak and evening peak time intervals, while two TCs are deployed in the noon off-peak time interval and three TCs are utilized in the evening off-peak time interval.

5.2.7.2. Combination of the TC200 and TUR40 Scenarios (C-TC200TUR40). In this scenario, the capacities of all TCs are increased by 200%, and trucks traveling between PCs and CCs are assumed to be loaded at 40% capacity. The revised capacities of the TCs are presented in Table 5.158. When the results of the C-TC100TUR40 scenario are examined, except for only one TC, all of TCs are fully utilized for all intervals (regarding heavy trucks and trucks). Therefore, this combined scenario is created to see how the results would be affected in case of a further capacity expansion of TCs.

Table 5.158. Capacities of TCs in the C-TC200TUR40 scenario (in number of vehicles).

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Truck and Heavy Truck	1,560	2,280	2,280	2,970
Panel van and Electric van	1,020	1,500	1,500	1,980

The obtained results of the C-TC200TUR40 scenario are presented in Tables 5.159-5.165. Previously, the TC100 and TUR40 scenarios are combined (C-TC100TUR40). Therefore, while analyzing the results of the C-TC200TUR40 scenario, they are compared with the results of the C-TC100TUR40 scenario.

Table 5.159. The transportation, CO_2 emission, and total costs in the C-TC100TUR40 and C-TC200TUR40 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
C-TC100TUR40	4,535,583	141,000	4,676,583
C-TC200TUR40	4,290,040	136,863	4,426,903

As presented in Table 5.159, the transportation cost is 4,290,040 ₺ , the CO_2 emission cost is 136,863 ₺ , and the total cost is calculated as 4,426,903 ₺ . Both the transportation and CO_2 emission costs (and accordingly the total cost) are lower than those in the C-TC100TUR40 scenario. The transportation cost decreases 5% and the CO_2 emission cost decreases 3% compared to the C-TC100TUR40 scenario. Similar to the results of the TC capacity scenarios, as the capacities of TCs are expanded, the costs decrease. Furthermore, distributing products to CCs through TCs is a less costly alternative, instead of sending them directly from PCs to CCs, primarily because trucks usually cannot be fully loaded in direct shipments.

The amount of NO_x emitted from non-electric vehicles is 4,338,412 g. It increases 20% compared to the C-TC100TUR40 scenario. The amount of CO emitted from these vehicles is 6,449,658 g, which is 7% lower than the amount in the C-TC100TUR40 scenario. Compared to the C-TC100TUR40 scenario, as the capacities of TCs increase,

the number of trucks and heavy trucks increases, and the number of panel vans decreases. The unit NO_x emissions of heavy trucks and trucks are higher than the unit NO_x emissions of panel vans. Accordingly, the increase in the number of heavy trucks and trucks causes the total NO_x amount to increase. In addition to this, the unit CO of panel vans in the evening off-peak time interval is higher than that of trucks. The increase in the number of trucks and the decrease in the number of panel vans in that time interval explains the decrease of the total amount of CO compared to the C-TC100TUR40 scenario.

Table 5.160. The total number of vehicles in all zones in each time interval in the C-TC200TUR40 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	1,646	1,829	1,371	1,210	6,056
Truck	7,628	11,851	7,329	16,610	43,418
Panel van		3,000		119,071	122,071
Electric van	50,000	50,000	50,000	50,000	200,000

The total number of vehicles in all zones in each time interval in the C-TC200TUR40 scenario is displayed in Table 5.160. Furthermore, Table 5.161 is provided in order to compare the number of vehicles in the C-TC100TUR40 and C-TC200TUR40 scenarios. As the capacities of TCs are expanded, more vehicles can use the TCs. The number of heavy trucks increases 19% (968 heavy trucks) and the number of trucks increases 46% (13,666 trucks) compared to the C-TC100TUR40. The increase in the number of heavy trucks seen in comparison with the C-TC100TUR40 scenario is mainly due to the increase in the flow between two TCs. Moreover, the number of panel vans decreases 15% (21,777 panel vans) compared to the C-TC100TUR40 scenario. Compared to the C-TC100TUR40 scenario, the direct shipment from PCs to CCs decreases and the usage of TCs increases; as the freight flows incoming to TCs and outgoing from TCs increase, the deployment of trucks increases because trucks can be fully loaded in these flows. The deployment of panel vans decreases since most of them are used in direct shipments, which as explained has decreased. The number of electric vans is still at the upper bound value of 200,000.

Table 5.161. The total number of vehicles in all zones in the C-TC100TUR40 and C-TC200TUR40 scenarios.

	C-TC100TUR40	C-TC200TUR40
Heavy Truck	5,088	6,056
Truck	29,752	43,418
Panel van	143,848	122,071
Electric van	200,000	200,000
Total	378,688	371,545

The freight flow of each vehicle type, in each time interval in the C-TC200TUR40 scenario is displayed in Table 5.162. Compared to the C-TC100TUR40 scenario, the total amount of products shipped directly from PCs to CCs decreases 12% (78,100 tonnes). There is a sharp increase in the shipment between the two TCs, (from 1 to 1,719 tonnes) compared to the C-TC100TUR40 scenario. Also, the amount of external zone shipments increases 17% (17,657 tonnes). Compared to the C-TC100TUR40 scenario, as the capacities of TCs are increased, the amount of products coming from the external zones increases because these products are shipped through TCs. Although the majority of flows are still direct shipments from PCs to CCs, the amount of these shipments decreases as the capacities of all TCs are increased. Therefore, the products sent from PCs to TCs and TCs to CCs increase. This increase in the usage of TCs also causes an increase in the flow between the two TCs.

Similar to the C-TC100TUR40 scenario, the most intense time of the freight flow is the evening off-peak time interval, and its intensity is 55.6%, while this intensity is 60.5% in the C-TC100TUR40 scenario. As the capacities of TCs are increased in the C-TC200TUR40 scenario, and most of the TCs reach their full capacity in that time interval, some vehicles shift to the other intervals. In the C-TC200TUR40 scenario, the intensity in the evening off-peak time interval decreases 4.9% compared to the C-TC100TUR40 scenario. However, in the C-TC100TUR40 scenario, it decreases 13.4% compared to the base scenario. This implies that, in the C-TC200TUR40 scenario, fewer vehicles shift to other time intervals compared to those in the

C-TC100TUR40 scenario. The reason for this is that when the C-TC200TUR40 and C-TC100TUR40 scenarios are compared, only the effects of increasing the capacities of TCs are seen while comparing the C-TC100TUR40 and base scenarios, the effects of both increasing the capacities of TCs and reducing the truck utilization rates are seen.

Table 5.162. Freight flow of each vehicle type, in each time interval in the C-TC200TUR40 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	7,784	39,748	11,747	63,762	123,040	
	Panel van				13,734	13,734	136,775
	Electric van						
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	16,065	46,648	15,012	77,941	155,666	
	Panel van				6,930	6,930	162,596
	Electric van						
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	38,157	28,652	29,663	24,399	120,871	
	Panel van		5,250		7,056	12,306	133,177
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	14,275	3,466	16,873		34,614	
	Panel van		5,250		6,930	12,180	46,794
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck						
	Panel van				382,099	382,099	582,099
	Electric van	50,000	50,000	50,000	50,000	200,000	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck	1,719				1,719	1,719
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				1,878	1,878	1,878
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	31,200	36,572	27,430	22,319	117,521	117,521
Total		159,200	215,586	150,725	657,048	1,182,558	
Rate		13.5%	18.2%	12.7%	55.6 %	100%	

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are presented in Tables 5.163 and 5.164. Compared to the C-TC100TUR40 scenario, the TC usage for incoming products from PCs increases from 15.3% to 23.6% (see Tables 5.155 and 5.163), and the TC usage for outgoing products to CCs increases from 25.1% to 34% (see Tables 5.156 and 5.164). The primary reason for the increase

in the active usage of TCs is enlarging the capacities of TCs. Due to the increase in the capacities of TCs, more products are shipped from the external zones to CCs through the TCs, which results in an increase in the usage of TCs. Furthermore, the decrease in direct shipments from PCs to CCs leads to a rise in the shipment of products through TCs. For incoming products from PCs, the TC in the 69th zone is started to be used (as depicted in Table 5.163) due to the increased usage of TCs.

Table 5.163. Total freight flow activities outgoing from PCs to CCs and TCs in the C-TC200TUR40 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	582,099	76.4%			
From PCs to TCs on the European Side (W_{si}^{pvt})	133,177	17.5%	Zone 10	Zone 12	Zone 38
			44,914	50,132	38,132
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	46,794	6.1%	Zone 64	Zone 69	Zone 97
			17,741	2,438	26,615
Total	762,070				

Table 5.164. Total freight flow activities incoming to CCs from PCs and TCs in the C-TC200TUR40 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	582,099	66.0%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	136,775	15.5%	Zone 10	Zone 12	Zone 38
			44,914	52,009	39,850
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	162,596	18.4%	Zone 64	Zone 69	Zone 97
			38,341	64,407	59,848
Total	881,470				

Table 5.165 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the C-TC200TUR40 scenario. Compared to the C-TC100TUR40 scenario, since the capacities of TCs are expanded, more vehicles are able to use them. However, most of the TCs reach their maximum capacity and are considered inadequate except during the evening peak time interval. Regarding heavy trucks and trucks; in the C-TC200TUR40 scenario, in the noon peak, noon off-peak and evening off-peak time intervals, all TCs are fully utilized as in the C-TC100TUR40 scenario. In the C-TC200TUR40 scenario, in the evening peak time interval, except for the one TC, all the other TCs are utilized similar to the C-TC100TUR40 scenario. In the C-TC100TUR40 scenario, in the evening peak time interval, five TCs are fully utilized (each with a capacity of 1,520 vehicles). Similarly, in that time interval, in the C-TC100TUR40 scenario, five TCs are utilized, but only three of them are fully utilized (each with a capacity of 2,280 vehicles).

Table 5.165. Capacities and deployments of the TCs in each time interval for different vehicle types in the C-TC200TUR40 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	1,560	1,560	1,560	1,560	1,560	1,560
	Noon Peak Occupied Capacity	1,560	1,560	1,560	1,560	1,560	1,560
	Noon Off-peak Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Noon Off-peak Occupied Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Evening Peak Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Evening Peak Occupied Capacity	1,480	2,280	381		2,280	2,280
	Evening Off-peak Capacity	2,970	2,970	2,970	2,970	2,970	2,970
	Evening Off-peak Occupied Capacity	2,970	2,970	2,970	2,970	2,970	2,970
Panel vans and Electric vans	Noon Peak Capacity	1,020	1,020	1,020	1,020	1,020	1,020
	Noon Peak Occupied Capacity						
	Noon Off-peak Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Noon Off-peak Occupied Capacity		1,500				1,500
	Evening Peak Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Evening Peak Occupied Capacity						
	Evening Off-peak Capacity	1,980	1,980	1,980	1,980	1,980	1,980
	Evening Off-peak Occupied Capacity	1,980	1,980	1,980		1,980	1,980

Regarding panel vans and electric vans; in the noon peak time interval, no TC is deployed at all in the C-TC200TUR40 scenario (while in that time interval, three TCs are fully utilized in the C-TC100TUR40 scenario). In the noon off-peak time interval,

two TCs are deployed at full capacity in the C-TC200TUR40 scenario (while in that time interval, four TCs are utilized, with three of them reaching full capacity in the C-TC100TUR40 scenario). In the evening peak time interval, no TC is deployed at all in the C-TC200TUR40 and C-TC100TUR40 scenarios. In the evening off-peak time interval, five TCs are deployed at full capacity in the C-TC200TUR40 scenario (while in that time interval, all TCs are utilized, with five of them reaching full capacity in the C-TC100TUR40 scenario). These findings indicate that the expansion of capacities is crucial for heavy trucks and trucks, but it is less essential for panel vans and electric vans.

5.2.7.3. Combination of the EVR and EVL Scenarios (C-EVREVL). In this scenario, the range of electric vans is considered as 100 km and the limit on the number of electric vans in each time interval is raised to 100,000. When electric vans become more attractive by increasing their range, significant changes are observed in the flows and emissions (NO_x and CO). In addition, by increasing the number of electric vans, it is aimed to see how the usage of TCs and the preferred vehicles change in these flows.

The obtained results of the C-EVREVL scenario are presented in Tables 5.166 to 5.172. As shown in Table 5.166, the transportation cost is 3,286,007 ₺ , the CO_2 emission cost is 157,274 ₺ , and the total cost is calculated as 3,443,281 ₺ . The transportation cost decreases 9% compared to the EVR scenario and 7% compared to the EVL scenario. The CO_2 emission cost increases 11% compared to the EVR scenario and 6% compared to the EVL scenario. The decrease in the number of heavy trucks, trucks, and panel vans causes a reduction in transportation cost. The fact that electric vans can travel longer (as in the EVR scenario) and the increase in their numbers (as in the EVL scenario) lead to the rise in CO_2 emission cost.

The amount of NO_x emitted from non-electric vehicles is 3,789,113 g, which decreases 43% compared to the EVR scenario and 31% compared to the EVL scenario. The amount of CO emitted from these vehicles is 3,252,408 g, and this is 44% lower than that of the EVR scenario and 31% lower than that of the EVL scenario. The

decline in the number of heavy trucks, trucks and panel vans (compared to the EVR and EVL scenarios) leads to a decrease in the amount of NO_x and CO in the C-EVREVL scenario.

Table 5.166. The transportation, CO_2 emission, and total costs in the EVR, EVL, and C-EVREVL scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
EVR	3,606,361	141,900	3,748,262
EVL	3,523,135	148,123	3,671,258
C-EVREVL	3,286,007	157,274	3,443,281

The total number of vehicles in all zones in each time interval in the C-EVREVL scenario is displayed in Table 5.167. Additionally, in order to compare the number of vehicles in the EVR, EVL and C-EVREVL scenarios, Table 5.168 is provided. The number of heavy trucks decreases 8% (138 heavy trucks) compared to the EVR scenario. However, it increases only 1% (14 heavy trucks) compared to the EVL scenario. Moreover, the number of trucks decreases 29% (26,288 trucks) compared to the EVR scenario, and only 1% (896 trucks) compared to the EVL scenario. Panel vans are not used at all in this scenario. The number of electric vans reaches the upper bound value of 400,000. The increase in the number of electric vans leads to a decrease in the need for other vehicle types, as in the EVL scenario. Furthermore, the increase in the range of electric vans is another factor in the decline of the number of heavy trucks and trucks.

Table 5.167. The total number of vehicles in all zones in each time interval in the C-EVREVL scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	140	744		809	1,693
Truck	2,460	3,795	137	59,555	65,947
Panel van					
Electric van	100,000	100,000	100,000	100,000	400,000

Table 5.168. The total number of vehicles in all zones in the EVR, EVL, and C-EVREVL scenarios.

	EVR	EVL	C-EVREVL
Heavy Truck	1,831	1,678	1,693
Truck	92,235	66,843	65,947
Panel van	1,522		
Electric van	200,000	400,000	400,000
Total	295,588	468,521	467,640

Table 5.169. Freight flow of each vehicle type, in each time interval in the C-EVREVL scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	11,821	5,631		16,550	34,002	34,302
	Panel van						
	Electric van		300			300	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	9,004	7,295	1,375	21,608	39,282	41,102
	Panel van						
	Electric van	340	500	320	660	1,820	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	3,779	16,964		13,150	33,892	33,893
	Panel van						
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck		8,064			8,064	8,064
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck				408,185	408,185	806,065
	Panel van						
	Electric van	99,660	99,200	99,680	99,340	397,880	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		410			410	410
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck						
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	2,792	14,472		16,185	33,448	33,449
Total		127,396	152,836	101,375	57,5678	957,283	
Rate		13.3%	16.0%	10.6%	60.1%	100%	

The freight flow of each vehicle type, in each time interval in the C-EVREVL scenario is displayed in Table 5.169. The total amount of products shipped directly from PCs to CCs increases 1% compared to the EVR (6,138 tonnes) and EVL (8,031 tonnes) scenarios. There is a 47% (364 tonnes) drop in the amount of products transported between two TCs compared to the EVR scenario and 70% (956 tonnes) compared to the EVL scenario. The decrease in the amount of external zone shipments is 7% (2,393 tonnes) compared to the EVR scenario and 4% (1,244 tonnes) compared to the EVL scenario. The majority of flows are still direct shipments from PCs to CCs. Most of the electric vans are used in direct shipments from PCs to CCs. The most intense time of the freight flow is the evening off-peak time interval (60.1%), and the least intense time is the evening peak time interval (10.6%) as in the EVR and EVL scenarios. The increased range and number of electric vans makes them more advantageous in this scenario, especially in direct shipments. Since PCs directly meet the demands of more CCs, not only PCs ship fewer products through TCs, but also fewer products are needed from the external zones. Accordingly, there is a decrease in the utilization of TCs.

Table 5.170. Total freight flow activities outgoing from PCs to CCs and TCs in the C-EVREVL scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	806,065	95.1%			
From PCs to TCs on the European Side (W_{si}^{pvt})	33,893	4.0%	Zone 10	Zone 12	Zone 38
			11,350	11,350	11,192
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	8,064	1.0%	Zone 64	Zone 69	Zone 97
			3,090		4,974
Total	848,022				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are presented in Tables 5.170 and 5.171. Compared to the EVR scenario, the

TC usage for incoming products from PCs decreases from 5.4% to 4.9% (see Tables 5.91 and 5.170), and the TC usage for outgoing products to CCs decreases from 9.3% to 8.6% (see Tables 5.92 and 5.171). Meanwhile, this TC usage for incoming products from PCs is 6% in the EVL scenario, and the TC usage for outgoing products to CCs is 9.5% in the EVL scenario. The fact that PCs ship more products directly to CCs and fewer products via TCs is the reason for the decrease in the incoming products coming to TCs. Furthermore, shipment of fewer products from external zones to TCs is another reason for the decrease in TC usage.

Table 5.171. Total freight flow activities incoming to CCs from PCs and TCs in the C-EVREVL scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	806,065	91.4%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	34,302	3.9%	Zone 10	Zone 12	Zone 38
			11,350	11,350	11,603
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	41,102	4.7%	Zone 64	Zone 69	Zone 97
			10,363	17,263	13,475
Total	881,469				

Table 5.172 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the C-EVREVL scenario. Compared to the EVR and EVL scenarios, the number of heavy trucks and trucks decreases in the C-EVREVL scenario since most of them are used in direct shipments. Therefore, the number of vehicles that use TCs also decreases compared to the EVR and EVL scenarios. Regarding heavy trucks and trucks; in the C-EVREVL scenario, five TCs are fully utilized in the noon peak time interval, while all TCs are deployed at full capacity in the noon off-peak and evening off-peak time intervals, and only one TC is utilized in the evening peak time interval. In the EVL scenario, all TCs are utilized, with five of them reaching full capacity in the noon peak time interval as in the EVR scenario.

In the EVL scenario, all TCs are deployed at full capacity in the noon off-peak and evening off-peak time intervals, similar to those in the EVR and C-EVREVL scenarios. In the evening peak time interval, while five TCs are utilized in the EVL scenario, three TCs are utilized in the EVR scenario. Compared to the EVR and EVL scenarios, in the noon peak and evening peak time intervals, fewer vehicles use TCs in C-EVREVL scenario.

Table 5.172. Capacities and deployments of the TCs in each time interval for different vehicle types in the C-EVREVL scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520		520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity					137	
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity					340	
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity			300		500	
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity					320	
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity					660	

Contrary to the results of the EVR scenario, no panel van uses the TCs in the C-EVREVL scenario since panel vans are not utilized in this scenario. Additionally, the direct shipments from PCs to CCs increase, and most electric vans are used for direct shipments. For these reasons, the docs reserved for panel vans and electric vans are more idle than those in the EVR and EVL scenarios which results in under utilization of TCs. Regarding electric vans; in the C-EVREVL scenario, only one TC is deployed in the noon peak, evening peak, and evening off-peak time intervals, while two TCs are utilized in the noon off-peak time interval. In the EVR scenario, only one TC is deployed in the noon peak, noon off-peak, and evening peak time intervals. Four TCs are utilized, with three of them reaching full capacity in the evening off-peak time

interval. In the EVL scenario, five TCs are deployed at full capacity in the noon peak, noon off-peak, and evening off-peak time intervals. Four TCs are utilized in the evening peak time interval. As can be seen that, the number of vehicles using the TCs is lowest in the C-EVREVL scenario compared to the EVR and EVL scenarios. However, the number of vehicles using the TCs is the highest in the EVL scenario.

5.2.7.4. Combination of the TC200, EVL, EVP, and EVR Scenarios (C-TC200EVRLP). In this scenario, i) the capacities of all TCs are increased by 200%, ii) the range of electric vans is considered as 100 km, iii) the upper bound on the number of electric vans in each time interval is raised to 100,000, and iv) the electric vans and panel vans are allowed to ship products between two TCs. In the C-EVREVL scenario, there are significant changes in the flows and in the utilization of other vehicles when both the range and the upper bound on the electric vans are increased. In order to observe how the usage of TCs would be affected by increasing the capacity of TCs and allowing the other types of vehicles to be used between TCs, such a combined scenario is prepared. While analyzing the results of the C-TC200EVRLP scenario, the results of the C-EVREVL, TC200, and EVP scenarios are compared.

The obtained results of the C-TC200EVRLP scenario are presented in Tables 5.173-5.179. As can be seen in Table 5.173, in the C-TC200EVRLP scenario, the transportation cost is 3,159,463 ₺ , the CO_2 emission cost is 149,281 ₺ , and the total cost is calculated as 3,308,744 ₺ . The transportation cost decreases 17% compared to the EVP scenario, 12% compared to the TC200 scenario, and 4% compared to the C-EVREVL scenario. The CO_2 emission cost increases 11% compared to the EVP scenario and 17% compared to the TC200 scenario. However, it has decreases 5% compared to the C-EVREVL scenario. Compared to the EVP and TC200 scenarios, the decrease in the number of trucks and panel vans and the doubling of electric vans causes a reduction in transportation cost. Compared to the C-EVREVL scenario, both the transportation and CO_2 emission costs decrease when the capacities of TCs are increased (It is still more expensive to ship products directly from PCs to CCs).

There is a decrease in the amount of NO_x and CO emissions. The amount of NO_x emitted from non-electric vehicles is 3,738,592 g, and it decreases 53% compared to the EVP scenario, 48% compared to the TC200 scenario, and 1% compared to the C-EVREVL scenario. Similarly, the amount of CO emitted from these vehicles decreases 57% compared to the EVP scenario, 49% compared to the TC200 scenario, and 8% compared to the C-EVREVL scenario, and it drops to 2,989,524 g. The great decreases in the amounts of CO and NO_x emissions observed in this scenario are due to major reductions in truck and panel van deployments, while the doubling of electric vans has no negative effects since they do not emit CO or NO_x. On the other hand, NO_x emissions of the C-EVREVL and C-TC200EVRLP scenarios are about the same (since compared to the C-EVREVL scenario, the numbers of heavy trucks and trucks decrease in the evening off-peak time interval and increase in the noon peak and noon off-peak time intervals in the C-TC200EVRLP scenario) while CO emission of the C-TC200EVRLP scenario is 8% lower (due to the difference in CO emissions of each vehicle, in each zone and in each time interval).

Table 5.173. The transportation, CO_2 emission, and total costs in the EVP, TC200, C-EVREVL, and C-TC200EVRLP scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
EVP	3,795,724	134,158	3,929,882
TC200	3,581,155	127,769	3,708,924
C-EVREVL	3,286,007	157,274	3,443,281
C-TC200EVRLP	3,159,463	149,281	3,308,744

Table 5.174. The total number of vehicles in all zones in each time interval in the C-TC200EVRLP scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	371	1,946		612	2,929
Truck	6,600	9,454		55,710	71,764
Panel van					
Electric van	100,000	100,000	100,000	100,000	400,000

Table 5.175. The total number of vehicles in all zones in the EVP, TC200, C-EVREVL, and C-TC200EVRLP scenarios.

