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Optimization of İzmir's public transportation system by linear programming and sensitivity analysis

İzmir'in toplu ulaşım sisteminin doğrusal programlama ve duyarlılık analizi aracılığıyla optimizasyonu

Çağla GÖRGÜLÜ[1], Lale GÖRGÜLÜ[1], Yavuz DUVARCI[1]*

[1]City and Regional Planning Department, Faculty of Architecture, İzmir Institute of Technology, İzmir, Türkiye.
caglagorgulu18@gmail.com, lalegorgulu22@gmail.com, yduvarci@gmail.com

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Abstract

This study will focus on public transportation problems in terms of energy consumption, excessive travel time, and fares. The study seeks the best solutions for such concerns in the Izmir case. It aims to optimize these subjects for the tramway and bus systems, which are comparable in terms of origin and destination points. This study, also, draws attention to the integration issue of the transportation modes. The methods employed in this study are linear programming and sensitivity analysis. For this study, nine routes, which have both tramway and bus lines, were determined. The routes sharing the same transfer points were taken to investigate which transportation type would be the most convenient or useful, what their drawbacks and positive outcomes would be, and which one would be environmentally friendly, with especially the lowest cost. For linear programming, the Solver tool of Microsoft Excel® software was utilized. Initially, the objective functions were identified as minimization of energy consumption, minimization of route length and minimization of passenger costs. The data about energy consumptions, speeds, and passenger volumes were collected are constraints of optimizations. Finally, sensitivity analysis was conducted to assess the findings. The best solutions with bus and tram options were found for both passengers and operators. Optimal routes are Fahrettin Altay-Alsancak, Fahrettin Altay-Halkapınar, Mavişehir-Bostanlı and Egekent-Bostanlı. The study contributes to the literature using the time matrix besides to the transport cost matrix. Thus, this research serves not only for monetary aims but also for environmental and social aims.

Keywords: Public transportation, Operations research, Linear programming, Sensitivity analysis, Energy consumption.

Öz

Bu çalışma, enerji tüketimi, seyahat süresi ve ulaşım ücreti perspektiflerinden toplu ulaşım problemlerine odaklanmaktadır. Çalışmanın amacı İzmir örneğinde görülen benzer ulaşım sorunlarına yönelik güzergâh açısından karşılaştırılabilir olan tramvay ve otobüs sistemleri için en iyi çözümleri sunmaktır. Ayrıca, bu çalışma farklı ulaşım tipleri arasındaki bütünleşme konusuna dikkat çekmektedir. Çalışmada kullanılan yöntemler doğrusal programlama ve duyarlılık analizidir. Bu çalışma için hem tramvay hem de otobüs hattına sahip dokuz rota belirlenmiştir. Hangi ulaşım tipinin daha uygun veya kullanışlı olduğunu, bunların olumsuz ve olumlu sonuçlarının neler olduğunu ve hangisinin çevre dostu ve yolcu bütçesine dost olduğunu incelemek üzere aynı aktarma noktalarını paylaşan rotalar seçilmiştir. Doğrusal programlama Microsoft Excel® yazılımının bir uzantısı olan çözücü aracıyla gerçekleştirilmiştir. İlk olarak, amaç fonksiyonları en küçük enerji tüketimi, en küçük rota uzunluğu ve en küçük yolcu ücreti olarak tanımlanmıştır. Elde edilen enerji tüketimi, hız ve yolcu hacmi verileri optimizasyonların kısıtlarıdır. Son olarak, bulgular duyarlılık analizi aracılığıyla değerlendirilmiştir. Hem yolcular hem ulaşım işletmecileri için otobüs ve tramvay seçenekli en iyi sonuçlar tespit edilmiştir. En uygun rotalar Fahrettin Altay-Alsancak, Fahrettin Altay-Halkapınar, Mavişehir-Bostanlı ve Egekent-Bostanlı rotalarıdır. Bu çalışma, ulaşım maliyet matrisinin yanı sıra seyahat süresi matrisini kullanarak literatüre katkı sağlamaktadır. Böylece, bu araştırma sadece mali amaçlara değil, çevresel ve sosyal amaçlara da hizmet etmektedir.

Anahtar kelimeler: Toplu ulaşım, Yöneylem araştırması, Doğrusal programlama, Duyarlılık analizi, Enerji tüketimi.

1 Introduction

The study focuses on public transportation problems in Izmir in terms of environmental, economic, and social perspectives. The aim is to offer the best solutions for specifically the three significant problems; energy consumption, fare cost, and excessive travel time. The study investigates these problems, highlighting the usefulness of integrating transportation systems, such as buses and trams. By employing the sensitivity analysis technique, solutions found were evaluated in terms of feasibility.

Our daily life routines, such as commuting to work, school, house, and all alike, highly depend on the connectivity of transport options. Thus, transportation affects urban plans, investments, sectoral relationships, and accessibility to urban services. Rapid urbanization process in Türkiye accompanied by a growing urban population leads to some organization problems in cities. Transportation activity, which is one source of the problems, leads to environmental, economic, and social issues. For example, the global call for reducing carbon emissions stemming from transit has recently arisen [1]. In line with this, usage of the electric power in transportation systems was encouraged. Another transportation problem is the excessive travel time, especially in metropolitan cities. According to Vuchic (2005), the dominant objective should be the minimization of travel time for the preferability of public transit systems [2]. The number of transfer points, choices of passengers, occupancy rates, transportation options, headway, and frequencies are the basic parameters that significantly determine travel time [2]. Passengers wish to minimize their travel time. People prompt the required amount of

*Corresponding author/Yazışılan Yazar

infrastructure supply for their travels such that they can minimize their travel time and transportation costs, whereas they want to maximize their travel comfort. With the increasing demands, the need for optimization has been raised as an important issue. As an example, Popescu (2022) emphasized timetable optimization for urban public transportation services [1]. Usually, transportation problems are solved through various optimization methods of operations research (OR).