	EVP	TC200	C-EVREVL	C-TC200EVRLP
Heavy Truck	1,855	3,191	1,693	2,929
Truck	93,038	98,257	65,947	71,764
Panel van	660	83		
Electric van	200,000	200,000	400,000	400,000
Total	295,553	301,531	467,640	474,693

The total number of vehicles in all zones in each time interval in the C-TC200EVRLP scenario is presented in Table 5.174. Furthermore, Table 5.175 is provided in order to compare the number of vehicles in the EVP, TC200, C-EVREVL, and C-TC200EVRLP scenarios. As shown in Table 5.174, the deployment of electric vans reaches the maximum limit of 100,000 in all time intervals and panel vans are not deployed in the C-TC200EVRLP scenario. Heavy trucks and electric vans are less costly than trucks and panel vans. Since heavy trucks can only carry products between two TCs and from external zones to TCs, trucks and electric vans are preferred in shipments between other center pairs (from PCs to TCs, TCs to CCs, and PCs to CCs). Increasing the range of electric vans to 100 km is another factor that causes electric vans to be preferred more. There is a 58% increase in the number of heavy trucks (1,074 heavy trucks) compared to the EVP scenario and a 73% increase (from 1,693 to 2,929 heavy trucks) compared to the C-EVREVL scenario, while it decreases 8% (262 heavy trucks) compared to the TC200 scenario. Due to the increase in the capacities of the TCs, a significant increase is observed in the usage of the TCs. Therefore, an increase in the products coming from the external zones to TCs and the shipment between the two TCs is seen. This results in an increase in the number of heavy trucks since only heavy trucks can be utilized in these flows. Regarding the number of trucks, it decreases 23% (21,274 trucks) compared to the EVP scenario, decreases 27% (26,493 trucks) compared to the TC200 scenario, and increases 9% (5,817 trucks) compared to the C-EVREVL scenario. As the capacities of TCs increase by 200%, the amount of products from PCs to TCs and TCs to CCs increases compared to the C-EVREVL

scenario. More trucks can use the TCs. Since these vehicles are used both inbound to TCs and outbound from TCs (rather than the single trip associated with a direct shipment), this two-tiered transportation leads to more vehicle deployment.

Table 5.176. Freight flow of each vehicle type, in each time interval in the C-TC200EVRLP scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	13,271	22,473		63,019	98,763	98,763
	Panel van						
	Electric van						
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	16,188	7,490		69,123	92,802	96,326
	Panel van						
	Electric van	15	1,500	30	1,980	3,525	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	25,241	45,927		24,567	95,734	95,735
	Panel van						
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	11,304	18,654		13,853	43,811	43,811
	Panel van						
	Electric van						
From PCs to CSs (Z_{sk}^{pvt})	Truck				289,904	289,904	686,379
	Panel van						
	Electric van	99,985	98,500	99,970	98,020	396,475	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck				3,029	3,029	3,029
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck						
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	7,414	38,911		9,219	55,545	55,544
Total		173,418	233,455	100,000	572,714	1,079,588	
Rate		16.1%	21.6%	9.3%	53.0%	100%	

The freight flow of each vehicle type, in each time interval in the C-TC200EVRLP scenario is displayed in Table 5.176. The total amount of products shipped directly from PCs to CCs decreases 14% (107,876 tonnes) compared to the EVP scenario and 15% (119,685 tonnes) compared to the C-EVREVL scenario, while it increases 1% (4,418 tonnes) compared to the TC200 scenario. The amount of products transported between the two TCs increases 234% (from 908 to 3,029 tonnes) compared to the EVP scenario and 639% (from 410 tonnes to 3,029 tonnes) compared to the C-EVREVL scenario. However, it decreases 32% (1,403 tonnes) compared to the TC200 scenario.

The increase in the capacities of the TCs causes more products to be transported between the two TCs. In the TC200 scenario, by increasing the range of electric vans (by combining the C-EVREVL scenario with the TC200 scenario), an increase in direct shipments and a decrease in the usage of TCs are observed since electric vans are mostly used in direct shipments. This results in less product shipment between the two TCs compared to the TC200 scenario. The amount of external zone shipments increases 53% (19,358 tonnes) compared to the EVP scenario and 66% (22,096 tonnes) compared to the C-EVREVL scenario. However, it decreases 6% (3,834 tonnes) compared to the TC200 scenario. Compared to the C-EVREVL scenario, since the capacities of TCs are increased, PCs send more products through TCs, which causes a decrease in the amount of direct shipment. In addition, expanding the capacities of TCs enable more product flows from the external zones through TCs. The reason for the decrease in the amount of external zone shipments can be explained as follows: Since the range of electric vans and the bound on the number of electric vans are increased compared to the TC200 scenario (by combining the C-EVREVL scenario), the direct shipments from PCs to CCs increase. This increase in direct shipments causes CCs to receive fewer products from the external zones through TCs.

Similar to the EVP, TC200, and C-EVREVL scenarios, the most intense time of the freight flow is the evening off-peak time interval (53.0%). The reason is that the majority of products are distributed by trucks, and the least cost time interval to transport by trucks is the evening off-peak time interval.

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.177 and 5.178. Compared to the EVP scenario, the TC usage for incoming products from PCs increases from 6% to 16.9% (see Tables 5.97 and 5.177) in the C-TC200EVRLP scenario. The TC usage for outgoing products to CCs increases from 9.9% to 22.1% (see Tables 5.98 and 5.178). Meanwhile, this TC usage for incoming products from PCs is 17% in the TC200 scenario and 4.9% in the C-EVREVL scenario. The TC usage for outgoing products to CCs is 22.6% in the TC200 scenario and 8.6% in the C-EVREVL scenario. Compared to the EVP and

C-EVREVL scenarios, it is seen that there is an increase in the usage rates of TCs due to the increased capacities of TCs in the C-TC200EVRLP scenario. This increase in the usage of TCs leads to more vehicle deployment since more vehicles are used both inbound to TCs and outbound from TCs (rather than the single trip associated with a direct shipment) in this two-tiered transportation. Contrary to the EVP, TC200, and C-EVREVL scenarios, for incoming products from PCs, the TC in the 69$^{\text{th}}$ zone is utilized (as can be seen in Table 5.177) due to the increase in the usage of TCs.

Table 5.177. Total freight flow activities outgoing from PCs to CCs and TCs in the C-TC200EVRLP scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	686,379	83.1%			
From PCs to TCs on the European Side (W_{si}^{pvt})	95,735	11.6%	Zone 10	Zone 12	Zone 38
			33,503	34,050	28,181
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	43,811	5.3%	Zone 64	Zone 69	Zone 97
			13,853	1,068	28,890
Total	825,925				

Table 5.178. Total freight flow activities incoming to CCs from PCs and TCs in the C-TC200EVRLP scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	686,379	77.9%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	98,763	11.2%	Zone 10	Zone 12	Zone 38
			33,503	34,050	31,210
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	96,326	10.9%	Zone 64	Zone 69	Zone 97
			13,163	47,394	35,770
Total	881,468				

Table 5.179. Capacities and deployments of the TCs in each time interval for different vehicle types in the C-TC200EVRLP scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	1,560	1,560	1,560	1,560	1,560	1,560
	Noon Peak Occupied Capacity	1,451	1,560	841		1,560	1,560
	Noon Off-peak Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Noon Off-peak Occupied Capacity	2,280	2,280	2,280		2,280	2,280
	Evening Peak Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Evening Peak Occupied Capacity						
	Evening Off-peak Capacity	2,970	2,970	2,970	2,970	2,970	2,970
	Evening Off-peak Occupied Capacity	2,970	2,970	2,970	2,970	2,970	2,970
Panel vans and Electric vans	Noon Peak Capacity	1,020	1,020	1,020	1,020	1,020	1,020
	Noon Peak Occupied Capacity					15	
	Noon Off-peak Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Noon Off-peak Occupied Capacity					1,500	
	Evening Peak Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Evening Peak Occupied Capacity					30	
	Evening Off-peak Capacity	1,980	1,980	1,980	1,980	1,980	1,980
	Evening Off-peak Occupied Capacity					1,980	

Table 5.179 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the C-TC200EVRLP scenario. In the C-TC200EVRLP scenario, the usage of TCs increases compared to the C-EVREVL scenario since the capacities of TCs are expanded by 200%. Thus, considering heavy trucks and trucks, there are more vehicles in TCs. Similar to the C-EVREVL scenario, the number of electric vans reaches the maximum limit of 100,000 in the C-TC200EVRLP scenario, and panel vans are not utilized. Regarding panel vans and electric vans, since the number of electric vans in the flow from PCs to CCs is higher in the C-TC200EVRLP scenario, fewer vehicles visit TCs compared to the C-EVREVL scenario. Regarding heavy trucks and trucks; in the C-TC200EVRLP scenario, five TCs are utilized in the noon peak and noon off-peak time intervals. None of the TCs is utilized in the evening peak time interval, and all TCs are deployed at full capacity. In the EVP scenario, the usage of TCs is higher than that of the C-TC200EVRLP scenario. All TCs are utilized in the noon peak, noon off-peak, and evening off-peak time intervals, while five TCs are deployed in the evening peak time interval in the EVP scenario. In the TC200 scenario, the usage of TCs is very similar to that of the C-TC200EVRLP scenario in the noon peak, evening peak, and evening off-peak time

intervals, while all TCs are utilized in the noon off-peak scenario. In the C-EVREVL scenario, the usage of TCs is very similar to that of the C-TC200EVRLP scenario in the noon peak and evening off-peak time intervals, while all TCs are utilized in the noon off-peak time interval, and only one TC is utilized in the evening peak time interval.

Regarding panel vans and electric vans; in the C-TC200EVRLP scenario, only one TC is utilized in each time interval. In the EVP scenario, the TC usage is higher than that of the C-TC200EVRLP scenario, in which two TCs are fully utilized in the noon peak and evening peak time intervals, four TCs are deployed at full capacity in the noon off-peak time interval, and five TCs are fully utilized in the evening off-peak time interval. In the TC200 scenario, the TC usage is less than that of the C-TC200EVRLP scenario. The TCs are utilized only in the noon off-peak (one TC) and evening off-peak time intervals (two TCs). In the C-EVREVL scenario, the usage of TCs is very similar to that of the C-TC200EVRLP scenario in the noon peak, evening peak and evening off-peak time intervals. Unlike in the C-TC200EVRLP scenario, two TCs are deployed in the noon off-peak time interval.

5.2.7.5. Combination of the TC200 and EVU Scenarios (C-TC200EVU). In this scenario, the TC200 and EVU scenarios are combined. In other words, the capacities of all TCs are increased by 200%, and the upper bound on the number of electric vans in each time interval is removed. In the EVU scenario, the TCs are deployed at full capacity regarding electric vans. Therefore, such a combined scenario is created in order to see how the results would be changed by increasing the capacities of TCs.

The obtained results of the C-TC200EVU scenario are presented in Tables 5.180-5.186. The transportation cost is 2,810,289 ₺ , the CO_2 emission cost is 142,143 ₺ , and the total cost is calculated as 2,952,432 ₺ . As can be observed from Table 5.180, the transportation cost decreases 22% compared to the TC200 scenario and 4% compared to the EVU scenario. The CO_2 emission cost decreases 3% compared to the EVU scenario though it increases 11% compared to the TC200 scenario. One of the most noteworthy results observed in the TC capacity scenarios is the decrease

in transportation and CO_2 emission costs compared to the base scenario. The EVU scenario also causes a reduction in transportation cost compared to the base scenario. When these two scenarios are combined, the transportation cost becomes even lower in the C-TC200EVU scenario. The significant increase in the number of electric vans also causes an increase in the CO_2 emission cost as in the EVU scenario. When the TC200 scenario is combined with the EVU scenario, the CO_2 emission cost is much higher in the C-TC200EVU scenario than in the TC200 scenario even though the increase in the capacities of TCs (thus, the increase in their usage) reduces the CO_2 emission cost.

Table 5.180. The transportation, CO_2 emission, and total costs in the TC200, EVU, and C-TC200EVU scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
EVU	2,912,709	146,560	3,059,269
TC200	3,581,155	127,769	3,708,924
C-TC200EVU	2,810,289	142,143	2,952,432

Table 5.181. The total number of vehicles in all zones in each time interval in the C-TC200EVU scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck		8		1,811	1,819
Truck	125	4,416		16,456	20,997
Panel van					
Electric van	22,590	7,469	731,417	8,506	769,982

The total number of vehicles in all zones in each time interval in the C-TC200EVU scenario is displayed in Table 5.181. Additionally, Table 5.182 provides for the comparison of the number of vehicles in the TC200 and EVU scenarios. The number of heavy trucks decreases 43% (1,371 heavy trucks) compared to the TC200 scenario and increases 17% (270 heavy trucks) compared to the EVU scenario. The number of trucks decreases 79% (77,260 trucks) compared to the TC200 scenario, while it increases 20% (3,519 trucks) compared to the EVU scenario. Moreover, panel vans

are not used at all in the C-TC200EVU scenario as in the EVU scenario. However, it is used in the TC200 scenario (only 83 panel vans). Since the upper bound on the deployment of electric vans is removed, the total number of electric vans increases to 769,982. The number of electric vans in the EVU scenario is 773,039, while it is 200,000 in the TC200 scenario (due to the upper bound on the number of electric vans). As can be seen, the usage of vehicles in this scenario is similar to those in the EVU scenario. When the TC200 scenario is combined with the EVU scenario, the number of electric vans increases significantly (since the upper bound on the deployment of electric vans is removed. Thus, the number of other vehicles decreases (trucks, heavy trucks, and panel vans) in the C-TC200EVU scenario. The underlying reason is that electric vans have low unit CO_2 emissions and unit transportation costs.

Table 5.182. The total number of vehicles in all zones in the TC200, EVU, and C-TC200EVU scenarios.

	TC200	EVU	C-TC200EVU
Heavy Truck	3,191	1,549	1,819
Truck	98,257	17,478	20,997
Panel van	83		
Electric van	200,000	773,039	769,982
Total	301,531	792,066	792,798

There is a decrease in the amount of NO_x and CO emissions. The amount of NO_x released from these vehicles is 2,458,753 g, and it decreases 66% compared to the TC200 scenario and 8% compared to the EVU scenario. Similarly, the amount of CO emitted from these vehicles is 1,834,401 g. It decreases 69% compared to the TC200 scenario and 14% compared to the EVU scenario. Since the amount of NO_x and CO emissions are lower in both the EVU and TC200 scenarios compared to the base scenario, it is seen that the NO_x and CO emissions are even lower when these two scenarios are combined. As can be seen, in the C-TC200EVU scenario, although the number of non-electric vehicles is higher than those in the EVU scenario, the total amounts of NO_x and CO decline. The underlying reason is the decrease in the total

distance traveled and the lower unit emission rates of fully loaded trucks (compared to partially loaded trucks).

Table 5.183. Freight flow of each vehicle type, in each time interval in the C-TC200EVU scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck		13,557		45,024	58,582	64,691
	Panel van						
	Electric van	1,717	1,393	3,000		6,110	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	1,243	46		49,086	50,374	59,503
	Panel van						
	Electric van	1,548	1,500	4,100	1,980	9,128	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck		7,882		41,806	49,688	60,153
	Panel van						
	Electric van	1,343	3,076	1,500	4,546	10,464	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	4	22,675		4,127	26,806	32,198
	Panel van						
	Electric van	1,512	1,500	400	1,980	5,392	
From PCs to CCs (Z_{sk}^{pvt})	Truck				18,389	18,389	757,276
	Panel van						
	Electric van	16,470		722,417		738,886	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck				4,539	4,539	4,539
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck						
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck		158		31,685	31,843	31,843
Total		23,837	51,787	731,417	203,162	1,010,201	
Percentage		2.4%	5.1%	72.4%	20.1%	100%	

The freight flow of each vehicle type, in each time interval in the C-TC200EVU scenario is displayed in Table 5.183. The vast majority of flows are observed in direct shipments from PCs to CCs. The total amount of products shipped directly from PCs to CCs increases 11% (75,313 tonnes) compared to the TC200 scenario. However, it decreases 6% (45,525 tonnes) compared to the EVU scenario. The external zone shipments decrease 46% (27,536 tonnes) compared to the TC200 scenario and increase 21% (5,614 tonnes) compared to the EVU scenario. Furthermore, the amount

of products transported between two TCs increases 2% (107 tonnes) compared to the TC200 scenario and decreases 4% (195 tonnes) compared to the EVU scenario. When the results of the TC200 scenario are examined, it is observed that the direct shipments from PCs to CCs decrease and the external shipments increase. However, when the TC200 scenario is combined with the EVU scenario, the direct shipments from PCs to CCs increase and the external shipments decrease in the C-TC200EVU scenario compared to the TC200 scenario. The reason is that electric vans are more advantageous in terms of unit transportation and CO_2 emission costs. In addition, the fact that the trucks are not fully loaded in direct shipments makes electric vans more attractive. When the limit on the number of electric vans is removed, the direct shipments from PCs to CCs and the usage of electric vans in these shipments increase. Thus, fewer products come from external zones.

The most intense time of the freight flow is the evening off-peak time interval since it is the cheapest time interval to transport by trucks, and most of the shipments are made by trucks in the TC200 scenario. However, similar to the EVU scenario, the most intense time of the freight flow is the evening peak time interval (72.4%), and the least intense time is the noon peak time interval (2.4%) in the C-TC200EVU scenario. The underlying reason is that electric vans have the lowest unit transportation cost in the evening peak time interval, and most of the shipments are made by electric vans in this combined scenario.

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.184 and 5.185. The TC usage for incoming products from PCs increases from 6.1% to 10.9% compared to the EVU scenario (as can be seen in Tables 5.85 and 5.185) while it is 17% in the TC200 scenario (see Table 5.28). The TC usage for outgoing products to CCs increases from 8.9% to 14.1% compared to the EVU scenario (as can be seen in Tables 5.84 and 5.184). However, it is 22.6% in the TC200 scenario (see Table 5.27). In the EVU scenario, TCs are heavily utilized, and also the docks of TCs reserved for panel vans and electric vans are fully utilized. When this scenario is combined with the TC200, that is, when the capacities of the TCs are

extended, more vehicles have the opportunity to use TCs, and thus, the utilization rates of the TCs are increased. For incoming products from PCs, the TC in zone 69 is still unused (see Table 5.185).

Table 5.184. Total freight flow activities outgoing from PCs to CCs and TCs in the C-TC200EVU scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	757,276	89.1%			
From PCs to TCs on the European Side (W_{si}^{pvt})	60,153	7.1%	Zone 10	Zone 12	Zone 38
			25,785	20,634	13,733
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	32,198	3.8%	Zone 64	Zone 69	Zone 97
			5,547		26,651
Total	849,627				

Table 5.185. Total freight flow activities incoming to CCs from PCs and TCs in the C-TC200EVU scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	757,276	85.9%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	64,691	7.3%	Zone 10	Zone 12	Zone 38
			25,785	20,634	18,272
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	59,503	6.8%	Zone 64	Zone 69	Zone 97
			4,755	23,800	30,948
Total	881,470				

Table 5.186 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the C-TC200EVU scenario. In the EVU scenario, most of the shipments are made by electric vans since their advantages regarding costs and emissions. Due to their ranges, they are preferred not only for

short-distance direct shipments but also for short-distance PCs-TCs and TCs-CCs flows. When the EVU scenario is combined with the TC200 scenario (with expanding capacities of TCs), more electric vans are utilized in the flows from PCs to TCs and from TCs to CCs. The amount of direct shipments from PCs to CCs decreases, and the amount of external zone shipments increases. Thus, the utilization of TCs increases.

Table 5.186. Capacities and deployments of the TCs in each time interval for different vehicle types in the C-TC200EVU scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	1,560	1,560	1,560	1,560	1,560	1,560
	Noon Peak Occupied Capacity						125
	Noon Off-peak Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Noon Off-peak Occupied Capacity	1,587	557				2,280
	Evening Peak Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Evening Peak Occupied Capacity						
	Evening Off-peak Capacity	2,970	2,970	2,970	2,970	2,970	2,970
	Evening Off-peak Occupied Capacity	2,970	2,970	2,970	1,192	2,970	2,970
Panel vans and Electric vans	Noon Peak Capacity	1,020	1,020	1,020	1,020	1,020	1,020
	Noon Peak Occupied Capacity	1,020	1,020	1,020	1,020	1,020	1,020
	Noon Off-peak Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Noon Off-peak Occupied Capacity	1,500	1,500	1,469		1,500	1,500
	Evening Peak Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Evening Peak Occupied Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Evening Off-peak Capacity	1,980	1,980	1,980	1,980	1,980	1,980
	Evening Off-peak Occupied Capacity	1,980	1,980	586		1,980	1,980

Regarding heavy trucks and trucks; in the C-TC200EVU scenario, in the noon peak time interval, only one TC is utilized (while, in that time interval, five TCs are utilized individually in the TC200 and EVU scenarios). In the C-TC200EVU scenario, in the noon off-peak time interval, three TCs are utilized, with one of them reaching full capacity (while, in that time interval, all TCs are fully utilized in the EVU scenario and all TCs are deployed, with five of them reaching full capacity in the TC200 scenario). In the C-TC200EVU scenario, in the evening peak time interval, TCs are not utilized as in the TC200 scenario (while, in that time interval, two TCs are deployed in the EVU scenario). In the C-TC200EVU scenario, in the evening off-peak time interval, all TCs are utilized, with five of them reaching full capacity (while, in that time interval, all TCs are deployed at full capacity in the EVU and TC200 scenarios).

Regarding panel vans and electric vans in the C-TC200EVU scenario, in the noon peak and evening peak time intervals, all TCs are fully utilized as in the EVU scenario. However, in that time interval, no TC is utilized in the TC200 scenario. In the C-TC200EVU scenario, in the noon off-peak time interval, five TCs are deployed, with four of them reaching full capacity while, in that time interval, all TCs are fully utilized in the EVU scenario, and only one TC is fully utilized in the TC200 scenario. Similarly, in the C-TC200EVU scenario, in the evening off-peak time interval, five TCs are deployed, with four of them reaching full capacity while, in that time interval, all TCs are fully utilized in the EVU scenario, and two TCs are deployed in the TC200 scenario.

5.2.7.6. Combination of the VNL and TC200 Scenarios (C-VNLTC200). In this scenario, for each zone, the limit on the number of vehicles per km^2 in each time interval is reduced (thus, the upper bounds of the constraint set 4.12 are set as 1000, 2,000, 3,000, and 4,500) as in the VNL scenario and the capacities of all TCs are increased by 200% as in the TC200 scenario. In the VNL scenario, the capacities of TCs are insufficient especially for heavy trucks and trucks. Therefore, such a combined scenario is created in order to see how the results would be changed by increasing the capacities of TCs.

The obtained results of the C-VNLTC200 scenario are presented in Tables 5.187-5.193. The transportation cost is 3,794,043 ₺ , the CO_2 emission cost is 132,964 ₺ , and the total cost is calculated as 3,927,006 ₺ . As can be observed from Table 5.187, the transportation cost increases 6% compared to the TC200 scenario. However, it decreases 6% compared to the VNL scenario. The CO_2 emission cost increases 4% compared to the TC200 scenario though it decreases 5% compared to the VNL scenario. As explained in the results of the VNL scenario, density limits on the number of vehicles result in increased costs, as vehicles are forced to operate on more costly routes and time intervals. However, when the capacities of TCs are increased as well, a decrease in costs is observed. The main reason is that it is less costly and more "vehicle efficient-less density causing" to distribute products through TCs rather than sending them directly.

Table 5.187. The transportation, CO_2 emission, and total costs in the TC200, VNL, and C-VNLTC200 scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
TC200	3,581,155	127,769	3,708,924
VNL	4,057,578	140,321	4,197,900
C-TC200VNL	3,794,043	132,964	3,927,006

The amount of NO_x emitted from non-electric vehicles is 7,410,475 g. Although it decreases 8% compared to the VNL scenario, it increases 3% compared to the TC200 scenario. The amount of CO emitted from these vehicles is 6,030,468 g, and it decreases 13% compared to the VNL scenario, while it increases 2% compared to the TC200 scenario. The reason for the increase in the amount of NO_x and CO emissions compared to the TC200 scenario is related to the increase in the number of heavy trucks and panel vans while the reason for the decrease in emissions, compared to the VNL scenario may be related to the decrease in the total distance traveled.

The total number of vehicles in all zones in each time interval in the C-VNLTC200 scenario is presented in Table 5.188. In order to compare the number of vehicles in the VNL, TC200, and C-VNLTC200 scenarios, Table 5.189 is provided. The number of heavy trucks increases 89% (2,246 heavy trucks) compared to the VNL scenario and 49% (1,573 heavy trucks) compared to the TC200 scenario. Although the number of trucks decreases 5% (4,932 trucks) compared to the TC200 scenario, it increases 7% (5,839 trucks) compared to the VNL scenario. When panel vans are examined, a significant increase is observed compared to the TC200 scenario (from 83 to 7,435 panel vans). However, there is a 36% decrease (4,285 panel vans) in the number of panel vans compared to the VNL scenario. The number of electric vans is still at the upper bound value of 200,000, as seen in Table 5.188. When the VNL scenario is combined with the TC200 scenario, the expanded capacities of TCs lead to a rise in the number of trucks and heavy trucks. Shipping products by trucks from PCs to CCs through TCs is more advantageous than shipping them directly since trucks cannot be fully loaded in direct shipments. Furthermore, the increase in the amount of products

coming from the external zones through TCs provides another reason for the increase in heavy truck usage. Additionally, the increase in the number of heavy trucks and trucks decreases the need for panel vans compared to the VNL scenario. All these help reduce the disadvantages of the pure VNL scenario. On the other hand, when the C-VNLTC200 scenario is compared with the pure TC200 scenario, it can be seen that the additional density limits leads to more panel van usage in direct shipments and to longer shipment routes (leading to higher costs and emissions).

Table 5.188. The total number of vehicles in all zones in each time interval in the C-VNLTC200 scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	674	3,150		940	4,764
Truck	13,020	25,343	2,338	52,625	93,326
Panel van			208	7,310	7,518
Electric van	50,000	50,000	50,000	50,000	200,000

Table 5.189. The total number of vehicles in all zones in the TC200, VNL, and C-VNLTC200 scenarios.

	TC200	VNL	C-TC200VNL
Heavy Truck	3,191	2,517	4,764
Truck	98,257	87,487	93,326
Panel van	83	11,804	7,518
Electric van	200,000	200,000	200,000
Total	301,531	301,808	305,608

The freight flow of each vehicle type, in each time interval in the C-VNLTC200 scenario is displayed in Table 5.190. The total amount of products shipped directly from PCs to CCs decreases 16% (127,595 tonnes) compared to the VNL scenario and 4% (29,784 tonnes) compared to the TC200 scenario. There is no product transported between two TCs as in the VNL scenario. The external zone shipments increase 87% (from 50,344 to 94,045 tonnes) compared to the VNL scenario and 58% (from 59,379 to 94,045 tonnes) compared to the TC200 scenario. The increase in the capacities of TCs increases the utilization rate of the TCs and decreases the direct shipments from

PCs to CCs. Furthermore, compared to the TC200 scenario, the limits on the number of vehicles cause a decrease not only in the total number of trucks but also in the number of trucks used in direct shipments. Thus, the amount of products transported in direct shipments also decreases. In addition, the increase in the capacities of TCs leads to higher usage of heavy trucks and, thus, an increase in shipments from the external zones since the external zone shipments are only transported by heavy trucks. Similar to the VNL and TC200 scenarios, the most intense time of the freight flow is the evening off-peak time interval (47.8%), and the least intense time is the evening peak time interval (6.6%), as in the VNL and TC200 scenarios. Electric vans are mostly used in direct shipments from PCs to CCs.

Table 5.190. Freight flow of each vehicle type, in each time interval in the C-VNLTC200 scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	21,025	17,496		66,696	105,217	105,217
	Panel van						
	Electric van						
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	17,349	19,234	7,825	76,961	121,369	124,074
	Panel van						
	Electric van	725			1,980	2,705	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	25,775	50,295	4,138	21,018	101,226	101,226
	Panel van						
	Electric van						
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	7,114	12,412	10,368	4,127	34,020	34,021
	Panel van						
	Electric van						
From PCs to CCs (Z_{sk}^{pvt})	Truck	44,202	115,493	789	268,084	428,569	652,178
	Panel van			729	25,586	26,315	
	Electric van	49,275	50,000	50,000	48,020	197,295	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck		1,219			1,219	1,219
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				2,772	2,772	2,772
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	13,474	61,776		16,024	91,274	91,274
Total		178,939	327,925	73,849	531,268	1,111,981	
Percentage		16.1%	29.5%	6.6%	47.8%	100%	

Table 5.191. Total freight flow activities outgoing from PCs to CCs and TCs in the C-VNLTC200 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	652,178	82.8%			
From PCs to TCs on the European Side (W_{si}^{pvt})	101,226	12.9%	Zone 10	Zone 12	Zone 38
			31,971	34,050	35,204
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	34,021	4.3%	Zone 64	Zone 69	Zone 97
			16,222		17,798
Total	787,425				

Table 5.192. Total freight flow activities incoming to CCs from PCs and TCs in the C-VNLTC200 scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	652,178	74.0%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	105,217	11.9%	Zone 10	Zone 12	Zone 38
			34,743	34,050	36,424
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	124,074	14.1%	Zone 64	Zone 69	Zone 97
			25,275	47,204	51,595
Total	881,469				

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.191 and 5.192. Compared to the VNL scenario, the TC usage for incoming products from PCs increases from 6.2% to 17.2% (see Tables 5.111 and 5.191), and the TC usage for outgoing products to CCs increases from 11.5% to 26.0% (see Tables 5.112 and 5.192) because of the expanded capacities of TCs. Meanwhile, this TC usage for incoming products from PCs is 17.0%, and the TC usage for outgoing products to CCs is 22.6% in the TC200 scenario. These results imply that increasing the capacities of TCs leads to an increase in the utilization of TCs in this combined scenario compared to the VNL scenario. As the direct shipments

from PCs to CCs decrease, more products are shipped from PCs to TCs. Furthermore, the increase in the external zone shipments through TCs also results in the increased usage of TCs in the C-VNLTC200 scenario.

Table 5.193 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the C-VNLTC200 scenario. In this scenario, regarding heavy trucks and trucks, the usage of TCs is higher than that of both the TC200 and VNL scenarios. Regarding panel vans and electric vans, although the number of vehicles using the TCs is higher than that of the TC200 scenario, it is less than that of the VNL scenario. Compared to the VNL scenario, since the capacities of TCs are increased, inflow to and outflow from TCs increase in the C-VNLTC200 scenario. Thus, the number of trucks utilized in flows incoming to and outgoing from TCs increases (because trucks are fully loaded in non-direct shipments). The number of heavy trucks used in the external zone shipments also increases. Regarding heavy trucks and trucks; in the C-VNLTC200 scenario, except for one TC, all TCs are fully utilized in the noon peak and noon off-peak time intervals. Two TCs are utilized in the evening peak time interval. All TCs are deployed at full capacity in the evening off-peak time interval. In the TC200 scenario, all TCs are utilized in the noon off-peak and evening off-peak time intervals, similar to the C-VNLTC200 scenario. Five TCs are deployed in the noon peak time interval. However, unlike the C-VNLTC200 scenario, none of them is utilized in the evening peak time interval in the TC200 scenario. In the VNL scenario, all TCs are fully utilized in the noon peak, noon off-peak, and evening off-peak time intervals and four TCs are deployed at full capacity in the evening peak time interval.

Regarding panel vans and electric vans; there is a limited usage of panel vans and electric vans. In the C-VNLTC200 scenario, only one TC is utilized in the noon peak and evening off-peak time intervals, while none of the TCs is utilized in the noon off-peak and evening peak time intervals. In the TC200 scenario, none of the TCs is utilized in the noon peak and evening peak time intervals, one TC is deployed at full capacity in the noon off-peak time interval, and two TCs are utilized in the evening

off-peak time interval. In the VNL scenario, two TCs are deployed in the noon peak time interval, three TCs are utilized in the noon off-peak time interval, and five TCs are deployed at full capacity in the evening off-peak time interval. However, none of the TCs is utilized in the evening peak time interval.

Table 5.193. Capacities and deployments of the TCs in each time interval for different vehicle types in the C-VNLTC200 scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	1,560	1,560	1,560	1,560	1,560	1,560
	Noon Peak Occupied Capacity	1,560	1,560	1,560		1,560	1,560
	Noon Off-peak Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Noon Off-peak Occupied Capacity	2,280	2,280	2,280	1,754	2,280	2,280
	Evening Peak Capacity	2,280	2,280	2,280	2,280	2,280	2,280
	Evening Peak Occupied Capacity			414			1,819
	Evening Off-peak Capacity	2,970	2,970	2,970	2,970	2,970	2,970
	Evening Off-peak Occupied Capacity	2,970	2,970	2,970	2,970	2,970	2,970
Panel vans and Electric vans	Noon Peak Capacity	1,020	1,020	1,020	1,020	1,020	1,020
	Noon Peak Occupied Capacity					725	
	Noon Off-peak Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Noon Off-peak Occupied Capacity						
	Evening Peak Capacity	1,500	1,500	1,500	1,500	1,500	1,500
	Evening Peak Occupied Capacity						
	Evening Off-peak Capacity	1,980	1,980	1,980	1,980	1,980	1,980
	Evening Off-peak Occupied Capacity					1,980	

5.2.7.7. Combination of the EVU and VNL Scenarios (C-EVUVNL). In this scenario, the upper bound on the number of electric vans in each time interval is removed as in the EVU scenario, and the limit on the number of vehicles per km^2 in each time interval, in each zone is reduced (thus, the upper bounds of the constraint set 4.12 are set as 1000, 2,000, 3,000, and 4,500) as in the VNL scenario. In the EVU scenario, there is a huge number of electric vans in the already dense evening peak time interval, which is quite unrealistic. Therefore, such a combined scenario is created in order to see how the results would be changed by limiting the number of vehicles in some zones and in some time intervals.

The obtained results of the C-EVUVNL scenario are presented in Tables 5.194-5.200. The transportation cost is 3,629,213 ₺ , the CO_2 emission cost is 147,259 ₺ , and

the total cost is calculated as 3,776,472 ₺ . As shown in Table 5.194, the transportation cost increases 25% compared to the EVU scenario, but it decreases 11% compared to the VNL scenario. The CO_2 emission cost increases only 0.5% compared to the EVU scenario and 5% compared to the VNL scenario. These results can be interpreted as follows: The EVU scenario leads to a decrease in transportation costs compared to the base scenario. When it is combined with the VNL scenario, the C-EVUVNL scenario experiences even lower transportation costs than the pure VNL scenario. This cost reduction is attributed to a decrease in the number of trucks and an increase in the number of electric vans in the combined scenario, as electric vans have lower unit transportation costs than trucks. However, the reduced upper bound values on the number of vehicles per unit area in the VNL scenario result in vehicles shifting to different routes and higher cost time intervals. This causes higher costs in the C-EVUVNL scenario compared to the EVU scenario. Moreover, due to the significant increase in the number of electric vans, the CO_2 emission cost increases in the EVU scenario compared to the base scenario. For this reason, the cost of CO_2 emissions is much higher in the C-EVUVNL scenario than in the VNL scenario.

Table 5.194. The transportation, CO_2 emission, and total costs in the EVU, VNL, and C-EVUVNL scenarios (₺).

	Transportation Cost	CO_2 Emission Cost	Total Cost
EVU	2,912,709	146,560	3,059,269
VNL	4,057,578	140,321	4,197,900
C-EVUVNL	3,629,213	147,259	3,776,472

The amount of NO_x emitted from non-electric vehicles is 5,551,579 g. Although it decreases 31% compared to the VNL scenario, it more than doubles compared to the EVU scenario. The amount of CO emitted from these vehicles is 5,036,659 g. It decreases 27% compared to the VNL scenario, but it more than doubles compared to the EVU scenario. The reason for the decrease in the amount of NO_x and CO emissions in the C-EVUVNL scenario compared to the VNL scenario is related to major reductions in truck deployments. The doubling of electric vans has no negative effects since they do not contribute to CO or NO_x emissions.

The total number of vehicles in all zones in each time interval in the C-EVUVNL scenario is presented in Table 5.195. In order to compare the number of vehicles in the EVU, VNL, and C-EVUVNL scenarios, Table 5.196 is provided. The number of heavy trucks increases 66% (1,020 heavy trucks) compared to the EVU scenario and only 2% (52 heavy trucks) compared to the VNL scenario. Although the number of trucks increases 169% (from 17,478 to 46,968 trucks) compared to the EVU scenario, it decreases 46% (40,519 trucks) compared to the VNL scenario. Panel vans are not used at all in the EVU scenario. However, the number of panel vans increases 37% (4,381 panel vans) compared to the VNL scenario. The total number of electric vans is 200,000 in the VNL scenario. Since the upper bound on the deployment of electric vans is removed, it increases to 488,938 in the C-EVUVNL scenario (while it is 773,039 in the EVU scenario). Due to this increase in the number of electric vans, there is a significant decrease in the number of trucks compared to the VNL scenario. Combining the EVU scenario with VNL scenario results in a decrease in the number of electric vans since there is a limit on the number of vehicles in each zone, which prevents the utilization of too many electric vans. Thus, the number of heavy trucks and panel vans is higher than that of the VNL scenario. Another reason for the increase in the number of these vehicles is related to the density they create. As the relevant constraint becomes tighter, there is an increase in the number of high-capacitated vehicles, such as heavy trucks. The usage of heavy trucks can be advantageous in reducing density in zones since their PCE value is 3.5 and the load-carrying capacity is 20 tonnes. It can be seen that the additional density limits lead to more panel van usage in direct shipments.

Table 5.195. The total number of vehicles in all zones in each time interval in the C-EVUVNL scenario.

	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
Heavy Truck	587	916	662	404	2,569
Truck	2,598	9,252	2,388	32,730	46,968
Panel van	169	378		15,639	16,186
Electric van	149,795	77,613	227,753	33,777	488,938

Table 5.196. The total number of vehicles in all zones in the EVU, VNL, and C-EVUVNL scenarios.

	EVU	VNL	C-EVUVNL
Heavy Truck	1,549	2,517	2,569
Truck	17,478	87,487	46,968
Panel van		11,804	16,186
Electric van	773,039	200,000	488,938
Total	792,066	301,808	552,092

The freight flow of each vehicle type, in each time interval in the C-EVUVNL scenario is displayed in Table 5.197. The total amount of products shipped directly from PCs to CCs decreases 3% (24,357 tonnes) compared to the EVU scenario and only 0.2% (1,331 tonnes) compared to the VNL scenario. There is no product transported between two TCs as in the VNL scenario. The external zone shipments increase 96% (25,162 tonnes) compared to the EVU scenario and 2% (from 1,046 tonnes) compared to the VNL scenario. As the restrictions on the number of vehicles per unit area in the zones become tighter, transporting freights with heavy trucks (with a load-carrying capacity of 20 tonnes and a PCE value of 3.5) provides a significant advantage. Since the primary transportation mode in the external zone shipments is heavy trucks, the amount of external zone shipments increases in the C-EVUVNL scenario compared to the EVU scenario. Furthermore, the amount of direct shipments decreases as the external zone shipments increase. 761,039 of 773,039 electric vans are utilized in direct shipments from PCs to CCs in the EVU scenario since electric vans are the low-cost delivery alternative. Combining this scenario with the VNL scenario (which makes the restrictions on the number of vehicles tighter) results in less vehicle usage. Therefore, the number of electric vans utilized in direct shipments decreases to 477,598 and the usage of higher capacitated vehicles (such as trucks and panel vans) increases. This sharp decrease in the amount of electric vans also leads to a reduction in direct shipments. The noon off-peak time interval (17.9%) is the least intense time in the C-EVUVNL scenario. However, the most intense time of the freight flow is the evening off-peak time interval (36.2%), similar to the VNL scenario, although it is the evening peak in the EVU scenario. Moreover, although it seems unrealistic to utilize 746,943

electric vans in the evening peak time interval in the EVU scenario, it decreases to 227,753 in the C-EVUVNL scenario in that time interval. Limiting the number of vehicles in each zone prevents the excessive increase in the number of electric vans. Thus, more realistic results are obtained.

Table 5.197. Freight flow of each vehicle type, in each time interval in the C-EVUVNL scenario (tonnes).

		Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total (Row)	Total
From TCs on the European Side to CCs (X_{ik}^{pvt})	Truck	6,061	15,136	2,351	18,972	42,520	46,311
	Panel van						
	Electric van	1,020	310	1,439	1,022	3,792	
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	Truck	6,500	13,644	3,835	28,875	52,855	56,714
	Panel van						
	Electric van	680	1,000	1,000	1,180	3,860	
From PCs to TCs on the European Side (W_{si}^{pvt})	Truck	9,539	7,664	12,957	7,513	37,673	39,882
	Panel van						
	Electric van		1,190	61	958	2,208	
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	Truck	3,226		4,740		7,966	11,756
	Panel van				2,310	2,310	
	Electric van	340	500	500	140	1,480	
From PCs to CCs (Z_{sk}^{pvt})	Truck	492	42,057		203,958	246,506	778,444
	Panel van	590	1,322		52,427	54,338	
	Electric van	147,755	74,613	224,753	30,477	477,598	
From TCs on the European Side to TCs on the Asian Side (U_{ij}^{pvt})	Heavy Truck						
From TCs on the Asian Side to TCs on the European Side (ϑ_{ji}^{pvt})	Heavy Truck						
From External Zone to TCs on the European Side (Y_i^{pt})	Heavy Truck				6,431	6,431	6,431
From External Zone to TCs on the Asian Side (Y_j^{pt})	Heavy Truck	11,749	18,312	13,249	1,649	44,960	44,959
Total		187,952	175,748	264,885	355,912	984,497	
Percentage		19.1%	17.9%	26.9%	36.1%	100%	

The active usage rates of TCs and the amount of freight arrivals/departures at each TC are reported in Tables 5.198 and 5.199. Compared to the EVU scenario, the TC usage for incoming products from PCs increases from 6.1% to 6.2% (see Tables 5.84 and 5.198), and for the TC usage for outgoing products to CCs increases from 8.9% to 11.7% (see Tables 5.85 and 5.199). Meanwhile, in the VNL scenario, this TC usage for incoming products from PCs is 6.2% (which is almost the same as in the

C-EVUVNL scenario), and the TC usage for outgoing products to CCs is 11.5%. Due to the decrease in direct shipments and increase in the external zone shipments, the amount of products transported through TCs increases. This increase in the inflows to TCs results in an increase in the outflows from TCs. Nonetheless, the limited capacities of TCs prevent a significant rise in TCs' utilization rates.

Table 5.198. Total freight flow activities outgoing from PCs to CCs and TCs in the C-EVUVNL scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	778,444	93.8%			
From PCs to TCs on the European Side (W_{si}^{pvt})	39,882	4.8%	Zone 10	Zone 12	Zone 38
			10,837	12,894	16,150
From PCs to TCs on the Asian Side (W_{sj}^{pvt})	11,756	1.4%	Zone 64	Zone 69	Zone 97
			3,365		8,390
Total	830,082				

Table 5.199. Total freight flow activities incoming to CCs from PCs and TCs in the C-EVUVNL scenario (tonnes).

From PCs to CCs (Z_{sk}^{pvt})	778,444	88.3%			
From TCs on the European Side to CCs (X_{ik}^{pvt})	46,311	5.3%	Zone 10	Zone 12	Zone 38
			12,926	17,235	16,150
From TCs on the Asian Side to CCs (X_{jk}^{pvt})	56,714	6.4%	Zone 64	Zone 69	Zone 97
			15,345	21,533	19,837
Total	881,469				

Table 5.200 presents the current capacities of the TCs and how much of the capacity is occupied in each time interval in the C-EVUVNL scenario. In this scenario, regarding heavy trucks and trucks, the usage of TCs is slightly higher than that of both the VNL and EVU scenarios. In the C-EVUVNL scenario, all TCs are fully utilized

in the noon peak, noon off-peak, and evening off-peak time intervals as in the VNL scenario. In the evening peak time interval, five TCs are utilized, and four of them are deployed at full capacity in the C-EVUVNL scenario, while in that time interval, four TCs are fully utilized in the VNL scenario. In the EVU scenario, five TCs are deployed at full capacity in the noon peak time interval, all TCs are fully utilized in the noon off-peak and evening off-peak time intervals as in the C-EVUVNL scenario, and only two TCs are deployed in the evening peak time interval.

Regarding panel vans and electric vans; in the C-EVUVNL scenario, all TCs are fully utilized in all time intervals as in the EVU scenario. However, in the VNL scenario, two TCs are deployed in the noon peak time interval, three TCs are utilized in the noon off-peak time interval, no TC is deployed at all in the evening peak time interval, and five TCs are fully utilized in the evening off-peak time interval.

Table 5.200. Capacities and deployments of the TCs in each time interval for different vehicle types in the C-EVUVNL scenario (in number of vehicles).

		Zone 10	Zone 12	Zone 38	Zone 64	Zone 69	Zone 97
Heavy Trucks and Trucks	Noon Peak Capacity	520	520	520	520	520	520
	Noon Peak Occupied Capacity	520	520	520	520	520	520
	Noon Off-peak Capacity	760	760	760	760	760	760
	Noon Off-peak Occupied Capacity	760	760	760	760	760	760
	Evening Peak Capacity	760	760	760	760	760	760
	Evening Peak Occupied Capacity	11	760	760		760	760
	Evening Off-peak Capacity	990	990	990	990	990	990
	Evening Off-peak Occupied Capacity	990	990	990	990	990	990
Panel vans and Electric vans	Noon Peak Capacity	340	340	340	340	340	340
	Noon Peak Occupied Capacity	340	340	340	340	340	340
	Noon Off-peak Capacity	500	500	500	500	500	500
	Noon Off-peak Occupied Capacity	500	500	500	500	500	500
	Evening Peak Capacity	500	500	500	500	500	500
	Evening Peak Occupied Capacity	500	500	500	500	500	500
	Evening Off-peak Capacity	660	660	660	660	660	660
	Evening Off-peak Occupied Capacity	660	660	660	660	660	660

5.2.8. Validation of the Results

This section presents the validation of the results obtained from this study. In particular, the number of vehicles deployed in the scenarios is compared with the number of freight vehicles in İstanbul traffic. Vehicle counts made in 67 sections of 7 curtains in the study of IMM are taken into account [83]. In these counts, the numbers of minivans, panel vans, pickup trucks, trucks, and heavy trucks are considered, and passenger car equivalent values of these vehicle types are calculated. Next, the total PCE values of these vehicles at 06:00-10:00 (in the noon peak time interval), 10:00-16:00 (in the noon off-peak time interval), 16:00-22:00 (in the evening peak time interval), and 22:00-06:00 (in the evening off-peak time interval) are examined. Then, the counts in the section(s) closest to each zone (created in our study) are determined. Thus, the number of vehicles in each zone and each interval is determined, and these numbers are divided by the area of the zone to obtain the number of vehicles per unit area. This detailed table is given in Appendix A.16.

Furthermore, the number of vehicles per unit area in each zone and each interval obtained in the base scenario is also represented in Appendix A.17. Table 5.201 displays the total number of vehicles per unit area for all time intervals in each zone, obtained from the data of IMM and the base scenario, as follows:

Table 5.201. The total number of vehicles per unit area.

Zone	IMM Data	Base Scenario	Zone	IMM Data	Base Scenario
1	2.7	1.5	35	9,950.5	3,437.5
2	4.8	5.5	36	3,173.9	2,264.2
3	1.2	13.2	37	5,431.7	3,077.4
4	2.7	67.8	38	6,922.8	1,631.5
5	1,026.6	106.1	39	17,720.3	3,639.3
6	584.9	80.7	40	12,858.5	2,440.1
7	485.2	57.3	41	11,239.8	3,070.6
8	24.7	10.1	42	10,626.0	11,524.7
9	46.2	5.9	43	9,375.9	6,062.7
10	2,342.3	1,135.4	44	1,584.1	3,056.6
11	2,949.5	2,650.4	45	22,435.0	4,322.8
12	1,026.9	2,252.5	46	10,795.6	4,662.4
13	137.6	4,134.3	47	508.3	4,035.4
14	2,873.2	1,758.8	48	2,584.9	6,044.2
15	247.1	170.1	49	10,972.6	3,013.6
16	54.8	73.9	50	12,956.1	2,452.6
17	914.9	16.7	51	14,065.7	5,255.4
18	115.0	641.4	52	2,860.3	1,821.2
19	410.0	3,593.7	53	11,800.8	2,599.0
20	287.7	5,340.3	54	7,027.4	1,425.4
21	1,317.9	1,082.9	55	1,459.0	224.4
22	1,167.3	1,975.1	56	1,517.7	23.0
23	5,169.6	3,307.5	57	3.8	6.1
24	3,289.7	7,726.4	58	1.9	3.6
25	1,980.2	5,017.7	59	2.2	123.4
26	1,845.2	8,353.7	60	77.2	37.5
27	6,532.7	4,033.0	61	87.8	33.6
28	6,579.5	9,153.6	62	22.9	8.3
29	6,666.1	6,170.1	63	128.8	110.8
30	4,307.8	3,401.7	64	1,767.3	591.2
31	8,855.0	1,888.6	65	52.2	282.7
32	4,007.0	4,172.4	66	45.2	189.4
33	3,310.1	6,376.2	67	808.0	449.6
34	1,146.4	7,146.2	68	357.6	130.3

Table 5.201. The total number of vehicles per unit area. (cont.)

Zone	IMM Data	Base Scenario
69	494.7	1,424.3
70	104.3	646.6
71	918.4	2,134.5
72	1,098.4	4,265.6
73	331.9	2,530.0
74	3,716.7	2,459.9
75	1,335.2	2,669.2
76	7,872.5	5,962.5
77	322.1	2,000.6
78	613.4	3,281.5
79	2,533.6	1,129.0
80	12,186.6	6,653.1
81	12,579.8	5,951.8
82	657.8	959.9
83	573.5	9,118.8
84	399.4	5,470.0
85	559.1	2,342.3
86	798.8	3,435.5
87	860.2	2,965.4
88	475.9	3,074.4
89	657.8	2,087.0
90	4,565.3	1,546.9
91	5,084.9	1,726.5
92	366.6	3,209.7
93	225.9	4,608.8
94	5,693.0	3,959.3
95	8,184.6	5,516.2
96	585.5	1,174.4
97	7,403.6	4,339.6
98	3,019.3	3,693.7
99	3,435.2	1,997.9
100	2,060.4	2,278.4
101	4,279.4	1,093.2
102	5,168.9	2,910.8
103	399.4	7,125.5
104	23,634.7	4,981.8
105	1,758.7	44.7

For the validation of the data obtained from the base scenario, these two columns in Table 5.201 are compared to each other, and their similarity is investigated. For this purpose, Spearman's rank correlation test is used. While applying this test, using the data obtained from the IMM, the most intense 25 zones and the least intense 25 zones, a total of 50 zones, are selected. Similarly, using the data in the base scenario, a total of 50 zones are selected by looking at the most intense 25 zones and the least intense 25 zones. It is observed that 33 of them are common in the base scenario and IMM data. Considering the remaining 67 zones, these two data sets are ranked [84]. The ranked values of these two data sets are given in Table 5.202, and the steps of the method are applied. The Spearman's rank correlation coefficient is calculated as 0.62, which indicates that there is an average positive correlation between the two data sets [85]. Furthermore, according to the study conducted by Leclezio et al. [86], this correlation

value represents the strong relationship between these two data sets. Therefore, it can be concluded that the findings obtained from our study, that is, the results of the base scenario, are compatible with the real case of İstanbul.

Table 5.202. The ranked values of the zones considering the data received from IMM and the base scenario.

Zone	IMM Data	Base Scenario
1	4	1
2	7	3
3	1	8
4	5	15
5	32	18
6	30	17
7	28	14
8	9	7
9	11	4
13	19	42
15	21	22
16	13	16
17	31	9
18	17	26
20	22	51
24	41	63
25	39	49
26	38	64
27	44	41
28	45	66
29	46	58
31	52	30
33	42	59
34	34	62
35	54	38
38	47	29
39	65	39
40	62	32
41	58	37
42	55	67
43	53	57
45	66	44
46	56	47
48	40	56

Zone	IMM Data	Base Scenario
49	57	36
50	63	33
51	64	50
53	59	35
54	48	28
55	35	24
56	36	10
57	6	5
58	2	2
59	3	20
60	14	12
61	15	11
62	8	6
63	18	19
65	12	25
66	10	23
68	25	21
70	16	27
72	33	43
73	24	34
76	50	55
77	23	31
80	60	60
81	61	54
83	29	65
84	26	52
93	20	46
94	43	40
95	51	53
97	49	45
103	27	61
104	67	48
105	37	13

6. CONCLUSION

The main objective of this research has been to create a linear optimization model and solution approach that can help improve the city logistics problems of large cities. The developed model and solution approach has been applied to the freight transportation in İstanbul. Additionally, the research features various scenarios related to the current state and the urban freight transportation difficulties of İstanbul. The main contributions of this study have been (i) the development of detailed city logistics model of İstanbul at a strategic level, (ii) extensive data collection, compilation and interpretation regarding freight movement activities, (iii) scenario analyses focusing on alternative proposals and strategies regarding city logistics problems of İstanbul.

Firstly, in this study, İstanbul's urban transportation network is investigated and based on certain criteria, İstanbul is divided into 105 zones, and supply and demand points are determined. Then, using this network, İstanbul's city logistics structure and activities are mathematically modeled by taking into account ten product categories, four vehicle categories and four time intervals.

The following are the basic assumptions considered in this thesis: i) PCs may ship their products to CCs directly or through TCs, ii) all the products sent from other cities to İstanbul are assumed to originate at one of two imaginary "external zones", iii) there is one PC, one CC, and at most one TC in each zone, iv) there are six TCs, three of them on the European side (in the 10^{th}, 12^{th}, and 38^{th} zones) and three of them on the Asian side (in the 64^{th}, 69^{th}, and 97^{th} zones), v) each zone has a certain production capacity, vi) only the planning of a single day is considered since the freight flow balance among the time intervals of a single day, rather than freight scheduling of a longer time period, is the primary focus.

This thesis deals with many issues encountered in city logistics in a comprehensive and integrated way. Our objective function features transportation and CO_2 emission

cost, including those of the deadheading trips. Furthermore, some novel methods are used in estimating distances between the zones and within the zones. To calculate the overall distance between two different zones, the distance between zone centers and the average distance traveled within the origin zone and within the destination zone are used, considering the zone types . Additionally, a preprocessor is utilized to estimate the zones on the path. Furthermore, limiting harmful emissions such as NO_x and CO and considering density in the zones are among the main issues addressed. The capacities of TCs are another important issue considered in this thesis. Moreover, some limitations are set on the flow of products in order to cope with the problems caused by product aggregation.

This model is applied to the real logistics data set of İstanbul, and various scenarios are developed to evaluate the potential impacts of different logistics settings. The alternative scenarios created in this study are presented in seven groups, which are, (i) TC capacity scenarios, (ii) truck utilization rate scenarios, (iii) product flow based scenarios, (iv) vehicle based scenarios, (v) deadheading scenarios, (vi) emission scenarios, and (vii) combination scenarios.

The proposed model is used to solve the base scenario by utilizing the compiled data. The results of the base scenario reveal that the transportation cost is 97%, and the CO_2 emission cost is 3% of the total cost. Electric vans are found to be highly favored, with their deployment reaching the maximum limit of 50,000 in all time periods. Panel van usage is very low. Trucks are highly preferred (more than 90,000 trucks). The majority of products are transported during the evening off-peak time interval (73.9%), while the least amount is transported during the evening peak time interval (6.8%). The TC usage for incoming products from PCs is 6%, and for outgoing products to CCs is 9.9%. It is found that the existing capacities of TCs are highly inadequate, especially for heavy trucks and trucks.

The first group of alternative scenarios is TC capacity scenarios. These scenarios involve expanding the capacities of TCs by 50%, 100%, and 200% (The TC50, TC100,

and TC200 scenarios). In these scenarios, transportation and CO_2 emission costs decrease due to TC capacity increase, since it is more cost-effective to ship products to CCs through TCs than to ship them directly from PCs to CCs. The primary reason behind that is trucks are assumed to be not fully loaded in the direct flows from PCs to CCs. However, they are fully loaded when they go through TCs. Additionally, NO_x and CO emissions decrease, despite an increase in the total number of vehicles deployed. While the most intense time of freight flows is the evening off-peak, and the least intense time is the evening peak time intervals. The usage rate of TCs regarding total freight flow increases. These results imply that while the capacity increase of TCs is highly desirable, more of the increased capacity should be allocated to trucks and heavy trucks.

The second group of alternative scenarios is truck utilization rate scenarios. In the base scenario, the trucks traveling between PCs and CCs are assumed to be loaded at 75% capacity. However, in this set of scenarios, the utilization rates of trucks are reduced to 60% and 40% (the TUR60 and TUR40 scenarios). The truck utilization rate scenarios indicate that reducing the truck utilization rates in direct shipments between PCs and CCs leads to the increase in the transportation and total costs since more vehicles are required to transport the same amount of products. In addition, the total number of panel vans increases. Since the direct shipments from PCs to CCs becomes more costly (as truck utilization rates decrease), the amount of external zone shipments increase. Furthermore, the usage of TCs is slightly increased, since almost all TCs reach their limited capacities in most time intervals. As the truck utilization rate decreases, the intensity in the evening off-peak time interval decreases. Some vehicles shift to other time intervals to take advantage of the available TC capacities in these less intense time intervals, so the intensity in other time intervals increases. While the least intense time of freight flows is the evening peak time interval in most of the scenarios, it is the noon peak time interval in the truck utilization rate scenarios. Compared to the base scenario, the TC usage for incoming products from PCs increases from 6% to 7.3% and for outgoing products to CCs increases from 9.9% to 13.5%. The TC usage for incoming products from PCs to TCs is 0.3% higher, and the TC usage for

outgoing products from TCs to CCs is 1.1% higher than those in the TUR60 scenario. Regarding heavy trucks and trucks, TCs are almost fully utilized. This reveals that due to the capacity limitation on TCs, their utilization rate increase is less than what is expected.

The third group of alternative scenarios is product flow related scenarios. In this group, there are four scenarios. In the SZPC10 scenario, PCs can send up to 10% of their products to CCs in the same zone with them, while the remainder is sent to CCs in other zones. This scenario reveals that sending a higher proportion of products to CCs within their own zones directly leads to an increase in intra-zone shipments and a decrease in TC usage. This decrease in the usage of TCs also leads to a decrease in the number of heavy trucks and trucks since more vehicles are required both inbound to TCs and outbound from TCs (rather than the single trip associated with a direct shipment). This scenario also brings about lower transportation and CO_2 costs and reductions in CO and NO_x emissions. In the product flow based scenario group, there are also two scenarios which dictate that the percentage of incoming and outgoing products to the TC in the same zone should be less than 20% and 40% of all incoming and outgoing products from all zones (the SZTC20 and SZTC40 scenarios). The results of these scenarios indicate that as the upper bound on the inflow to and outflow from a TC increases, both the transportation and CO_2 emission costs (and hence the total cost) slightly decrease since shipping products from/to a TC in the same zone is less expensive due to shorter distance. The amount of NO_x and CO emissions also slightly decreases. While the number of heavy trucks and panel vans increases, the number of trucks decreases. As TCs can receive more products from PCs and ship more products to CCs in their own zones, the usage of TCs increases. Additionally, with shipping more products through TCs, the direct shipments from PCs to CCs decrease and external zone shipments increase. Overall, these findings suggest that optimizing product flows within zones can lead to more efficient and sustainable transportation practices.

Furthermore, an EXT scenario is developed in this product flow based scenario group. In this scenario, PCs are forced to produce up to their capacities, which lead to

the shipment of their excess capacities to external zones. The outcomes of this scenario indicate that both the transportation and CO_2 emission costs (and hence the total cost) slightly increase because of forcing the satisfaction of all demand of CCs first through the products of PCs (rather than relying on supplies from external zones). This leads to a decrease in the number of heavy trucks but an increase in the number of trucks and panel vans, resulting in a slight increase in the amount of NO_x and CO emissions. Since PCs have to send their products either to CCs or to the external zones through TCs, the amount of products that CCs receive from PCs increase and the amount of products supplied from the external zones decrease.

The fourth set of alternative scenarios is vehicle based scenarios. In this group, there are six scenarios. In the EVL scenario, when the upper bound on the number of electric vans is revised as 100,000, the deployment of electric vans reaches the maximum limit of 100,000 in all time intervals. In the EVU scenario, even this upper bound is removed, and the total number of electric vans increases to 773,039. Of these, 746,943 electric vans are deployed during the evening-peak time interval, which has the lowest unit transportation and unit CO_2 emission costs for electric vans. So, while the most intense time of the freight flow is the evening off-peak time interval in the base scenario, this shifts to the evening-peak time interval (78.0%) in the EVU scenario. Nevertheless, assigning this huge number of vehicles to the already dense evening peak time interval may be quite unrealistic. Furthermore, due to this tremendous increase in the number of electric vans, the usage of heavy trucks and trucks decreases compared to the base scenario. This decrease in the number of heavy trucks and trucks is also observed in the deployment of TCs. Regarding electric vans, all TCs are fully utilized in all time intervals. As the limit on the number of electric vans is removed, the transportation cost decreases. The amount of NO_x and CO emissions decreases due to the decrease in the number of heavy trucks, trucks, and panel vans. Although the total amount of products shipped directly from PCs to CCs slightly increases, the external zone shipments decrease considerably compared to the base scenario. Since trucks are not fully loaded in direct shipments, electric vans become more appealing for these shipments. Therefore, the increase in the number of electric vans results in a rise in

direct shipments. Additionally, since most of the trucks and panel vans are replaced by electric vans and transporting the same load with electric vans rather than trucks and panel vans requires more vehicles. However, the low capacities of TCs for electric vans prevent the increase in the utilization rate of TCs, thus the external zone shipments through TCs.

In the EVR scenario (which is another vehicle based scenario), the range of electric vans is revised from 30 km to 100 km. The results reveal that as the range of electric vans increases, the transportation cost decreases since the number of heavy trucks and trucks declines. However, despite the decrease in the number of these vehicles, the CO_2 emission cost increases due to the fact electric vans now travel longer distances. Additionally, the increase in the number of panel vans contributes to this cost. Although electric vans have CO_2 emissions (due to the consumption of energy resources used in the production of electricity required to charge electric vans), they do not emit NO_x and CO. So, the increased range of electric vans does not contribute to NO_x and CO emissions. Therefore, with the decrease in the number of trucks and heavy trucks, there is a reduction in the amount of NO_x and CO emissions. With the increase in the range of electric vans, shipping products directly from PCs to CCs is more favorable than shipping products to CCs through TCs, since electric vans can carry freights for longer distances. As a result of the increase in direct shipments, the need for shipping products over TCs decreases, leading to a reduction in external zone shipments. Thus, the utilization of TCs decreases. These findings suggest that the use of electric vans with increased ranges can be an effective solution for sustainable and cost-effective transportation.

Although the utilization of panel vans and electric vans between TCs are allowed in the EVP scenario, panel vans and electric vans are not utilized in this shipment. Therefore, the results of the EVP and base scenarios are almost the same.

There are also VNM and VNL scenarios in the group of vehicle based scenarios. In these scenarios, in each zone, for each time interval, the limit on the number of

vehicles per km^2 is reduced. As the upper bound of the relevant constraint becomes tight, vehicles shift to different routes and higher cost time intervals. Therefore, both the transportation and CO_2 emission costs increase. Considering the density vehicles create, the number of panel vans significantly increases. However, the number of trucks decreases since trucks are not loaded at full capacity in direct shipments. The number of heavy trucks increases. The usage of TCs provides the opportunity to consolidate loads and enable them to be transported by larger vehicles. This is the reason why external zone shipments, which are done only by heavy trucks, increase. The capacities of TCs seem to be insufficient for heavy trucks and trucks. In these scenarios, the most intense time of the freight flow is the evening off-peak time interval, and the least intense time is the evening peak time interval, similar to the base scenario.

The fifth group of alternative scenarios is deadheading scenarios. In these scenarios, deadheading trip percentages are considered at different levels (the DHM and DHL scenarios). The results show that decreasing deadheading trip percentages can lead to several interesting outcomes. Firstly, transportation and CO_2 emission costs are reduced when deadheading percentages are lowered. Secondly, there is an increase in direct shipments from PCs to CCs, which lead to a reduction in the usage and utilization of TCs, external zone shipments, and heavy trucks. Lastly, reducing deadheading trip percentages also result in a decrease in density level, NO_x and CO emissions.

The sixth group of alternative scenarios involves emission scenarios. In the EMCO2 scenario, different CO_2 emission values than those used in the base scenario are deployed. Specifically, the unit CO_2 emissions of heavy trucks and electric vans higher than those in the base scenario, while the unit CO_2 emissions of trucks and panel vans are lower. The results reveal that although the transportation and total costs increase slightly, the CO_2 emission cost rises significantly (about 26% higher than the base scenario) due to the increased unit CO_2 emissions of heavy trucks and electric vans. The number of heavy trucks slightly decreases, and the number of trucks slightly increases due to the increase/decrease in their CO_2 emissions. The number of vehicles using the TCs remains mostly unchanged. The total amount of products

shipped directly from PCs to CCs slightly increases, as most of the products sent directly from PCs to CCs are transported by trucks, which have lower CO_2 emission rates. Furthermore, the external zone shipments decrease, which is in line with the reduced number of heavy trucks.

There are also EM15 and EM30 scenarios in the group of emission scenarios. In these scenarios, the upper bound on the amount of NO_x and CO emissions is decreased by 15% and 30%. Reducing NO_x and CO emissions is a crucial environmental goal due to their harmful effects on air quality and human health. The results of the EM15 and EM30 scenarios are very similar to each other, especially the freight flow activities and usage of TCs. However, there is a notable difference between the utilization of vehicles in these scenarios. The results of these scenarios indicate that as the restrictions on the amount of NO_x and CO emissions become tighter, the transportation and CO_2 emission costs increase since reducing NO_x and CO emissions leads to the distribution of vehicles across different intervals, as well as changes in the number and types of vehicles utilized. In addition, the usage of heavy trucks and trucks, which are known to emit higher levels of NO_x and CO, decreases, while the usage of panel vans, which tend to have lower emissions, increases. Furthermore, the amount of direct shipments from PCs to CCs and the external zone shipments decrease, while shipments through TCs (from PCs to CCs and from TCs to CCs) increase. Hence, for heavy trucks and trucks, most TCs are fully utilized. One interesting result is that the intensity on the evening off-peak time interval decreases. While the base and EM15 scenarios experience the highest intensity during the evening off-peak time interval, the EM30 scenario has the highest intensity during the noon peak time interval, accounting for 43.8% of the freight flow.

The final group of scenarios is the combination scenarios, which are comprised via various combinations of the previous scenarios. There are six combination scenarios in total. Firstly, the TC100 and TUR40 scenarios are combined. In the resulting C-TC100TUR40 scenario, the transportation and CO_2 emission costs are higher than those in the TC100 scenario, since the truck utilization rate between PCs and CCs (as

in the TUR40 scenario) is reduced to 40%, which means more vehicles are needed to transport the same amount of load, resulting in increased costs. There is a significant change in the number of vehicles, especially in the number of panel vans. As in the TUR40 scenario, trucks are not preferred for transportation between PCs and CCs since they are loaded at 40% capacity in this transportation. Accordingly, panel vans are widely used instead of trucks in direct shipments from PCs to CCs. Combining the TC100 and TUR40 scenarios result in an increase in the TC capacities compared to the TUR40 scenario, which reduces the utilization of panel vans and increases the utilization of heavy trucks and trucks. This leads to a higher NO_x emission and lower CO emissions compared to the TUR40 scenario. Decreased truck utilization rate between PCs and CCs and increased capacities of TCs lead to fewer direct shipments from PCs to CCs and, thus an increase in the amount of products coming from the external zones. The increased capacities of TCs also allow for more vehicles to use them.

Another combined scenario is the C-TC200TUR40, in which the capacities of all TCs are increased by 200%, and trucks traveling between PCs and CCs are assumed to be loaded at 40% capacity. Compared to the C-TC100TUR40 scenario, this further capacity expansion of TCs brings about similar outcomes. Compared to the C-TC100TUR40 scenario, this scenario leads to a reduction in transportation and CO_2 emission costs, as well as a decrease in NO_x and CO emissions, although the total number of vehicles deployed increases. The usage rate of TCs increases in the C-TC200TUR40 scenario. The TC usage for incoming products from PCs is 23.6%, and for outgoing products to CCs is 34% in the C-TC100TUR40 scenario, which means this is the scenario with the highest TC utilization. The most important reasons for the increase in the active usage of TCs is enlarging the capacities of TCs and lower truck utilization rate between PCs and CCs. Considering density levels, similar to the base and C-TC100TUR40 scenarios, the most intense time of the freight flow is the evening off-peak time interval in the C-TC100TUR40 scenario. As the capacities of TCs are increased, some vehicles shift to other intervals.

The third combined scenario is called C-EVREVL. It combines the features of the EVR and EVL scenarios, where the range of electric vans is 100 km, and the number of electric vans allowed in each time interval is increased to 100,000. Thus, electric vans become much more attractive. In this combined scenario, transportation cost decrease due to the decrease in the number of heavy trucks, trucks, and panel vans. However, CO_2 emission cost increases compared to the EVR and EVL scenario despite the decrease in the number of non-electric vehicles. This is because of the increased range of electric vans (as in the EVR scenario) and an increase in the number of electric vans (as in the EVL scenario). Furthermore, the decline in the number of heavy trucks, trucks and panel vans leads to a decrease in the amount of NO_x and CO emissions. Since electric vans are more advantageous, especially in direct shipments, the total amount of products shipped directly from PCs to CCs increases. Thus, not only PCs ship fewer products through TCs, but also fewer products are needed from the external zones. Accordingly, there is a decrease in the utilization of TCs. The most intense time of the freight flow is the evening off-peak time interval, and the least intense time is the evening peak time interval, as in the base, EVR, and EVL scenarios. Although the intensity ratio in the evening off-peak time interval decreases and the intensity ratios in the other time intervals increase compared to the base scenario, the increase in the number of electric vans is quite pronounced in the evening off-peak time interval since the deployment of electric vans reaches the maximum limit of 100,000 in all time intervals.

The fourth combined scenario is the C-TC200EVRLP scenario, in which the capacities of all TCs are increased by 200%, the range of electric vans is considered as 100 km, the upper bound on the number of electric vans in each time interval is raised to 100,000, and the electric vans and panel vans are allowed to ship products between two TCs. Compared to the EVP and TC200 scenarios, the decrease in the number of trucks and panel vans and the doubling of electric vans causes a reduction in transportation cost. Compared to the C-EVREVL scenario, both the transportation and CO_2 emission costs decrease when the capacities of TCs are increased (it is still more expensive to ship products directly from PCs to CCs). The great decreases in the

amounts of CO and NO_x emissions observed in this scenario are due to major reductions in truck and panel van deployments, while the doubling of electric vans has no negative effects since they do not emit CO or NO_x. The deployment of electric vans reaches the maximum limit of 100,000 in all time intervals, and panel vans are not deployed in the C-TC200EVRLP scenario. The increased range of electric vans to 100 km makes them more desirable. Compared to the C-EVREVL scenario, since the capacities of TCs are increased, PCs send more products through TCs, causing a decrease in the amount of direct shipment. In addition, expanding the capacities of TCs enables more product flows from the external zones through TCs. For these reasons, the usage of TCs for incoming products from PCs increases from 4.9% to 16.9%, and the usage of TCs for outgoing products to CCs increases from 8.6% to 22.1% compared to the C-EVREVL scenario. Similar to the EVP, TC200, and C-EVREVL scenarios, the most intense time of the freight flow is the evening off-peak time interval (53.0%). Compared to the C-EVREVL, EVP, TC200, and base scenarios, there is a decrease in intensity during the evening off-peak time interval, and some vehicles shift to other time intervals. As a result of the high utilization of electric vans, at least 100,000 vehicles are deployed in each time interval.

The fifth combined scenario is the C-VNLTC200 scenario, and it involves reducing the upper bound that limits the number of vehicles per km^2 in each zone for each time interval (thus, the upper bounds of the constraint set 4.12 could be 1000, 2,000, 3,000, and 4,500 in each zone and each time interval) and increasing the capacities of all TCs by 200%. The transportation and CO_2 emission costs increase compared to the TC200 scenario. However, they decrease compared to the VNL scenario. The density limits on the number of vehicles result in increased costs as vehicles are forced to operate on more costly routes and time intervals. However, when the capacities of TCs are increased as well, a decrease in costs is observed. Compared to the TC200 scenario, the restriction on the number of vehicles in each zone leads to increased NO_x and CO emissions due to the additional distance traveled by all vehicles. When the C-VNLTC200 scenario is compared with the pure TC200 scenario, it becomes evident that the additional density limits lead to more panel van usage in direct shipments and longer shipment routes

(leading to higher costs and emissions). Furthermore, a panel van has a PCE value of 1 and can carry up to 3.5 tonnes of load, while a truck has a PCE value of 2.5 and can carry up to 10 tonnes of load. Moreover, trucks traveling between PCs and CCs are assumed to be loaded at 75% capacity, which means that they are not fully utilized. Therefore, despite trucks being more cost-effective, panel vans are preferred due to the density they cause. Additionally, increasing the capacities of TCs leads to higher heavy truck usage and, thus, more external zone shipments since external zone shipments are only transported by heavy trucks. Similar to the VNL and TC200 scenarios, the most intense time of the freight flow is the evening off-peak time interval (47.8%), and the least intense time is the evening peak time interval (6.6%). In this particular scenario, there is a decrease in the intensity of the evening off-peak time interval, and vehicles are observed to shift to other time intervals, especially to the noon off-peak time interval.

The sixth combined scenario is the C-TC200EVU scenario in which the capacities of all TCs are increased by 200%, and the upper bound on the number of electric vans in each time interval is removed. In this scenario, the transportation cost gets even lower than those in the EVU and TC200 scenarios. However, the CO_2 emission cost is lower than that of the EVU scenario and higher than that of the TC200 scenario. The CO_2 emission costs are relatively higher in scenarios where the number of electric vans are increased. In the C-TC200EVU scenario, the need for other vehicle types decreases, and the number of electric vans increases to 769,982. Since trucks are not fully loaded in direct shipments, electric vans become more attractive. Thus, direct shipments from PCs to CCs and the usage of electric vans in these shipments increases. The amount of NO_x and CO emissions decrease since electric vans do not emit NO_x and CO emissions. In addition, fewer products come from external zones. In the EVU scenario, TCs are heavily utilized, with the docks reserved for panel vans and electric vans being fully utilized. When this scenario is combined with the TC200, that is, when the capacities of the TCs are extended, more vehicles have the opportunity to use TCs. The TC usage for incoming products from PCs increases from 6.1% to 10.9% compared to the EVU scenario, while it is 17% in the TC200 scenario. The TC usage for outgoing products to CCs decreases from 8.9% to 14.1% compared to the EVU scenario. However, it is

22.6% in the TC200 scenario. Although the most intense time of the freight flow is the evening off-peak time interval in most scenarios, it is the evening peak time interval (72.4%) in the C-TC200EVU scenario. The underlying reason is that electric vans have the lowest unit transportation cost in the evening peak time interval, and most of the shipments are made by electric vans in this combined scenario. However, it may be highly improbable to allocate such a large number of electric vans to the already congested evening peak time interval. The least intense time is the noon peak time interval (2.4%), similar to the EVU scenario.

The seventh combined scenario is the C-EVUVNL scenario, in which the upper bound on the number of electric vans in each time interval is removed and the upper bound that limits the number of vehicles per km^2 in each zone for each time interval is reduced (thus, the upper bounds of the constraint set 4.12 could be 1000, 2,000, 3,000, and 4,500 in each zone and each time interval). The transportation and CO_2 emission costs increase compared to the TC200 scenario. However, they decrease compared to the VNL scenario. The density limits on the number of vehicles result in increased costs as vehicles are forced to operate on more costly routes and time intervals. However, when the capacities of TCs are increased as well, a decrease in costs is observed. Compared to the TC200 scenario, the restriction on the number of vehicles in each zone leads to increased NO_x and CO emissions due to the additional distance traveled by all vehicles. When the C-VNLTC200 scenario is compared with the pure TC200 scenario, it becomes evident that the additional density limits lead to more panel van usage in direct shipments and longer shipment routes (leading to higher costs and emissions). Furthermore, a panel van has a PCE value of 1 and can carry up to 3.5 tonnes of load, while a truck has a PCE value of 2.5 and can carry up to 10 tonnes of load. Moreover, trucks traveling between PCs and CCs are assumed to be loaded at 75% capacity, which means that they are not fully utilized. Therefore, despite trucks being more cost-effective, panel vans are preferred due to the density they cause. Additionally, increasing the capacities of TCs leads to higher heavy truck usage and, thus, more external zone shipments since external zone shipments are only transported by heavy trucks. Similar to the VNL and TC200 scenarios, the most intense time of the freight

flow is the evening off-peak time interval (47.8%), and the least intense time is the evening peak time interval (6.6%). In this particular scenario, there is a decrease in the intensity of the evening off-peak time interval, and vehicles are observed to shift to other time intervals, especially to the noon off-peak time interval.

Considering the effects of scenarios individually, the scenarios in which the TCs are used the most are the scenarios in which the capacities of the TCs are extended. In a nutshell, the results of these scenarios reveal that expanding the capacities of TCs have several benefits, such as reducing the transportation and CO_2 emission costs, lowering the NO_x and CO emissions, and increasing the usage of TCs. This can also lead to improved supply chain efficiency.

Among these scenarios, the deadheading scenarios have the lowest CO_2 emission cost. These scenarios highlight the importance of minimizing deadheading trip percentages in the transportation industry to improve efficiency, reduce costs, and decrease environmental impact.

The scenarios with the highest transportation cost are mostly those with reduced truck utilization rates. Especially, the TUR40 scenario incurs the greatest transportation and total costs among the prepared scenarios. Furthermore, considering the NO_x and CO emissions, the TUR60 has the highest amount of NO_x and CO emissions.

The results of the combined scenarios imply that most of these scenarios have relatively low NO_x and CO emissions. Especially by combining TC200 and EVU scenarios, transportation and total costs, and the amount of NO_x and CO emissions significantly decrease in the C-TC200EVU scenario. Moreover, in this scenario, vehicles shift to other time intervals. Unlike other scenarios, the majority of products are transported during the evening peak time interval, while the least amount is transported during the noon peak time interval. Among the combined scenarios, the C-TC200TUR40 scenario has the highest the usages of TCs (the TC usage for incoming products from PCs increases is 23.6%, and for outgoing products to CCs is 34.0%).

In future studies, different scenarios can be constructed by changing constraints, parameters or assumptions. For example, in addition to the TC capacity scenarios, various scenarios can be developed by increasing the number of docks reserved for only panel vans and electric vans or the number of docks reserved for only heavy trucks and trucks. In addition to truck utilization scenarios, scenarios in which different types of vehicles have different occupancy rates can be prepared. When considering emission scenarios, Sulfur dioxide gas, which is a significant contributor to air pollution in addition to NO_x and CO gases, can be taken into account. Furthermore, in the automotive sector, technology is developing rapidly. Considering different technologies, different scenarios can be prepared by making changes in the unit costs and emission values of vehicles. Additionally, it is possible to generate scenarios for different congestion levels, providing an opportunity to observe the resulting effects on city logistics. Moreover, combinations of these different scenarios can be developed.

This study sheds light on the solution of the problems encountered in the city logistics of İstanbul. The results of the study and scenario analyses demonstrate that the demand for the usage of electric vans is quite high. The reason behind this is that electric vans are environmentally friendly and less costly alternatives in terms of transportation costs. However, the usage of many electric vans also brings some problems. The huge number of electric vans increases the already dense traffic even more, especially in the evening peak time interval. In order to overcome this problem, high-capacitated electric vehicles may be preferred. However, this requires significant investment costs. In addition, there needs to be more charging stations for such a large number of electric vans. Therefore, it is recommended to have many charging stations for electric vehicles at the planned new TCs.

Additionally, the importance of the usage of TCs has also been observed as a result of the analyses of TC capacity scenarios. For this reason, the number and capacities of TCs can be increased. TCs are the areas where there is a heavy inflow and outflow. Therefore, TCs should be constructed in an area where passenger traffic is not heavy. An adequate infrastructure should be established to optimize traffic

flow, considering incoming and outgoing roads. Furthermore, TCs should be made more attractive by providing appropriate technical opportunities since they are quite advantageous in some cases.

Furthermore, various scenarios have been prepared to understand the effects of both CO_2 emissions and NO_x/CO emissions. The effects of emissions on city logistics can be observed better with these scenarios. Thus, this study provides valuable ideas for choosing a low-emission zone for Istanbul.

Finally, this proposed model can be used to model and propose solution approaches to the city logistics problems of other metropolitan cities. Moreover, considering the problems of the city whose city logistics will be modeled, different parameters can be added, or the existing parameters or constraints can be adapted.

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APPENDIX A: DATA TABLES

Table A.1. Literature review.

Paper Information		Objectives				Methodology			Problem Types					
Author	Year	Economic	Efficiency	Environment	Other	Heuristics	Simulation	Mathematical model	Multi-commodity	Location and routing	Vehicle routing	Time dependent	Network capacity model	Two-echelon
Taniguchi [6]	2014		+	+										
Taniguchi and Heijden [7]	2000	+		+		+		+			+	+		
Crainic et al. [11]	2004	+							+	+				
Amaral and Aghezzaf [12]	2015	+						+			+	+		+
Lim et al. [14]	2004	+										+	+	
Zhang and Li [15]	2009	+				+		+	+					
Üster and Agrahari [16]	2010	+				+		+			+		+	
Ozturk and Patrick [17]	2018				+	+		+					+	
Enthoven et al. [18]	2020	+				+		+			+			+
Liu et al. [19]	2020	+		+		+		+			+	+		
Gmira et al. [20]	2021				+	+					+	+	+	
Groß et al. [21]	2019	+				+					+			+
Eshtehadi et al. [22]	2020	+				+		+			+			
Li et al. [23]	2018	+				+		+				+	+	+
Groß et al. [24]	2015	+			+		+	+			+			
Fontaine et al. [25]	2022	+						+						+
Trecozzi et al. [26]	2021				+							+		
Slávik and Gnap [27]	2019				+							+		
Munuzuri et al. [28]	2018			+							+			
Yang et al. [29]	2019	+		+										
Yang et al. [30]	2016	+		+				+					+	
Cui et al. [31]	2022		+		+									
Bandyopadhyay et al. [32]	2023	+	+											

Table A.2. Longitudes and latitudes of zone centers.

Zone	Latitude	Longitude	Zone	Latitude	Longitude	Zone	Latitude	Longitude
1	41° 24’ 21.79”N	28°11’32.88”E	36	41° 3’43.40”N	28°55’33.63”E	71	40°52’17.11”N	29°16’55.79”E
2	41° 18’ 2.27”N	28°20’8.28”E	37	41° 5’20.24”N	28°53’33.74”E	72	40°54’35.31”N	29°17’27.76”E
3	41°10’37.37”N	28° 4’59.71”E	38	41° 5’45.70”N	28°57’29.65”E	73	40°55’6.06”N	29°15’18.78”E
4	41° 5’49.98”N	28°13’3.64”E	39	41° 3’54.36”N	28°58’7.26”E	74	40°53’46.86”N	29°13’50.31”E
5	41° 5’30.92”N	28°21’4.62”E	40	41° 3’10.22”N	28°57’40.10”E	75	40°53’39.28”N	29°10’42.32”E
6	41° 3’21.20”N	28°28’2.22”E	41	41° 2’23.76”N	28°58’4.04”E	76	40°54’54.20”N	29°11’23.74”E
7	41° 8’47.41”N	28°28’57.71”E	42	41° 1’48.52”N	28°58’17.99”E	77	40°55’33.86”N	29° 8’55.20”E
8	41°13’10.46”N	28°26’42.25”E	43	41° 2’2.67”N	28°59’1.41”E	78	40°56’56.26”N	29° 7’13.64”E
9	41°14’23.05”N	28°33’33.38”E	44	41° 3’5.51”N	29° 0’8.07”E	79	40°58’30.24”N	29° 8’31.02”E
10	41° 7’54.86”N	28°37’21.17”E	45	41° 3’3.64”N	28°58’58.07”E	80	40°58’27.88”N	29° 6’2.68”E
11	41° 1’7.62”N	28°38’25.79”E	46	41° 4’8.86”N	28°59’23.26”E	81	40°58’54.80”N	29° 4’30.76”E
12	40°59’30.20”N	28°37’40.01”E	47	41° 3’57.68”N	29° 0’41.54”E	82	40°58’20.22”N	29° 3’8.55”E
13	40°58’56.67”N	28°43’45.97”E	48	41° 4’53.54”N	28°59’59.81”E	83	40°59’26.53”N	29° 2’43.15”E
14	41° 3’29.08”N	28°39’57.76”E	49	41° 5’31.71”N	29° 2’2.35”E	84	40°59’41.52”N	29° 2’5.88”E
15	41° 7’37.12”N	28°44’51.49”E	50	41° 4’11.00”N	29° 1’42.64”E	85	41° 0’55.09”N	29° 1’45.14”E
16	41°11’57.06”N	28°45’54.46”E	51	41° 5’53.50”N	28°59’41.80”E	86	41° 1’32.64”N	29° 1’18.27”E
17	41°10’25.30”N	28°53’11.12”E	52	41° 7’5.19”N	28°59’41.93”E	87	41° 2’11.60”N	29° 2’32.35”E
18	41° 6’56.38”N	28°50’49.59”E	53	41° 6’44.66”N	29° 2’40.25”E	88	41° 1’25.02”N	29° 2’53.82”E
19	41° 2’45.85”N	28°48’20.81”E	54	41° 7’44.24”N	29° 2’47.81”E	89	41° 3’4.70”N	29° 3’44.48”E
20	41° 0’5.42”N	28°48’23.84”E	55	41° 9’43.70”N	29° 1’19.00”E	90	41° 3’33.17”N	29° 5’43.40”E
21	40°57’44.53”N	28°49’25.77”E	56	41°11’42.74”N	29° 2’36.65”E	91	41° 5’30.23”N	29° 5’18.86”E
22	40°58’29.71”N	28°52’34.83”E	57	41° 5’49.96”N	29°49’1.32”E	92	41° 1’58.28”N	29° 4’41.22”E
23	40°59’57.42”N	28°52’19.04”E	58	41° 5’20.09”N	29°40’36.92”E	93	41° 1’8.27”N	29° 5’31.86”E
24	40°59’40.69”N	28°50’27.55”E	59	41° 9’45.98”N	29°31’44.97”E	94	40°59’54.39”N	29° 7’8.98”E
25	41° 1’18.10”N	28°51’44.74”E	60	41° 8’27.75”N	29°20’40.04”E	95	40°59’52.81”N	29° 9’2.05”E
26	41° 2’39.29”N	28°50’51.75”E	61	41° 8’47.84”N	29°15’52.62”E	96	40°56’16.18”N	29°12’51.96”E
27	41° 3’32.76”N	28°53’20.78”E	62	41°10’14.27”N	29°13’32.61”E	97	40°59’35.09”N	29°11’27.01”E
28	41° 2’32.89”N	28°54’15.52”E	63	41° 7’26.47”N	29° 8’6.62”E	98	40°58’53.07”N	29°14’7.72”E
29	41° 0’9.55”N	28°54’12.24”E	64	41° 4’36.78”N	29° 9’4.74”E	99	40°57’40.27”N	29°17’16.97”E
30	40°59’12.02”N	28°54’7.09”E	65	41° 3’13.21”N	29°16’2.58”E	100	41° 1’16.42”N	29°12’59.02”E
31	40°59’52.76”N	28°55’51.50”E	66	41° 0’12.42”N	29°26’32.61”E	101	41° 2’11.37”N	29° 9’56.65”E
32	41° 0’40.50”N	28°56’6.68”E	67	40°55’59.31”N	29°19’33.52”E	102	41° 1’43.16”N	29° 7’26.37”E
33	41° 0’59.03”N	28°57’7.36”E	68	40°55’17.86”N	29°23’19.28”E	103	41° 0’25.65”N	29° 3’40.92”E
34	41° 0’29.37”N	28°58’14.97”E	69	40°53’39.48”N	29°21’10.92”E	104	40°57’34.47”N	29° 5’25.13”E
35	41° 1’50.45”N	28°56’17.40”E	70	40°49’56.13”N	29°19’22.76”E	105	41° 9’43.46”N	29° 5’28.80”E

Table A.3. The demand data of each zone (tonnes).

	Product Categories									
Zone	1	2	3	4	5	6	7	8	9	10
1	45.7	58.8	44.0	206.2	0.0	0.0	6.0	13.2	8.5	4.6
2	4.9	52.5	210.3	93.5	0.0	7.7	5.4	0.0	4.1	0.5
3	35.9	679.8	661.1	44.5	6.1	54.9	603.6	22.0	8.7	129.5
4	300.0	2,874.4	944.5	22.7	101.0	851.8	478.6	75.5	88.3	621.4
5	98.7	1,285.8	394.7	163.1	51.8	189.0	1,047.5	66.9	37.9	639.1
6	75.1	4,762.8	2,738.7	70.6	339.4	1,308.8	825.0	159.8	96.1	990.1
7	71.7	1,484.8	261.1	568.5	240.9	360.7	303.9	74.3	104.9	352.0
8	20.1	134.2	299.4	8.4	2.9	282.5	14.1	12.3	0.0	0.0
9	15.3	341.2	51.9	2.5	0.0	58.2	13.0	0.6	0.0	23.1
10	263.2	2,024.9	8,667.2	1,540.1	512.6	2,867.0	4,563.5	468.9	207.2	7,387.4
11	1,023.7	16,797.1	8,492.3	1,282.4	1,357.0	2,170.7	3,561.4	2,111.5	676.0	6,150.1
12	118.9	1,625.5	1,327.6	104.3	164.4	1,170.5	405.9	772.1	194.8	494.4
13	1,423.2	10,988.8	4,118.0	3,009.6	1,694.9	937.7	2,936.5	1,179.3	1,068.2	4,907.5
14	862.6	9,592.2	1,989.5	1,451.2	1,020.0	936.4	2,457.1	749.6	348.8	3,996.9
15	547.1	1,544.1	3,977.2	429.1	148.0	56.6	459.2	149.7	119.5	813.3
16	71.9	1,466.9	5,390.4	340.8	47.7	35.7	790.7	49.6	63.4	649.4
17	154.0	568.4	991.3	177.2	11.8	36.2	65.4	18.6	12.1	1,339.6
18	245.8	2,165.6	2,256.2	518.4	132.8	225.9	440.6	433.8	113.9	668.7
19	3,855.7	11,821.1	16,505.1	7,485.4	2,557.1	8,759.0	10,669.1	1,794.5	1,164.1	10,792.0
20	156.3	2,337.0	801.6	313.9	334.6	200.0	635.2	260.8	199.1	2,777.2
21	0.0	31.7	8.0	1.9	4.3	0.0	0.0	0.0	0.0	10.3
22	120.3	2,750.3	206.5	557.8	91.9	155.5	230.0	99.9	16.7	1,687.4
23	220.7	4,210.9	682.3	1,008.8	557.7	92.9	243.3	300.9	278.3	1,508.8
24	857.8	6,060.2	2,906.6	2,714.3	958.3	983.7	1,026.1	783.6	770.6	3,925.5
25	540.2	7,546.7	2,363.0	6,971.1	678.2	606.6	988.4	549.9	380.7	2,063.3
26	1,026.5	6,518.7	4,998.0	2,985.5	419.9	938.6	1,233.3	285.5	471.4	2,113.8
27	298.0	3,037.5	465.7	691.9	252.5	183.0	535.2	166.3	109.2	756.4
28	600.4	5,513.1	2,479.8	3,777.3	817.2	1,328.3	5,629.0	649.3	425.0	1,723.7
29	1,650.4	3,088.2	1,353.8	3,690.2	450.9	2,410.3	2,288.9	472.0	260.4	1,892.4
30	43.9	1,725.8	272.1	789.6	109.3	16.5	95.8	230.6	24.4	261.0
31	13.1	841.7	34.5	262.8	38.3	25.3	8.3	228.0	14.2	33.0
32	390.3	1,302.8	181.7	331.6	256.4	116.8	204.8	189.1	118.9	690.1
33	138.3	2,316.0	1,065.2	3,366.2	430.8	361.9	381.4	267.9	105.9	820.5

Table A.3. The demand data of each zone (tonnes). (cont.)

	Product Categories									
Zone	1	2	3	4	5	6	7	8	9	10
34	517.6	1,597.8	873.2	3,522.3	168.1	249.8	504.5	713.4	132.7	908.1
35	146.5	637.6	455.8	141.0	65.6	126.1	167.9	68.0	50.6	116.7
36	218.7	3,904.6	1,349.8	664.4	316.5	551.3	841.6	557.1	347.6	1,473.4
37	447.6	7,694.2	2,853.2	2,584.7	545.7	696.1	1,155.6	1,363.0	422.7	1,573.3
38	324.2	1,344.5	623.7	234.4	128.1	437.3	148.1	197.6	154.7	619.1
39	149.6	1,363.2	575.3	199.2	113.7	13.2	521.1	719.9	106.1	327.8
40	155.6	856.2	28.0	370.3	182.2	232.0	0.0	0.0	0.0	0.0
41	313.6	1,039.6	201.7	178.5	104.9	116.4	337.3	98.1	61.6	128.1
42	617.2	1,243.0	123.4	161.7	118.2	230.5	1,109.5	1,597.6	87.6	636.4
43	216.2	1,269.9	74.6	305.0	308.3	87.5	340.1	90.5	126.8	2,035.4
44	149.6	1,574.6	241.9	287.9	219.6	28.1	101.4	87.1	140.6	266.5
45	113.7	1,420.5	144.1	1,631.8	69.5	105.5	74.9	218.8	29.6	281.4
46	536.8	4,213.7	2,393.3	1,275.8	531.0	167.5	446.0	370.3	271.3	1,432.3
47	219.4	1,387.1	301.9	20.8	66.7	4.4	134.1	66.4	41.5	621.6
48	823.8	2,180.3	697.2	346.1	127.3	82.4	394.9	480.4	118.9	1,086.2
49	54.7	872.8	69.8	13.8	50.4	3.1	44.4	21.8	28.1	376.3
50	114.8	1,265.1	4.6	25.0	90.5	2.1	22.8	88.4	32.9	90.9
51	268.4	1,097.8	629.5	355.2	245.8	159.1	771.6	240.8	221.4	1,337.8
52	211.0	1,720.4	10,808.1	131.6	161.3	21.5	581.8	54.7	472.4	4,090.0
53	31.1	697.4	98.8	74.3	161.8	25.7	10.6	24.4	10.7	260.1
54	91.7	1,715.5	68.1	17.0	13.1	15.5	10.2	33.4	5.7	87.7
55	85.9	1,615.6	904.8	88.4	330.4	146.8	171.1	211.6	335.4	460.3
56	30.0	361.3	108.7	14.7	1.9	7.4	4.3	131.5	8.3	69.6
57	0.8	29.9	1,135.1	0.2	0.0	0.0	0.0	0.0	2.1	3.7
58	3.6	4.9	36.5	0.2	0.0	0.0	1.9	0.0	0.0	121.4
59	147.0	1,052.4	21,531.8	7.8	0.0	8.3	73.6	7.0	3.2	7,518.1
60	232.9	102.6	399.2	7.0	144.5	3.5	1.6	18.5	14.5	987.1
61	4.3	133.6	267.7	0.0	0.0	7.3	5.4	0.0	2.5	2.9
62	441.0	353.0	628.3	42.2	546.2	46.6	334.5	24.2	259.6	159.4
63	13.8	751.9	264.2	117.8	352.2	26.3	38.4	45.7	60.9	542.5
64	15.3	139.0	178.9	18.3	8.4	1.6	40.7	10.6	40.3	12.2
65	28.7	181.2	1,507.8	39.9	35.9	131.8	135.9	25.0	25.0	831.0
66	0.9	2.1	16.8	3.9	3.2	3.3	10.5	4.6	0.0	0.0

Table A.3. The demand data of each zone (tonnes). (cont.)

	Product Categories									
Zone	1	2	3	4	5	6	7	8	9	10
67	78.6	1,325.0	414.8	13.2	456.2	4.3	13.3	27.3	18.6	405.6
68	8.5	354.5	264.1	7.2	19.5	187.1	247.2	261.6	90.3	252.5
69	697.3	1,609.8	1,308.1	1,333.7	1,990.3	1,728.7	6,974.2	348.2	339.0	4,101.8
70	554.3	2,712.5	390.7	155.5	985.7	324.6	2,532.0	499.5	310.2	970.6
71	925.4	4,934.1	633.6	340.2	1,115.2	131.7	2,848.7	331.8	537.8	2,231.6
72	2,171.8	2,639.7	17,784.1	191.6	551.7	426.6	1,386.0	167.3	390.4	665.3
73	82.0	1,666.9	472.9	42.6	294.1	53.7	589.0	81.8	81.7	394.0
74	2,219.8	5,560.4	609.8	484.3	1,512.9	475.1	834.3	317.2	282.5	463.8
75	310.0	6,071.5	2,303.8	141.4	517.8	84.4	301.2	363.4	338.9	271.2
76	210.3	2,266.7	10,698.0	172.5	495.4	134.9	2,166.8	439.0	135.5	440.1
77	376.2	6,935.7	328.2	352.5	1,362.8	180.3	897.8	598.2	618.4	1,157.0
78	276.0	4,546.0	89.6	80.7	754.1	33.4	492.5	138.1	539.4	372.5
79	141.4	3,228.8	327.1	103.3	923.7	184.4	317.1	282.7	128.1	623.2
80	151.7	3,976.6	933.0	243.0	1,270.2	27.1	334.1	68.7	24.1	989.1
81	221.0	2,258.6	814.5	293.2	1,475.4	245.2	905.7	153.1	284.5	443.2
82	46.3	1,360.6	55.2	93.0	290.0	5.7	32.8	48.4	70.6	194.8
83	88.6	3,425.6	3,668.2	98.0	227.1	16.8	152.0	169.1	79.8	88.0
84	247.0	7,376.5	422.1	364.6	1,236.8	268.3	140.0	1,372.1	368.2	951.5
85	23.5	362.4	442.8	5.3	1.8	4.7	262.3	57.1	3.0	486.5
86	25.6	562.0	281.8	115.5	493.6	34.7	10.3	47.3	12.8	35.4
87	0.8	98.5	0.0	5.3	134.7	1.4	2.4	8.5	6.8	13.1
88	58.3	590.4	47.2	8.6	219.7	22.2	30.0	44.8	10.0	562.0
89	5.5	373.7	197.6	29.3	28.4	1.4	13.4	3.8	22.9	186.3
90	122.6	1,294.7	659.2	28.6	79.9	14.7	80.1	93.3	68.2	265.0
91	67.4	1,217.0	356.8	144.2	171.4	88.8	274.6	197.4	94.1	1,081.9
92	49.9	989.5	63.4	194.1	180.9	8.6	14.9	6.3	12.5	87.5
93	836.9	5,446.4	1,125.7	684.7	1,035.3	269.2	469.9	418.8	615.5	973.2
94	687.0	3,679.9	1,030.2	202.5	413.7	43.7	427.6	413.9	262.5	935.5
95	1,042.7	2,858.5	2,341.3	195.8	291.5	401.8	2,637.9	238.4	244.4	737.2
96	46.2	223.3	499.9	1.3	154.8	25.3	139.1	47.3	42.7	436.2
97	456.4	1,900.1	1,517.7	711.1	240.7	545.7	1,779.1	224.4	213.9	895.3
98	608.7	6,557.0	5,460.0	271.4	186.8	244.8	844.3	257.6	455.3	2,373.4
99	190.3	6,370.0	556.0	297.6	80.6	255.9	588.6	164.8	1,428.7	325.4

Table A.3. The demand data of each zone (tonnes). (cont.)

	Product Categories									
Zone	1	2	3	4	5	6	7	8	9	10
100	166.6	5,386.5	1,590.5	385.8	175.4	71.4	364.0	332.0	266.1	987.4
101	16.1	1,545.5	177.9	55.4	47.5	51.5	772.1	90.7	48.7	1,229.3
102	409.4	1,768.8	599.7	193.7	381.0	105.5	604.4	358.2	105.5	2,368.6
103	116.0	207.7	689.3	45.6	176.4	14.6	238.5	19.7	101.9	147.8
104	104.9	1,723.8	215.5	173.2	386.2	25.5	168.3	45.6	75.1	106.5
105	22.2	255.6	122.1	23.2	9.0	31.0	80.7	21.2	29.7	12.3

Table A.4. The production data of each zone (tonnes).

	Product Categories									
Zone	1	2	3	4	5	6	7	8	9	10
1	10.0	148.6	191.2	23.6	0.0	0.0	1.5	0.0	0.4	0.4
2	0.9	632.5	374.1	301.5	0.0	87.4	9.5	0.0	0.0	160.2
3	47.3	1,064.9	751.3	18.6	68.7	194.2	1,086.7	16.3	1.6	129.1
4	218.0	2,461.2	415.1	111.3	83.5	137.5	157.6	239.3	72.2	514.1
5	74.9	1,166.9	507.8	14.7	46.0	207.1	563.6	78.8	12.4	770.9
6	125.4	3,578.5	1,917.1	161.9	176.5	370.0	694.8	155.6	39.5	1,124.1
7	10.4	672.2	566.4	155.1	17.8	23.4	64.4	42.5	45.5	268.5
8	6.7	125.0	1,610.0	1.3	33.7	1.4	4.4	29.3	2.2	47.5
9	2.0	186.7	83.7	6.9	5.0	33.6	1.4	18.0	8.9	15.7
10	1,794.2	4,380.2	864.2	1,471.8	632.8	3,326.5	1,618.1	788.7	356.2	2,645.1
11	2,096.7	14,892.6	5,778.0	1,974.9	1,964.2	1,250.6	1,653.9	614.1	199.0	9,641.1
12	906.7	5,481.9	12,374.2	202.5	575.0	7,159.2	10,929.6	1,350.5	284.1	11,172.2
13	700.2	6,343.1	1,851.1	2,341.5	1,108.6	1,837.5	2,817.8	843.5	639.8	6,858.6
14	1,256.7	12,674.5	2,080.4	1,361.2	836.7	642.9	891.3	514.3	389.0	3,881.0
15	348.6	1,082.3	2,066.8	320.9	392.0	171.8	373.8	99.8	66.0	578.8
16	187.2	895.2	7,481.9	264.4	51.5	3,182.0	251.6	69.4	45.2	975.1
17	273.2	1,378.0	208.4	30.0	0.7	42.8	26.2	7.6	5.6	846.2
18	190.9	1,795.6	15,501.6	789.8	34.4	45.8	493.3	481.7	64.6	986.7
19	5,654.4	13,177.1	4,145.2	9,067.4	2,448.2	7,403.6	11,312.6	2,844.3	3,265.3	8,550.3
20	226.2	2,143.1	49.3	573.8	77.2	111.1	981.6	352.8	100.8	1,039.0
21	1.6	4.0	102.2	0.3	0.0	0.0	0.0	0.0	0.0	14.1
22	104.1	766.5	466.0	204.3	163.0	16.2	488.1	136.6	80.1	2,146.7
23	380.9	3,245.2	248.1	866.1	654.7	130.3	137.1	274.5	114.1	471.0
24	641.3	4,707.6	1,844.2	4,072.8	1,152.8	227.0	800.8	431.2	704.5	3,233.1
25	302.6	5,519.1	755.6	7,941.2	264.7	299.4	753.5	254.3	315.6	1,675.8
26	691.7	4,922.7	254.6	2,775.1	1,010.5	244.1	355.4	386.0	403.3	1,793.6
27	56.2	1,916.0	3,475.7	331.8	815.5	250.5	313.1	609.0	222.1	993.4
28	848.1	12,871.2	12,233.8	4,046.1	775.5	1,532.7	3,624.3	506.8	379.4	1,710.7
29	1,680.3	3,976.7	564.8	3,923.4	297.5	740.1	1,687.3	386.2	65.3	1,061.4
30	18.3	668.1	22.7	918.8	21.1	17.6	99.3	97.5	94.6	116.3
31	3.1	675.7	28.3	118.1	98.4	19.6	0.0	183.3	7.3	15.0
32	669.8	2,128.8	65.4	539.1	481.9	73.6	175.8	361.5	14.8	420.7
33	150.7	1,077.5	76.1	1,264.2	199.6	118.7	455.7	148.3	55.9	222.2

Table A.4. The production data of each zone (tonnes). (cont.)

	Product Categories									
Zone	1	2	3	4	5	6	7	8	9	10
34	660.7	1,402.7	893.8	5,048.9	182.8	304.4	319.2	1,521.7	59.0	765.4
35	379.5	398.1	118.9	102.9	14.9	64.0	197.1	33.6	36.5	43.2
36	265.4	8,615.1	510.5	686.3	333.3	168.8	354.2	852.2	75.0	1,474.9
37	229.9	8,169.6	1,257.0	2,475.7	648.6	292.8	1,027.0	696.4	491.6	760.6
38	188.3	3,695.0	268.7	115.5	588.5	91.7	81.5	187.8	202.4	1,110.0
39	114.5	1,018.0	107.7	169.6	159.3	27.2	144.0	557.6	60.5	171.7
40	95.0	541.6	46.3	210.9	107.2	18.1	0.0	0.0	0.0	0.0
41	54.1	205.9	89.9	58.6	103.4	15.6	119.3	33.3	36.4	184.2
42	128.2	349.2	183.9	78.2	20.5	116.7	971.5	2,438.2	46.1	491.6
43	101.1	386.1	9.1	202.5	101.0	57.8	141.6	41.1	94.0	233.8
44	70.5	439.1	41.3	200.0	132.5	11.6	90.6	31.9	114.7	227.5
45	21.2	358.7	30.7	1,787.2	16.7	5.5	69.5	164.0	83.8	172.5
46	315.0	1,461.4	189.5	922.6	278.5	75.1	329.7	600.9	152.1	951.6
47	52.0	823.5	16.3	31.1	60.9	59.4	411.2	78.7	12.9	493.0
48	331.6	1,260.0	103.7	144.2	131.6	43.1	84.6	216.3	236.3	845.8
49	59.4	701.1	3.8	10.6	15.1	0.0	108.7	27.8	10.1	343.0
50	88.8	643.9	2.1	29.3	8.6	3.3	6.7	73.4	20.2	61.4
51	238.2	1,548.7	170.6	259.9	835.6	86.1	734.4	232.3	1,004.0	869.1
52	90.3	2,672.9	13,817.7	264.5	120.4	40.5	423.0	98.1	6.7	3,858.1
53	70.4	331.1	26.6	18.7	5.6	0.6	43.2	16.0	30.8	153.4
54	46.2	395.7	1.6	13.5	6.3	14.9	0.4	4.7	1.9	56.9
55	29.5	1,093.3	7.8	44.8	14.8	18.4	47.7	72.3	15.8	489.8
56	21.2	175.6	48.6	0.0	0.2	0.0	6.7	12.4	1.2	4.5
57	1.5	116.2	50.0	0.0	0.0	0.0	0.7	2.8	8.2	0.0
58	0.4	31.6	21.3	15.3	0.0	2.8	6.9	0.0	28.4	18.5
59	16.2	207.8	225.3	24.3	14.0	5.5	11.0	3.7	1.8	76.4
60	230.1	198.3	128.7	0.0	4.0	10.7	9.4	0.0	14.6	977.0
61	1.4	44.6	17.0	5.1	0.0	0.0	7.9	0.0	0.0	11.0
62	115.4	360.2	50.2	17.9	640.8	9.5	10.0	90.2	5.8	104.8
63	9.6	1,264.0	100.1	82.0	6.4	14.7	44.6	13.4	58.1	97.8
64	1.3	94.9	87.4	6.4	2.8	2.0	22.1	0.3	6.5	27.8
65	297.5	1,498.6	1,600.4	72.9	32.2	808.3	48.3	95.3	30.3	392.7
66	4.3	274.7	17.4	0.0	9.7	0.0	0.0	6.4	1.1	12.0

Table A.4. The production data of each zone (tonnes). (cont.)

	Product Categories									
Zone	1	2	3	4	5	6	7	8	9	10
67	0.7	285.9	118.3	5.4	34.0	5.3	17.2	20.2	9.1	352.0
68	101.4	1,597.0	782.2	22.7	33.0	202.3	158.7	43.0	901.3	316.0
69	722.9	5,005.8	465.4	1,391.1	2,443.8	1,538.8	9,148.9	606.6	1,808.0	3,103.2
70	135.0	1,747.6	3,305.2	84.0	636.7	190.5	2,647.7	153.7	128.3	579.3
71	1,439.3	3,469.8	2,061.2	171.1	344.7	20.2	2,443.6	255.7	222.4	1,609.8
72	897.6	6,331.7	142.7	232.1	918.5	561.1	932.4	221.5	57.9	607.7
73	162.5	2,385.3	162.7	8.7	66.6	58.6	331.9	69.8	49.5	88.1
74	1,269.3	4,209.0	658.2	284.6	2,507.4	41.5	2,500.7	197.0	292.6	575.2
75	155.7	2,317.7	583.3	111.4	305.0	153.7	301.6	127.4	189.3	334.5
76	645.8	2,610.6	11,403.4	211.6	163.5	168.0	1,882.9	114.6	34.7	297.1
77	575.3	3,963.9	556.8	162.0	2,334.4	56.8	575.6	212.2	375.2	1,988.4
78	257.5	4,098.6	77.8	137.3	739.1	28.0	216.1	50.0	166.8	351.8
79	71.4	1,438.0	1,411.7	93.5	51.5	164.6	1,178.8	90.4	296.3	1,274.9
80	116.8	5,608.7	214.9	143.8	141.1	63.2	68.3	1,678.9	19.1	926.5
81	121.2	645.4	504.6	67.4	1,181.5	19.1	311.2	136.0	6.2	284.9
82	4.2	51.9	90.1	9.0	36.8	0.0	8.4	4.5	0.0	0.4
83	32.5	736.4	31.2	22.6	25.0	20.9	52.0	73.9	7.6	46.9
84	95.3	1,150.9	29.1	91.5	2,020.0	62.5	78.5	206.2	118.9	647.9
85	56.1	229.2	1,190.8	4.8	305.3	187.6	765.8	131.9	2.1	1,488.6
86	81.1	262.3	32.9	80.3	99.9	73.6	240.0	23.5	1.9	103.7
87	5.0	163.6	1.2	0.0	13.4	0.0	0.0	3.1	3.4	8.7
88	24.4	486.5	161.8	28.7	1,539.6	3.1	0.7	12.7	18.4	416.0
89	1.6	47.7	0.0	17.7	2.7	9.8	0.0	21.5	2.2	0.3
90	85.7	1,502.2	1,396.1	67.1	31.5	19.4	402.9	42.1	55.5	953.7
91	58.9	902.5	21.0	56.1	58.2	13.7	157.5	135.7	8.7	618.3
92	23.6	1,024.2	178.5	50.4	8.3	7.7	36.3	14.4	5.0	192.5
93	527.4	3,253.3	1,368.3	785.3	125.2	346.5	399.1	1,374.1	286.0	4,788.4
94	190.8	5,024.2	572.8	333.1	511.5	53.8	458.7	118.9	129.1	880.8
95	1,525.1	5,497.8	2,279.8	233.3	441.0	668.7	5,085.5	1,175.1	504.8	1,502.2
96	67.5	348.1	292.2	6.1	31.8	76.5	18.7	88.4	41.3	43.6
97	484.9	10,310.4	865.3	755.2	615.6	349.0	838.0	159.4	484.4	1,028.9
98	407.4	14,225.0	52,635.8	268.8	545.7	124.7	514.4	481.1	544.6	8,457.2
99	139.5	4,963.4	151.3	320.0	52.0	333.8	253.7	133.5	1,421.1	178.8

Table A.4. The production data of each zone (tonnes). (cont.)

	Product Categories									
Zone	1	2	3	4	5	6	7	8	9	10
100	948.1	5,375.3	2,278.6	320.2	116.3	38.4	352.9	180.7	81.3	1,127.2
101	6.0	1,069.4	33.6	58.4	48.0	57.8	214.9	42.6	255.3	990.6
102	477.3	3,383.9	531.9	184.2	1,725.5	226.9	1,085.3	67.1	60.8	2,405.5
103	22.1	3,265.6	98.3	16.3	54.4	6.7	37.0	33.3	3.1	318.7
104	44.9	328.1	51.8	46.5	13.9	48.6	47.1	16.0	40.6	39.0
105	0.0	118.9	0.0	10.3	69.4	35.2	4.8	13.9	61.1	69.1

Table A.5. Average speed in time intervals for each zone (km/h).

Zone	02:00	08:00	13:00	19:00
1	110	100	100	100
2	110	100	100	90
3	110	100	100	90
4	110	90	90	90
5	110	95	85	85
6	110	85	80	80
7	105	85	75	80
8	105	85	80	80
9	100	95	80	85
10	105	90	85	90
11	105	70	60	50
12	100	60	65	40
13	100	45	45	35
14	110	40	60	45
15	100	80	80	85
16	110	80	65	70
17	110	90	85	80
18	105	90	95	80
19	100	45	55	30
20	100	60	50	35
21	100	80	75	50
22	100	55	50	40
23	95	45	40	25
24	90	40	40	35
25	85	35	40	30
26	90	45	45	30
27	100	45	40	30
28	95	40	50	35
29	90	55	40	35
30	90	70	45	40
31	80	40	30	25
32	80	30	25	25
33	75	35	20	15
34	70	25	10	10

Zone	02:00	08:00	13:00	19:00
35	75	45	40	30
36	80	35	35	30
37	85	45	40	30
38	85	40	45	35
39	85	50	45	35
40	85	45	40	35
41	110	70	45	35
42	50	40	20	15
43	60	45	20	10
44	70	40	25	10
45	70	50	20	25
46	90	60	50	25
47	85	40	45	20
48	85	40	35	15
49	100	35	30	20
50	90	60	45	40
51	100	45	40	30
52	100	60	70	60
53	110	80	60	40
54	100	80	80	65
55	110	90	80	70
56	110	105	100	90
57	110	95	70	55
58	110	100	75	65
59	110	100	90	90
60	110	100	60	60
61	110	100	95	90
62	110	95	85	100
63	100	60	50	60
64	105	40	80	90
65	110	100	90	90
66	110	100	100	100
67	95	65	80	70
68	100	95	90	85

Table A.5. Average speed in time intervals for each zone (km/h). (cont.)

Zone	02:00	08:00	13:00	19:00
69	100	60	90	85
70	105	75	85	60
71	105	40	50	40
72	100	80	70	70
73	100	65	70	55
74	100	60	55	55
75	100	75	70	50
76	105	80	70	65
77	100	60	40	40
78	105	50	35	35
79	100	80	80	75
80	100	65	55	40
81	90	40	40	35
82	80	55	30	20
83	75	30	30	25
84	70	40	30	20
85	85	60	55	45
86	70	30	25	20
87	80	15	25	30

Zone	02:00	08:00	13:00	19:00
88	90	30	25	35
89	85	70	60	60
90	85	40	45	35
91	90	20	25	30
92	90	75	60	60
93	100	50	60	30
94	100	70	75	65
95	95	55	45	40
96	100	75	90	80
97	105	80	80	40
98	105	85	80	75
99	100	85	90	80
100	105	85	70	60
101	110	90	90	85
102	105	65	70	65
103	105	25	35	40
104	75	30	25	20
105	110	100	100	100

Table A.6. NO_x emissions for heavy trucks (g/km).

Zone	02:00	08:00	13:00	19:00
1	4.254	4.254	4.254	4.254
2	4.254	4.254	4.254	4.254
3	4.254	4.254	4.254	4.254
4	4.254	4.254	4.254	4.254
5	4.254	4.254	4.269	4.269
6	4.254	4.269	4.353	4.353
7	4.254	4.269	4.447	4.353
8	4.254	4.269	4.353	4.353
9	4.254	4.254	4.353	4.269
10	4.254	4.254	4.269	4.254
11	4.254	4.554	4.818	5.174
12	4.254	4.818	4.677	5.679
13	4.254	5.403	5.403	6.021
14	4.254	5.679	4.818	5.403
15	4.254	4.353	4.353	4.269
16	4.254	4.353	4.677	4.554
17	4.254	4.254	4.269	4.353
18	4.254	4.254	4.254	4.353
19	4.254	5.403	4.982	6.453
20	4.254	4.818	5.174	6.021
21	4.254	4.353	4.447	5.174
22	4.254	4.982	5.174	5.679
23	4.254	5.403	5.679	7.022
24	4.254	5.679	5.679	6.021
25	4.269	6.021	5.679	6.453
26	4.254	5.403	5.403	6.453
27	4.254	5.403	5.679	6.453
28	4.254	5.679	5.174	6.021
29	4.254	4.982	5.679	6.021
30	4.254	4.554	5.403	5.679
31	4.353	5.679	6.453	7.022
32	4.353	6.453	7.022	7.022
33	4.447	6.021	7.811	8.993
34	4.554	7.022	10.055	10.055

Zone	02:00	08:00	13:00	19:00
35	4.447	5.403	5.679	6.453
36	4.353	6.021	6.021	6.453
37	4.269	5.403	5.679	6.453
38	4.269	5.679	5.403	6.021
39	4.269	5.174	5.403	6.021
40	4.269	5.403	5.679	6.021
41	4.254	4.554	5.403	6.021
42	5.174	5.679	7.811	8.993
43	4.818	5.403	7.811	10.055
44	4.554	5.679	7.022	10.055
45	4.554	5.174	7.811	7.022
46	4.254	4.818	5.174	7.022
47	4.269	5.679	5.403	7.811
48	4.269	5.679	6.021	8.993
49	4.254	6.021	6.453	7.811
50	4.254	4.818	5.403	5.679
51	4.254	5.403	5.679	6.453
52	4.254	4.818	4.554	4.818
53	4.254	4.353	4.818	5.679
54	4.254	4.353	4.353	4.677
55	4.254	4.254	4.353	4.554
56	4.254	4.254	4.254	4.254
57	4.254	4.254	4.554	4.982
58	4.254	4.254	4.447	4.677
59	4.254	4.254	4.254	4.254
60	4.254	4.254	4.818	4.818
61	4.254	4.254	4.254	4.254
62	4.254	4.254	4.269	4.254
63	4.254	4.818	5.174	4.818
64	4.254	5.679	4.353	4.254
65	4.254	4.254	4.254	4.254
66	4.254	4.254	4.254	4.254
67	4.254	4.677	4.353	4.554
68	4.254	4.254	4.254	4.269

Table A.6. NO_x emissions for heavy trucks (g/km). (cont.)

Zone	02:00	08:00	13:00	19:00
69	4.254	4.818	4.254	4.269
70	4.254	4.447	4.269	4.818
71	4.254	5.679	5.174	5.679
72	4.254	4.353	4.554	4.554
73	4.254	4.677	4.554	4.982
74	4.254	4.818	4.982	4.982
75	4.254	4.447	4.554	5.174
76	4.254	4.353	4.554	4.677
77	4.254	4.818	5.679	5.679
78	4.254	5.174	6.021	6.021
79	4.254	4.353	4.353	4.447
80	4.254	4.677	4.982	5.679
81	4.254	5.679	5.679	6.021
82	4.353	4.982	6.453	7.811
83	4.447	6.453	6.453	7.022
84	4.554	5.679	6.453	7.811
85	4.269	4.818	4.982	5.403
86	4.554	6.453	7.022	7.811
87	4.353	8.993	7.022	6.453

Zone	02:00	08:00	13:00	19:00
88	4.254	6.453	7.022	6.021
89	4.269	4.554	4.818	4.818
90	4.269	5.679	5.403	6.021
91	4.254	7.811	7.022	6.453
92	4.254	4.447	4.818	4.818
93	4.254	5.174	4.818	6.453
94	4.254	4.554	4.447	4.677
95	4.254	4.982	5.403	5.679
96	4.254	4.447	4.254	4.353
97	4.254	4.353	4.353	5.679
98	4.254	4.269	4.353	4.447
99	4.254	4.269	4.254	4.353
100	4.254	4.269	4.554	4.818
101	4.254	4.254	4.254	4.269
102	4.254	4.677	4.554	4.677
103	4.254	7.022	6.021	5.679
104	4.447	6.453	7.022	7.811
105	4.254	4.254	4.254	4.254

Table A.7. NO_x emissions for trucks (g/km).

Zone	02:00	08:00	13:00	19:00
1	2.645	2.645	2.645	2.645
2	2.645	2.645	2.645	2.645
3	2.645	2.645	2.645	2.645
4	2.645	2.645	2.645	2.645
5	2.645	2.645	2.647	2.647
6	2.645	2.647	2.658	2.658
7	2.645	2.647	2.672	2.658
8	2.645	2.647	2.658	2.658
9	2.645	2.645	2.658	2.647
10	2.645	2.645	2.647	2.645
11	2.645	2.690	2.743	2.832
12	2.645	2.743	2.713	2.991
13	2.645	2.900	2.900	3.118
14	2.645	2.991	2.743	2.900
15	2.645	2.658	2.658	2.647
16	2.645	2.658	2.713	2.690
17	2.645	2.645	2.647	2.658
18	2.645	2.645	2.645	2.658
19	2.645	2.900	2.781	3.298
20	2.645	2.743	2.832	3.118
21	2.645	2.658	2.672	2.832
22	2.645	2.781	2.832	2.991
23	2.645	2.900	2.991	3.561
24	2.645	2.991	2.991	3.118
25	2.647	3.118	2.991	3.298
26	2.645	2.900	2.900	3.298
27	2.645	2.900	2.991	3.298
28	2.645	2.991	2.832	3.118
29	2.645	2.781	2.991	3.118
30	2.645	2.690	2.900	2.991
31	2.658	2.991	3.298	3.561
32	2.658	3.298	3.561	3.561
33	2.672	3.118	3.963	4.613
34	2.690	3.561	5.215	5.215
35	2.672	2.900	2.991	3.298
36	2.658	3.118	3.118	3.298
37	2.647	2.900	2.991	3.298
38	2.647	2.991	2.900	3.118
39	2.647	2.832	2.900	3.118
40	2.647	2.900	2.991	3.118
41	2.645	2.690	2.900	3.118
42	2.832	2.991	3.963	4.613
43	2.743	2.900	3.963	5.215
44	2.690	2.991	3.561	5.215
45	2.690	2.832	3.963	3.561
46	2.645	2.743	2.832	3.561
47	2.647	2.991	2.900	3.963
48	2.647	2.991	3.118	4.613
49	2.645	3.118	3.298	3.963
50	2.645	2.743	2.900	2.991
51	2.645	2.900	2.991	3.298
52	2.645	2.743	2.690	2.743
53	2.645	2.658	2.743	2.991
54	2.645	2.658	2.658	2.713
55	2.645	2.645	2.658	2.690
56	2.645	2.645	2.645	2.645
57	2.645	2.645	2.690	2.781
58	2.645	2.645	2.672	2.713
59	2.645	2.645	2.645	2.645
60	2.645	2.645	2.743	2.743
61	2.645	2.645	2.645	2.645
62	2.645	2.645	2.647	2.645
63	2.645	2.743	2.832	2.743
64	2.645	2.991	2.658	2.645
65	2.645	2.645	2.645	2.645
66	2.645	2.645	2.645	2.645
67	2.645	2.713	2.658	2.690
68	2.645	2.645	2.645	2.647

Table A.7. NO_x emissions for trucks (g/km). (cont.)

Zone	02:00	08:00	13:00	19:00
69	2.645	2.743	2.645	2.647
70	2.645	2.672	2.647	2.743
71	2.645	2.991	2.832	2.991
72	2.645	2.658	2.690	2.690
73	2.645	2.713	2.690	2.781
74	2.645	2.743	2.781	2.781
75	2.645	2.672	2.690	2.832
76	2.645	2.658	2.690	2.713
77	2.645	2.743	2.991	2.991
78	2.645	2.832	3.118	3.118
79	2.645	2.658	2.658	2.672
80	2.645	2.713	2.781	2.991
81	2.645	2.991	2.991	3.118
82	2.658	2.781	3.298	3.963
83	2.672	3.298	3.298	3.561
84	2.690	2.991	3.298	3.963
85	2.647	2.743	2.781	2.900
86	2.690	3.298	3.561	3.963
87	2.658	4.613	3.561	3.298
88	2.645	3.298	3.561	3.118
89	2.647	2.690	2.743	2.743
90	2.647	2.991	2.900	3.118
91	2.645	3.963	3.561	3.298
92	2.645	2.672	2.743	2.743
93	2.645	2.832	2.743	3.298
94	2.645	2.690	2.672	2.713
95	2.645	2.781	2.900	2.991
96	2.645	2.672	2.645	2.658
97	2.645	2.658	2.658	2.991
98	2.645	2.647	2.658	2.672
99	2.645	2.647	2.645	2.658
100	2.645	2.647	2.690	2.743
101	2.645	2.645	2.645	2.647
102	2.645	2.713	2.690	2.713
103	2.645	3.561	3.118	2.991
104	2.672	3.298	3.561	3.963
105	2.645	2.645	2.645	2.645

Table A.8. NO_x emissions for panel vans (g/km).

Zone	02:00	08:00	13:00	19:00
1	0.018	0.019	0.019	0.019
2	0.018	0.019	0.019	0.022
3	0.018	0.019	0.019	0.022
4	0.018	0.022	0.022	0.022
5	0.018	0.020	0.023	0.023
6	0.018	0.023	0.025	0.025
7	0.019	0.023	0.028	0.025
8	0.019	0.023	0.025	0.025
9	0.019	0.020	0.025	0.023
10	0.019	0.022	0.023	0.022
11	0.019	0.031	0.037	0.045
12	0.019	0.037	0.034	0.054
13	0.019	0.050	0.050	0.060
14	0.018	0.054	0.037	0.050
15	0.019	0.025	0.025	0.023
16	0.018	0.025	0.034	0.031
17	0.018	0.022	0.023	0.025
18	0.019	0.022	0.020	0.025
19	0.019	0.050	0.041	0.065
20	0.019	0.037	0.045	0.060
21	0.019	0.025	0.028	0.045
22	0.019	0.041	0.045	0.054
23	0.020	0.050	0.054	0.071
24	0.022	0.054	0.054	0.060
25	0.023	0.060	0.054	0.065
26	0.022	0.050	0.050	0.065
27	0.019	0.050	0.054	0.065
28	0.020	0.054	0.045	0.060
29	0.022	0.041	0.054	0.060
30	0.022	0.031	0.050	0.054
31	0.025	0.054	0.065	0.071
32	0.025	0.065	0.071	0.071
33	0.028	0.060	0.078	0.084
34	0.031	0.071	0.091	0.091

Zone	02:00	08:00	13:00	19:00
35	0.028	0.050	0.054	0.065
36	0.025	0.060	0.060	0.065
37	0.023	0.050	0.054	0.065
38	0.023	0.054	0.050	0.060
39	0.023	0.045	0.050	0.060
40	0.023	0.050	0.054	0.060
41	0.018	0.031	0.050	0.060
42	0.045	0.054	0.078	0.084
43	0.037	0.050	0.078	0.091
44	0.031	0.054	0.071	0.091
45	0.031	0.045	0.078	0.071
46	0.022	0.037	0.045	0.071
47	0.023	0.054	0.050	0.078
48	0.023	0.054	0.060	0.084
49	0.019	0.060	0.065	0.078
50	0.022	0.037	0.050	0.054
51	0.019	0.050	0.054	0.065
52	0.019	0.037	0.031	0.037
53	0.018	0.025	0.037	0.054
54	0.019	0.025	0.025	0.034
55	0.018	0.022	0.025	0.031
56	0.018	0.019	0.019	0.022
57	0.018	0.020	0.031	0.041
58	0.018	0.019	0.028	0.034
59	0.018	0.019	0.022	0.022
60	0.018	0.019	0.037	0.037
61	0.018	0.019	0.020	0.022
62	0.018	0.020	0.023	0.019
63	0.019	0.037	0.045	0.037
64	0.019	0.054	0.025	0.022
65	0.018	0.019	0.022	0.022
66	0.018	0.019	0.019	0.019
67	0.020	0.034	0.025	0.031
68	0.019	0.020	0.022	0.023

Table A.8. NO_x emissions for panel vans (g/km). (cont.)

Zone	02:00	08:00	13:00	19:00
69	0.019	0.037	0.022	0.023
70	0.019	0.028	0.023	0.037
71	0.019	0.054	0.045	0.054
72	0.019	0.025	0.031	0.031
73	0.019	0.034	0.031	0.041
74	0.019	0.037	0.041	0.041
75	0.019	0.028	0.031	0.045
76	0.019	0.025	0.031	0.034
77	0.019	0.037	0.054	0.054
78	0.019	0.045	0.060	0.060
79	0.019	0.025	0.025	0.028
80	0.019	0.034	0.041	0.054
81	0.022	0.054	0.054	0.060
82	0.025	0.041	0.065	0.078
83	0.028	0.065	0.065	0.071
84	0.031	0.054	0.065	0.078
85	0.023	0.037	0.041	0.050
86	0.031	0.065	0.071	0.078
87	0.025	0.084	0.071	0.065
88	0.022	0.065	0.071	0.060
89	0.023	0.031	0.037	0.037
90	0.023	0.054	0.050	0.060
91	0.022	0.078	0.071	0.065
92	0.022	0.028	0.037	0.037
93	0.019	0.045	0.037	0.065
94	0.019	0.031	0.028	0.034
95	0.020	0.041	0.050	0.054
96	0.019	0.028	0.022	0.025
97	0.019	0.025	0.025	0.054
98	0.019	0.023	0.025	0.028
99	0.019	0.023	0.022	0.025
100	0.019	0.023	0.031	0.037
101	0.018	0.022	0.022	0.023
102	0.019	0.034	0.031	0.034
103	0.019	0.071	0.060	0.054
104	0.028	0.065	0.071	0.078
105	0.018	0.019	0.019	0.019

Table A.9. c shape parameter values.

Zones (i)	Square Root of Area ($\sqrt{A}$)	(d1)	(d2)	(d3)	d(i) (average)	c(i)
1	22.7	12.7	15.4	29.2	19.1	0.84
2	16.8	5.0	14.5	24.8	14.8	0.88
3	20.0	6.9	18.8	23.3	16.3	0.82
4	13.3	3.5	12.1	27.1	14.2	1.07
5	9.5	3.8	10.9	13.6	9.4	1.00
6	12.5	20.2	19.9	25	21.7	1.73
7	11.4	6.5	16	20.1	14.2	1.25
8	14.9	4.8	22.4	29.9	19.0	1.28
9	13.5	1.7	16.5	16.4	11.5	0.86
10	8.2	6.2	5.9	10.5	7.5	0.92
11	7.8	1.2	6.6	16.9	8.2	1.05
12	5.4	1.5	3.4	8.5	4.5	0.82
13	5.4	3.1	8.5	10.1	7.2	1.33
14	7.8	2.4	9.2	10.1	7.2	0.93
15	11.6	6.2	17.4	19.5	14.4	1.24
16	15.3	2.0	19.3	55.3	25.5	1.67
17	12.8	7.7	9.9	18.6	12.1	0.94
18	8.8	1.1	12.1	13.5	8.9	1.01
19	7.7	2.3	9.5	14	8.6	1.12
20	3.8	0.5	2.8	7.4	3.6	0.94
21	1.8	0.3	1.6	3.1	1.7	0.94
22	1.9	0.9	1.6	3.1	1.9	0.99
23	3.1	1.4	4.3	3.4	3.0	0.97
24	3.9	1.3	4.6	6.2	4.0	1.03
25	3.5	0.4	2.3	5.6	2.8	0.78
26	3.6	1.2	2.9	4.4	2.8	0.78
27	3.8	1.1	10.2	12.1	7.8	2.03
28	2.8	1.3	1.8	2.8	2.0	0.71
29	2.8	1.1	2.5	5.2	2.9	1.06

Table A.9. c shape parameter values. (cont.)

Zones (i)	Square Root of Area ($\sqrt{A}$)	(d1)	(d2)	(d3)	d(i) (average)	c(i)
30	1.9	1.0	2.7	4.3	2.7	1.39
31	1.4	0.5	1.2	1.7	1.1	0.84
32	1.9	0.7	1.4	2.5	1.5	0.79
33	2.2	0.8	1.5	2.3	1.5	0.71
34	1.8	0.5	1.2	1.7	1.1	0.62
35	2.3	1.0	2.6	2.8	2.1	0.92
36	3.7	2.0	3.4	5.8	3.7	1.02
37	4.2	2.1	3.8	4.9	3.6	0.85
38	4.1	11.8	3.1	5.4	6.8	1.65
39	1.7	1.3	2.2	2.0	1.8	1.05
40	2.2	0.7	1.6	3.1	1.8	0.83
41	1.7	0.7	3.1	3.6	2.5	1.48
42	1.2	0.6	0.9	2.5	1.3	1.09
43	1.3	0.7	1.1	1.8	1.2	0.90
44	1.9	0.8	4.0	3.8	2.9	1.47
45	1.7	0.6	1.2	1.9	1.2	0.73
46	2.2	1.1	2.0	2.6	1.9	0.86
47	2.1	1.1	9.3	2.6	4.3	2.07
48	1.9	0.8	2.0	2.3	1.7	0.88
49	2.4	0.7	2.3	4.0	2.3	0.98
50	2.2	1.0	3.0	5.3	3.1	1.39
51	3.0	1.0	3.5	6.3	3.6	1.21
52	4.7	0.7	3.3	4.6	2.9	0.61
53	2.3	2.3	2.9	3.5	2.9	1.26
54	3.0	0.7	2.7	3.6	2.3	0.77
55	7.0	2.4	7.7	13.9	8.0	1.14
56	9.1	2.6	8.2	17.0	9.3	1.02
57	11.7	2.7	8.6	14.5	8.6	0.74

Table A.9. c shape parameter values. (cont.)

Zones (i)	Square Root of Area ($\sqrt{A}$)	(d1)	(d2)	(d3)	d(i) (average)	c(i)
58	16.6	5.7	22.4	18.3	15.5	0.93
59	15.5	7.8	15.2	30.3	17.8	1.15
60	9.2	18.4	13.2	13.3	15.0	1.62
61	8.1	0.9	12.6	17.5	10.3	1.28
62	8.8	12.8	9.1	18.4	13.4	1.53
63	6.7	2.2	5.7	8.0	5.3	0.80
64	6.2	3.5	4.7	20.1	9.4	1.52
65	11.2	5.0	22.1	19.3	15.5	1.38
66	12.0	10.5	9.0	20.7	13.4	1.11
67	8.9	14.7	9.2	13.8	12.6	1.41
68	7.3	2.4	9.7	12.2	8.1	1.12
69	6.7	2.9	8.6	7.5	6.3	0.94
70	5.9	2.0	6.3	8.6	5.6	0.96
71	3.9	1.5	3.5	4.1	3.0	0.78
72	3.6	0.9	3.4	5.1	3.1	0.86
73	4.4	1.0	3.8	7.8	4.2	0.96
74	3.8	1.8	2.9	4.1	2.9	0.77
75	2.6	0.9	2.7	4.5	2.7	1.05
76	2.9	1.8	3.7	5.2	3.6	1.21
77	3.9	2.2	3.1	5.0	3.4	0.88
78	2.8	2.0	3.6	4.7	3.4	1.25
79	3.8	0.8	2.7	7.7	3.7	0.98
80	2.5	0.8	2.0	3.6	2.1	0.84
81	2.5	1.0	2.0	3.2	2.1	0.82
82	1.8	0.5	1.4	3.4	1.8	0.96
83	2.0	0.9	2.1	4.8	2.6	1.30
84	2.4	0.6	3.8	3.6	2.7	1.13
85	2.0	1.0	2.6	4.6	2.7	1.37

Table A.9. c shape parameter values. (cont.)

Zones (i)	Square Root of Area ($\sqrt{A}$)	(d1)	(d2)	(d3)	d(i) (average)	c(i)
86	1.7	1.1	1.3	2.9	1.8	1.05
87	1.6	3.1	1.1	3.4	2.5	1.56
88	2.2	0.7	2.2	2.4	1.8	0.81
89	1.8	0.7	1.4	2.1	1.4	0.76
90	3.7	2.1	4.3	5.1	3.8	1.04
91	3.5	2.0	2.2	3.2	2.5	0.70
92	2.5	0.7	1.9	3.4	2.0	0.81
93	3.1	1.2	2.8	4.3	2.8	0.88
94	3.7	0.7	5.0	11.3	5.7	1.53
95	3.5	1.2	2.3	5.1	2.9	0.82
96	4.9	0.5	6.8	10.5	5.9	1.20
97	4.0	0.1	3.1	6.6	3.3	0.81
98	5.3	2.7	3.9	6.1	4.2	0.79
99	4.3	1.9	3.3	7.9	4.4	1.01
100	5.2	1.4	5.1	5.5	4.0	0.77
101	3.6	1.1	6.3	6.6	4.7	1.29
102	3.5	1.4	2.6	16.0	6.7	1.91
103	2.4	5.1	3.8	3.9	4.3	1.81
104	1.8	0.5	1.4	2.6	1.5	0.83
105	6.4	2.5	10.2	17.2	10.0	1.56
					Average of c(i)	1.08

Table A.10. Computation steps in which TC capacities are determined.

Step 1	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Heavy Truck	54	81	81	108
Truck	270	405	405	540
Panel van	420	630	630	840
Electric van	84	126	126	168
Step 2	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Truck+Heavy Truck	324	486	486	648
Panel van+Electric van	504	756	756	1,008
Step 3	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Truck+Heavy Truck	360	500	500	650
Panel van+Electric van	500	760	760	1,000
Total	860	1,260	1,260	1,650
Step 4	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Truck+Heavy Truck	516	756	756	990
Panel van+Electric van	344	504	504	660
Step 5	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
Truck+Heavy Truck	520	760	760	990
Panel van+Electric van	340	500	500	660

Table A.11. Average traveling distance in each zone (km).

Zones	Average Traveling Distance	Zones	Average Traveling Distance	Zones	Average Traveling Distance
1	26.5	36	4.3	71	4.5
2	19.6	37	4.9	72	4.2
3	23.3	38	4.8	73	5.1
4	15.6	39	2.0	74	4.4
5	11.0	40	2.5	75	3.0
6	14.6	41	1.9	76	3.4
7	13.2	42	1.4	77	4.6
8	17.4	43	1.5	78	3.2
9	15.7	44	2.3	79	4.4
10	9.5	45	1.9	80	2.9
11	9.1	46	2.6	81	2.9
12	6.3	47	2.4	82	2.1
13	6.4	48	2.2	83	2.3
14	9.1	49	2.8	84	2.7
15	13.5	50	2.6	85	2.3
16	17.8	51	3.5	86	2.0
17	15.0	52	5.5	87	1.9
18	10.3	53	2.7	88	2.5
19	9.0	54	3.5	89	2.2
20	4.4	55	8.2	90	4.3
21	2.1	56	10.6	91	4.1
22	2.2	57	13.6	92	2.9
23	3.6	58	19.3	93	3.7
24	4.6	59	18.1	94	4.3
25	4.1	60	10.7	95	4.1
26	4.2	61	9.4	96	5.8
27	4.5	62	10.2	97	4.7
28	3.2	63	7.8	98	6.2
29	3.2	64	7.2	99	5.0
30	2.2	65	13.0	100	6.1
31	1.6	66	14.0	101	4.2
32	2.3	67	10.4	102	4.1
33	2.5	68	8.5	103	2.7
34	2.1	69	7.8	104	2.1
35	2.7	70	6.8	105	7.5

Table A.12. A representation of distance matrix (km).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	24.6	63.7	82.8	79.3	84.9	117.8	82.5	78	86.2	98	103.1	101	109.4	101.5	120.1	113.7	122.3	128.1	130.5	131.6
2	63.1	18.1	80	65.2	58.6	77.5	55	50.6	58.8	70.5	75.7	73.6	82	74.1	92.6	86.3	94.9	100.7	103.1	104.1
3	82.1	79.1	21.6	61.5	75.7	85.1	93.9	93	101.2	99.9	94.8	92.7	107.8	99.6	118.7	135	140.1	118.7	110.2	111.2
4	78.7	65.2	60.1	14.4	40.1	55.4	68.6	68.3	76.4	74.5	65	63	71.4	74.2	93.3	109.7	114.7	93.3	84.8	85.9
5	86.5	58.6	67.1	39.4	10.2	42.3	39.1	51.1	58	66.8	52	49.9	58.3	66.5	85.6	101.9	94.1	85.5	77.1	66.3
6	96.3	69.4	91.7	66.5	53.5	13.5	42.8	54.8	61.6	48.8	46.2	44.2	56.6	48.4	67.5	83.9	88.9	67.5	59	60.1
7	81.8	55	94.2	59.5	39.2	50.9	12.3	40.3	44.8	41.6	49.1	47	55.4	51.9	63	72.3	80.9	71	62.5	63.6
8	77.4	50.6	93.6	68.3	51.1	62.8	40.4	16.1	41.7	53.4	61	58.9	67.4	57	75.5	69.2	77.8	83.6	86	87
9	99.6	72.8	115.7	90.4	70.8	79.5	57	55.7	14.6	40.9	55.5	54.5	86.3	50	63	56.7	65.2	71.1	73.4	74.5
10	94.1	67.3	99.6	74.4	61.5	56.3	41.8	50.2	44.7	8.8	32.2	31.2	41.5	26.8	42.7	45	73.8	52.3	43.8	44.9
11	100.7	73.8	94.3	64	50.8	42.2	47.2	59.2	56.7	33.8	8.5	18.7	25.4	24.6	47	65.1	70.1	48.7	40.2	33.4
12	100.4	73.6	94.1	63.7	50.5	41.9	46.9	59	56.1	33.3	19.2	5.9	25.3	30.1	46.7	64.8	69.8	48.4	39.9	33.3
13	106.5	79.7	100.2	69.8	56.6	48	53	65	63.8	40.9	23.6	23.9	5.9	28.3	44.9	59.7	64.8	44.8	32.3	23.5
14	101.2	74.3	97.3	72.1	59.1	53.9	50.2	57.2	51.8	28.9	23.9	29.2	29.9	8.4	40.9	57.2	62.3	40.8	32.3	33.4
15	115.4	88.5	116.8	91.6	78.6	73.4	69.7	71.4	67.4	40.8	44.9	45.1	51.1	39	12.5	40.1	50.4	35.5	38.3	39.4
16	113.9	87.1	133.9	108.7	95.7	90.5	71.3	70	65.9	43	63.7	63.9	57.2	56.1	40	16.5	48.7	41.5	44.3	45.4
17	122.1	95.3	140.9	115.7	102.7	97.5	79.5	78.2	74.1	63.1	70.7	70.9	64	63	51.1	48.5	13.9	48.8	51.2	52.2
18	125.4	98.6	118.4	93.2	80.2	75.1	71.4	81.5	77.4	45.2	48.3	48.5	41.7	40.6	33.6	39.4	44.5	9.5	28.9	30
19	118	91.2	111.6	86.4	73.4	68.2	64.5	76.5	69.3	46.4	41.4	41.6	30.5	33.8	39.9	45.8	50.8	30.8	8.3	18.7
20	118.2	91.4	111.8	86.6	73.6	54.1	64.7	76.7	69.5	46.6	29.6	29.9	18.3	34	40.1	45.9	51	31	18.6	4.1

Table A.13. Zones on the path.

From	To	Zones on the Path
1	2	1, 2
1	3	1, 3
1	4	1, 2, 3, 4
1	5	1, 2, 4, 5
1	6	1, 2, 3, 4, 5, 6
1	7	1, 2, 7, 8
1	8	1, 2, 8
1	9	1, 2, 8, 9
1	10	1, 2, 7, 8, 9, 10
1	11	1, 2, 6, 7, 8, 11
1	12	1, 2, 6, 7, 8, 11, 12
1	13	1, 2, 6, 7, 8, 10, 11, 13, 14
1	14	1, 2, 7, 8, 9, 10, 11, 14
1	15	1, 2, 7, 8, 9, 15
1	16	1, 2, 8, 9, 15, 16
1	17	1, 2, 8, 9, 16, 17, 18
1	18	1, 2, 8, 9, 15, 16, 17, 18, 19
1	19	1, 2, 7, 8, 9, 10, 15, 16, 17, 18, 19
1	20	1, 2, 7, 8, 9, 10, 14, 15, 16, 17, 18, 19, 20, 24
1	21	1, 2, 7, 8, 9, 10, 13, 14, 15, 16, 17, 18, 19, 20, 21, 24
1	22	1, 2, 7, 8, 9, 10, 14, 15, 16, 17, 18, 19, 20, 22, 23, 24
1	23	1, 2, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 23, 24, 25
1	24	1, 2, 7, 8, 9, 10, 14, 15, 16, 17, 18, 19, 20, 24
1	25	1, 2, 7, 8, 9, 10, 15, 16, 17, 18, 19, 25, 26
1	26	1, 2, 7, 8, 9, 10, 15, 16, 17, 18, 19, 26
1	27	1, 2, 7, 8, 9, 15, 16, 17, 18, 19, 27, 37, 38
1	28	1, 2, 7, 8, 9, 15, 16, 17, 18, 19, 26, 27, 28
1	29	1, 2, 7, 8, 9, 10, 15, 16, 17, 18, 19, 23, 25, 26, 27, 28, 29, 35, 36, 37, 38, 39, 40
1	30	1, 2, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 23, 24, 25, 26, 30
1	31	1, 2, 7, 8, 9, 10, 15, 16, 17, 18, 19, 25, 26, 28, 29, 30, 31, 32
1	32	1, 2, 7, 8, 9, 10, 15, 16, 17, 18, 19, 25, 26, 28, 29, 32
1	33	1, 2, 7, 8, 9, 10, 15, 16, 17, 18, 19, 26, 27, 28, 33, 35, 36, 37, 38, 39, 40, 41, 42, 43
1	34	1, 2, 7, 8, 9, 15, 16, 17, 18, 19, 26, 27, 28, 29, 32, 33, 34, 35
1	35	1, 2, 7, 8, 9, 15, 16, 17, 18, 19, 26, 27, 28, 35, 36, 37, 38, 39, 40

Table A.14. The limit on number of vehicles per covered area in the VNM scenario.

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
1	1,500	1,500	1,500	1,500
2	1,500	1,500	1,500	1,500
3	1,500	1,500	1,500	1,500
4	1,500	1,500	1,500	1,500
5	1,500	1,500	1,500	1,500
6	1,500	1,500	1,500	1,500
7	1,500	1,500	1,500	1,500
8	1,500	1,500	1,500	1,500
9	1,500	1,500	1,500	1,500
10	1,500	1,500	1,500	1,500
11	1,500	1,500	1,500	1,500
12	1,500	1,500	1,500	1,500
13	1,500	1,500	1,500	1,500
14	1,500	1,500	1,500	1,500
15	1,500	1,500	1,500	1,500
16	1,500	1,500	1,500	1,500
17	1,500	1,500	1,500	1,500
18	1,500	1,500	1,500	1,500
19	1,500	1,500	1,500	1,500
20	1,500	1,500	1,500	3,000
21	1,500	1,500	1,500	1,500
22	1,500	1,500	1,500	1,500
23	1,500	1,500	1,500	3,000
24	1,500	1,500	1,500	4,500
25	1,500	1,500	1,500	3,000
26	1,500	1,500	1,500	4,500
27	1,500	1,500	1,500	1,500
28	1,500	1,500	1,500	6,000
29	1,500	1,500	1,500	4,500
30	1,500	1,500	1,500	3,000
31	1,500	1,500	1,500	1,500
32	1,500	1,500	1,500	3,000
33	1,500	1,500	1,500	6,000

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
34	1,500	1,500	1,500	6,000
35	1,500	1,500	1,500	3,000
36	1,500	1,500	1,500	1,500
37	1,500	1,500	1,500	1,500
38	1,500	1,500	1,500	1,500
39	1,500	1,500	1,500	3,000
40	1,500	1,500	1,500	1,500
41	1,500	1,500	1,500	3,000
42	1,500	1,500	1,500	6,000
43	1,500	1,500	1,500	6,000
44	1,500	1,500	1,500	1,500
45	1,500	1,500	1,500	3,000
46	1,500	1,500	1,500	3,000
47	1,500	1,500	1,500	3,000
48	1,500	1,500	1,500	4,500
49	1,500	1,500	1,500	1,500
50	1,500	1,500	1,500	1,500
51	1,500	1,500	1,500	3,000
52	1,500	1,500	1,500	1,500
53	1,500	1,500	1,500	1,500
54	1,500	1,500	1,500	1,500
55	1,500	1,500	1,500	1,500
56	1,500	1,500	1,500	1,500
57	1,500	1,500	1,500	1,500
58	1,500	1,500	1,500	1,500
59	1,500	1,500	1,500	1,500
60	1,500	1,500	1,500	1,500
61	1,500	1,500	1,500	1,500
62	1,500	1,500	1,500	1,500
63	1,500	1,500	1,500	1,500
64	1,500	1,500	1,500	1,500
65	1,500	1,500	1,500	1,500
66	1,500	1,500	1,500	1,500

Table A.14. The limit on number of vehicles per covered area in the VNM scenario. (cont.)

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
67	1,500	1,500	1,500	1,500
68	1,500	1,500	1,500	1,500
69	1,500	1,500	1,500	1,500
70	1,500	1,500	1,500	1,500
71	1,500	1,500	1,500	1,500
72	1,500	1,500	1,500	1,500
73	1,500	1,500	1,500	1,500
74	1,500	1,500	1,500	1,500
75	1,500	1,500	1,500	1,500
76	1,500	1,500	1,500	4,500
77	1,500	1,500	1,500	1,500
78	1,500	1,500	1,500	3,000
79	1,500	1,500	1,500	1,500
80	1,500	1,500	1,500	3,000
81	1,500	1,500	1,500	3,000
82	1,500	1,500	1,500	1,500
83	1,500	3,000	1,500	4,500
84	1,500	1,500	1,500	1,500
85	1,500	1,500	1,500	1,500
86	1,500	1,500	1,500	3,000
87	1,500	1,500	1,500	1,500
88	1,500	1,500	1,500	1,500
89	1,500	1,500	1,500	1,500
90	1,500	1,500	1,500	1,500
91	1,500	1,500	1,500	1,500
92	1,500	1,500	1,500	1,500
93	1,500	1,500	1,500	3,000
94	1,500	1,500	1,500	1,500
95	1,500	1,500	1,500	3,000
96	1,500	1,500	1,500	1,500
97	1,500	1,500	1,500	3,000
98	1,500	1,500	1,500	1,500
99	1,500	1,500	1,500	1,500
100	1,500	1,500	1,500	1,500
101	1,500	1,500	1,500	1,500
102	1,500	1,500	1,500	1,500
103	1,500	1,500	1,500	3,000
104	1,500	1,500	1,500	3,000
105	1,500	1,500	1,500	1,500

Table A.15. The limit on number of vehicles per covered area in the VNL scenario.

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
1	1,000	1,000	1,000	1,000
2	1,000	1,000	1,000	1,000
3	1,000	1,000	1,000	1,000
4	1,000	1,000	1,000	1,000
5	1,000	1,000	1,000	1,000
6	1,000	1,000	1,000	1,000
7	1,000	1,000	1,000	1,000
8	1,000	1,000	1,000	1,000
9	1,000	1,000	1,000	1,000
10	1,000	1,000	1,000	1,000
11	1,000	1,000	1,000	1,000
12	1,000	1,000	1,000	1,000
13	1,000	1,000	1,000	1,000
14	1,000	1,000	1,000	1,000
15	1,000	1,000	1,000	1,000
16	1,000	1,000	1,000	1,000
17	1,000	1,000	1,000	1,000
18	1,000	1,000	1,000	1,000
19	1,000	1,000	1,000	1,000
20	1,000	1,000	1,000	2,000
21	1,000	1,000	1,000	1,000
22	1,000	1,000	1,000	1,000
23	1,000	1,000	1,000	1,000
24	1,000	1,000	1,000	2,000
25	1,000	1,000	1,000	1,000
26	1,000	1,000	1,000	2,000
27	1,000	1,000	1,000	1,000
28	1,000	1,000	1,000	4,500
29	1,000	1,000	1,000	2,000
30	1,000	1,000	1,000	1,000
31	1,000	1,000	1,000	1,000
32	1,000	1,000	1,000	2,000
33	1,000	1,000	1,000	3,000

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
34	1,000	1,000	1,000	3,000
35	1,000	1,000	1,000	1,000
36	1,000	1,000	1,000	1,000
37	1,000	1,000	1,000	1,000
38	1,000	1,000	1,000	1,000
39	1,000	1,000	1,000	1,000
40	1,000	1,000	1,000	1,000
41	1,000	1,000	1,000	1,000
42	1,000	1,000	1,000	4,500
43	1,000	1,000	1,000	3,000
44	1,000	1,000	1,000	1,000
45	1,000	1,000	1,000	2,000
46	1,000	1,000	1,000	2,000
47	1,000	1,000	1,000	1,000
48	1,000	1,000	1,000	2,000
49	1,000	1,000	1,000	1,000
50	1,000	1,000	1,000	1,000
51	1,000	1,000	1,000	1,000
52	1,000	1,000	1,000	1,000
53	1,000	1,000	1,000	1,000
54	1,000	1,000	1,000	1,000
55	1,000	1,000	1,000	1,000
56	1,000	1,000	1,000	1,000
57	1,000	1,000	1,000	1,000
58	1,000	1,000	1,000	1,000
59	1,000	1,000	1,000	1,000
60	1,000	1,000	1,000	1,000
61	1,000	1,000	1,000	1,000
62	1,000	1,000	1,000	1,000
63	1,000	1,000	1,000	1,000
64	1,000	1,000	1,000	1,000
65	1,000	1,000	1,000	1,000
66	1,000	1,000	1,000	1,000

Table A.15. The limit on number of vehicles per covered area in the VNL scenario. (cont.)

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak
67	1,000	1,000	1,000	1,000
68	1,000	1,000	1,000	1,000
69	1,000	1,000	1,000	1,000
70	1,000	1,000	1,000	1,000
71	1,000	1,000	1,000	1,000
72	1,000	1,000	1,000	1,000
73	1,000	1,000	1,000	1,000
74	1,000	1,000	1,000	1,000
75	1,000	1,000	1,000	1,000
76	1,000	1,000	1,000	2,000
77	1,000	1,000	1,000	1,000
78	1,000	1,000	1,000	1,000
79	1,000	1,000	1,000	1,000
80	1,000	1,000	1,000	2,000
81	1,000	1,000	1,000	1,000
82	1,000	1,000	1,000	1,000
83	1,000	1,000	1,000	2,000
84	1,000	1,000	1,000	1,000
85	1,000	1,000	1,000	1,000
86	1,000	1,000	1,000	1,000
87	1,000	1,000	1,000	1,000
88	1,000	1,000	1,000	1,000
89	1,000	1,000	1,000	1,000
90	1,000	1,000	1,000	1,000
91	1,000	1,000	1,000	1,000
92	1,000	1,000	1,000	1,000
93	1,000	1,000	1,000	1,000
94	1,000	1,000	1,000	1,000
95	1,000	1,000	1,000	2,000
96	1,000	1,000	1,000	1,000
97	1,000	1,000	1,000	1,000
98	1,000	1,000	1,000	1,000
99	1,000	1,000	1,000	1,000
100	1,000	1,000	1,000	1,000
101	1,000	1,000	1,000	1,000
102	1,000	1,000	1,000	1,000
103	1,000	1,000	1,000	2,000
104	1,000	1,000	1,000	2,000
105	1,000	1,000	1,000	1,000

Table A.16. The number of vehicles per unit area received from IMM.

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
1	0.5	1.2	1.0		2.7
2	0.9	2.2	1.7		4.8
3	0.3	0.6	0.3		1.2
4	0.6	1.4	0.7		2.7
5	167.8	447.3	280.1	131.4	1,026.6
6	95.6	254.8	159.6	74.9	584.9
7	71.7	205.9	131.8	75.8	485.2
8	3.6	12.8	8.3		24.7
9	6.7	23.3	16.1		46.2
10	342.8	987.1	590.5	421.9	2,342.3
11	472.6	1,308.3	801.5	367.1	2,949.5
12	201.6	475.3	282.9	67.0	1,026.9
13	31.2	78.5	27.5	0.4	137.6
14	443.9	1,266.1	784.7	378.5	2,873.2
15	44.9	112.4	71.1	18.7	247.1
16	11.4	26.6	16.9		54.8
17	153.9	426.1	263.0	72.0	914.9
18	26.5	54.9	33.6		115.0
19	67.2	183.1	117.4	42.4	410.0
20	65.3	164.1	57.5	0.8	287.7
21	299.2	751.8	263.2	3.7	1,317.9
22	265.0	665.9	233.1	3.3	1,167.3
23	867.7	2,379.2	1,174.4	748.3	5,169.6
24	552.1	1,514.1	747.3	476.2	3,289.7
25	324.4	884.2	566.7	204.8	1,980.2
26	302.3	823.9	528.1	190.8	1,845.2
27	1,134.6	3,003.0	1,593.1	802.0	6,532.7
28	1,104.3	3,028.1	1,494.7	952.4	6,579.5
29	1,118.8	3,068.0	1,514.3	964.9	6,666.1

Table A.16. The number of vehicles per unit area received from IMM. (cont.)

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
30	932.8	2,197.4	1,177.6		4,307.8
31	1,917.5	4,516.9	2420.6		8,855.0
32	889.7	1,913.9	1,203.3		4,007.0
33	735.0	1,581.1	994.0		3,310.1
34	245.6	639.5	261.2		1,146.4
35	1,711.7	4,549.9	2,330.8	1,358.1	9,950.5
36	612.7	1,592.3	921.5	47.3	3,173.9
37	943.3	2,496.9	1,324.6	666.8	5,431.7
38	1,268.0	3,175.3	1,739.6	739.8	6,922.8
39	3,060.8	8,167.8	4,047.2	2,444.5	17,720.3
40	2,224.5	5,858.2	3,043.8	1,732.1	12,858.5
41	2,081.1	5,272.0	2,803.9	1,082.8	11,239.8
42	2,301.0	5,420.3	2,904.7		10,626.0
43	2,030.3	4,782.6	2,562.9		9,375.9
44	290.8	731.2	347.0	215.1	1,584.1
45	3,980.0	10,477.3	5,358.6	2,619.1	22,435.0
46	1,795.4	4,894.8	2,441.9	1,663.5	10,795.6
47	66.9	151.8	103.8	185.8	508.3
48	588.8	1,097.8	677.3	220.9	2,584.9
49	1,840.5	4,724.1	2,558.9	1,849.1	10,972.6
50	2,157.1	5,519.1	3,008.4	2,271.5	12,956.1
51	2,337.2	6,029.9	3,180.7	2,517.9	14,065.7
52	470.8	1,220.9	626.6	542.0	2,860.3
53	1,979.4	5,080.7	2,752	1,988.7	11,800.8
54	1,178.8	3,025.6	1,638.8	1,184.3	7,027.4
55	173.1	539.2	405.5	341.2	1,459.0
56	206.0	630.7	478.6	202.4	1,517.7
57	0.8	1.3	1.7		3.8
58	0.4	0.7	0.9		1.9

Table A.16. The number of vehicles per unit area received from IMM. (cont.)

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
59	0.4	0.7	1.0		2.2
60	19.9	35.9	21.4		77.2
61	13.8	37.0	36.9		87.8
62	3.0	11.5	8.4		22.9
63	20.3	54.3	54.2		128.8
64	295.1	759.6	439.5	273.1	1,767.3
65	13.5	24.2	14.5		52.2
66	11.7	21.0	12.5		45.2
67	109.1	401.5	297.4		808.0
68	64.4	180.4	112.7		357.6
69	98.9	262.9	132.9		494.7
70	24.0	48.5	31.8		104.3
71	166.1	506.4	245.8		918.4
72	198.7	601.8	297.9		1,098.4
73	73.7	138.7	107.5	12.0	331.9
74	647.0	1,681.1	867.0	521.6	3,716.7
75	238.2	580.6	416.9	99.5	1,335.2
76	1,458.6	3,519.9	2,004.4	889.7	7,872.5
77	81.9	154.5	85.7		322.1
78	158.8	292.6	162.1		613.4
79	515.4	1,155.6	862.6		2,533.6
80	1,746.3	4,759.5	3,242.4	2,438.4	12,186.6
81	1,802.7	4,913.1	3,347.0	2,517.0	12,579.8
82	86.6	196.5	134.3	240.4	657.8
83	75.5	171.3	117.1	209.6	573.5
84	52.6	119.3	81.5	146.0	399.4
85	73.6	167.0	114.1	204.4	559.1
86	105.2	238.6	163.0	292.0	798.8
87	113.3	256.9	175.6	314.4	860.2

Table A.16. The number of vehicles per unit area received from IMM. (cont.)

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
88	62.7	142.1	97.1	173.9	475.9
89	86.6	196.5	134.3	240.4	657.8
90	765.8	1,965.5	1,064.6	769.3	4,565.3
91	852.9	2,189.2	1,185.8	856.9	5,084.9
92	48.3	109.5	74.8	134.0	366.6
93	29.7	67.5	46.1	82.6	225.9
94	815.8	2,223.4	1,514.7	1,139.1	5,693.0
95	1,244.8	3,361.4	2,219.5	1,358.9	8,184.6
96	129.0	251.6	204.9		585.5
97	1,196.3	3,092.6	2,097.6	1,017.1	7,403.6
98	449.2	1,197.3	827.2	545.6	3,019.3
99	464.0	1,706.9	1,264.3		3,435.2
100	361.2	950.5	540.8	207.9	2,060.4
101	750.3	1,974.2	1,123.3	431.7	4,279.4
102	867.0	2,225.4	1,205.4	871.1	5,168.9
103	52.6	119.3	81.5	146.0	399.4
104	3,386.8	9,230.6	6,288.3	4,728.9	23,634.7
105	208.7	650.0	488.8	411.2	1,758.7

Table A.17. The number of vehicles per unit area received from the base scenario.

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
1				1.4	1.4
2				5.5	5.5
3		0.4		12.8	13.2
4				67.8	67.8
5				106.1	106.1
6		6.4		74.3	80.7
7		0.6		56.7	57.3
8				10.1	10.1
9		0.4		5.5	5.9
10	369.0	48.3	453.7	264.5	1,135.4
11	923.4	153.4	263.7	1,310.0	2,650.4
12	256.2	106.4	71.1	1,818.8	2,252.5
13	1,862.4	411.8	511.4	1,348.7	4,134.3
14	362.7	62.5	747.0	586.5	1,758.8
15		5.6		164.5	170.1
16		3.2		70.7	73.9
17		1.0		15.6	16.7
18			395.2	246.2	641.4
19	61.7	524.8	722.4	2,284.8	3,593.7
20	2.3	811.6	198.4	4,328.2	5,340.3
21	10.3	26.3		1,046.3	1,082.9
22	9.2			1,965.9	1,975.1
23	3.3		287.4	3,016.8	3,307.5
24	2.1	1,574.1	182.9	5,967.3	7,726.4
25		1,036.0	229.0	3,752.7	5,017.7
26	275.3	2,070.9	927.6	5,079.8	8,353.7
27	245.6	973.5	637.0	2,176.9	4,033.0
28	472.0	170.5		8,511.2	9,153.6
29			370.6	5,799.4	6,170.1

Table A.17. The number of vehicles per unit area received from the base scenario. (cont.)

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
30				3,401.7	3,401.7
31				1,888.6	1,888.6
32				4,172.4	4,172.4
33				6,376.2	6,376.2
34				7,146.2	7,146.2
35				3,437.5	3,437.5
36	1.3			2,262.9	2,264.2
37	1.0	683.3	529.6	1,863.5	3,077.4
38	77.3	250.3	96.6	1,207.4	1,631.5
39		8.3		3,631.0	3,639.3
40		5.4		2,434.7	2,440.1
41				3,070.6	3,070.6
42				11,524.7	11,524.7
43				6,062.7	6,062.7
44			157.2	2,899.4	3,056.6
45			213.3	4,109.5	4,322.8
46	195.6	316.4		4,150.5	4,662.4
47	217.8	443.1	135.7	3,238.7	4,035.4
48	368.2	673.1	193.4	4,809.5	6,044.2
49	236.9	733.6	722.6	1,320.4	3,013.6
50	270.1	391.4	823.8	967.4	2,452.6
51	295.1	1,397.3	484.6	3,078.4	5,255.4
52	58.3	465.0	169.7	1,128.3	1,821.2
53		1,574.9	36.6	987.6	2,599.0
54		854.6	21.8	549.0	1,425.4
55	32.4	127.4	3.9	60.6	224.4
56	19.2		2.3	1.4	23.0
57				6.1	6.1
58				3.6	3.6

Table A.17. The number of vehicles per unit area received from the base scenario. (cont.)

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
59				123.4	123.4
60			7.8	29.7	37.5
61			11.1	22.4	33.6
62			0.8	7.5	8.3
63		51.3		59.4	110.8
64	48.7	193.8	121.7	227.1	591.2
65	7.9		39.2	235.6	282.7
66				189.4	189.4
67	170.2	71.7		207.8	449.6
68		1.8		128.4	130.3
69	55.2	519.6	90.2	759.3	1,424.3
70	19.7	273.1	12.8	341.0	646.6
71		430.1	36.7	1,667.7	2,134.5
72	1,032.6	336.0	42.6	2,854.4	4,265.6
73	712.0	196.8	29.3	1,591.9	2,530.0
74			38.7	2,421.2	2,459.9
75				2,669.2	2,669.2
76		617.7		5,344.8	5,962.5
77		106.2		1,894.4	2,000.6
78		215.2		3,066.3	3,281.5
79	52.6	1.4		1,074.9	1,129.0
80	118.4	2,425.3		4,109.4	6,653.1
81	122.2	2,503.5		3,326.0	5,951.8
82	222.9			737.0	959.9
83	194.3	3,974.6		4,949.8	9,118.8
84	135.3	2,386.5		2,948.2	5,470.0
85				2,342.3	2,342.3
86				3,435.5	3,435.5
87			229.7	2,735.7	2,965.4

Table A.17. The number of vehicles per unit area received from the base scenario. (cont.)

Zone	Noon Peak	Noon Off-peak	Evening Peak	Evening Off-peak	Total
88			127.1	2,947.3	3,074.4
89	397.2	561.0	175.7	953.1	2,087.0
90	112.5	421.2	342.8	670.4	1,546.9
91	109.8	413.0	381.8	821.9	1726.5
92	221.4	312.7	675.2	2,000.4	3,209.7
93		1,466.4	60.3	3,082.1	4,608.8
94	56.2	1,054.0	42.1	2,807.0	3,959.3
95	63.1	1,323.8		4,129.3	5,516.2
96		220.2		954.1	1,174.4
97	126.2	1,154.9	52.2	3,006.2	4,339.6
98	518.0	275.6	171.6	2,728.5	3,693.7
99	723.4	174.9		1,099.5	1,997.9
100	36.4	65.1	181.8	1,995.2	2,278.4
101	3.1	159.7		930.4	1,093.2
102	127.4	607.5	388.1	1,787.7	2,910.8
103	135.3	2,768.1		4,222.2	7,125.5
104		495.5		4,486.2	4,981.8
105		30.9		13.8	44.7