İzmir, as the case area, has witnessed and struggled with various public transportation problems. Various types of services (modes) are used in Izmir like tramways, buses, trains, cycles, the metro, and minibuses. A specific route, for example, might have various options for mode choice, and this offers a set of diverse options for passengers to decide. This study evaluated the best travel options with the possible integration between buses and tramways. Two tramway lines and five bus lines were investigated. This study focuses on some origins and destinations, which are also transfer points because these areas host dense transportation demand and supply due to their locations. The two transportation modes were compared to find the best solution for three problems.

Studies about the optimization of energy consumption in public transportation systems focus generally on the management of frequency and headway. In contrast, this study investigates energy consumption in different transportation modes (per passenger) and the effects of passengers' weight according to vehicle capacity on energy consumption. This study takes into account the passenger capacities of vehicles, passenger weights, vehicle weights, and working energies belonging to buses and trams for the optimization of energy consumption.

Section 2 presents literature review about transportation problems and their solutions. Section 3 explains data and method of this study. In section 3, decision variables and constraints were determined through primary and secondary data. By using a solver tool in data analysis software, linear programming was applied. Thus, the responses and solver sensitivity reports were obtained accordingly. Findings were investigated in Section 4 in terms of minimum energy consumption, minimum path length, and minimum passenger costs (fares). The results of the study were evaluated in Section 5.

2 Literature review

The major goal of transportation is to reduce travel time and costs for both passengers and operators [3]. Transportation plans focus on not only the demand of passengers but also operational efficiency [4]. The public transportation systems should be designed to provide a balance between operational costs and public demands. In addition, the integration of technology and public transit systems is a must for easy management because it will increase the efficient use of public transportation modes. If the public transportation system offers many options to choose, it will be more preferable. Yet primarily the mode selection is done by the urban planners based on passenger volumes, which is based on the outcome of demand models, and beforehand the choice of the individual passengers [2].

In addition, the operation of public transportation systems concerns the design of the line network. Deri and Kalpakcı (2014) stated that the transit line system is designed in two ways: trunk with branches and trunk with feeders [4]. Passenger volume is the dominant factor in the choice of branches and feeders [2]. Branch lines provide a service without delays because they have longer lines. They meet fewer station requirements, but the branch line has a high operational cost and is usually inefficient in attracting demand. In contrast, the feeder transit line system has more options in terms of modes of transportation, travel time, and vehicle types [4]. The feeder transit line usually has a smaller fleet size and lower operational costs. It enables more connectivity. The figure below presents a scheme of the integration of bus routes (Figure 1).

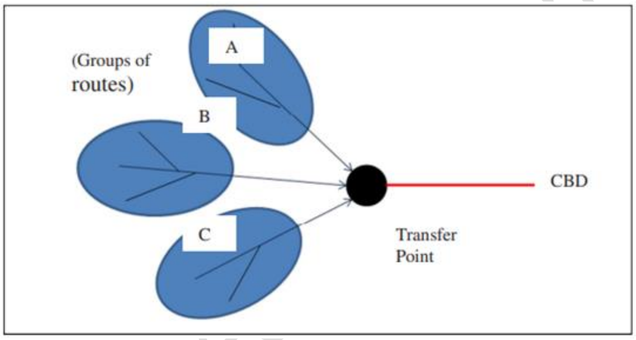

Figure 1: Integration of bus routes [4]

In the literature, there are many diverse range of studies on transportation problems like integration, environmental pollution, energy consumption, and travel time. For instance, Cervero and Golub (2007) examined the informal integration of transport systems, Nelson (2003) investigated demand-responsive transit, and Diana and others (2007) researched the reduction of emissions [5]. Energy efficiency has been a popular issue recently due to the general requirement for sustainability criteria. Metropolitan areas with their complicated transportation networks, in particular, have higher energy demands. According to Adams and others (2020), transport energy consumption is associated with environmental quality [6]. Transportation is one of the basic responsible sectors that have to adopt energy-efficiency criteria and technologies [7]. The consumption of energy depends on many parameters. For example, one of the parameters is transportation demand, such as kilowatts-hour per vehicle-kilometer, and kilowatts-hour per passenger-kilometer [7]. Also, different transportation modes have different energy consumption levels. According to Pérez-Martínez and Sorba (2010), the speed and occupancy levels affect their energy consumption levels [7]. For example, increased car capacity means increased weight, and it affects energy demand and speed. In addition, Song and others (2014) investigated energy consumption and energy efficiency in transportation by using the elasticity method [8].

Passenger travel time cost and operating costs are significant issues for transportation optimization. As Gulhan and Ozuysal (2018) highlighted, value of time is important issue to provide sustainable transportation planning and development [9]. Gulhan and Ozuysal (2018) examined public buses and paratransit modes through time and cost matrices to ensure efficient use of resources [9]. Doğan and Ozuysal (2017) draw attention to waiting time in İzmir public transportation systems since it affects quality of public transportation systems and choice of transportation modes and lines [10]. Considering time-dependent passenger demand, the time minimization subject was studied in railway operations by Qi and others (2021) [11]. Zhao and others (2021) highlighted minimizing passenger travel time and operating costs in different origin-destination pairs [12]. They used trajectory planning and sensitivity analysis methods with matrices in their studies. Murat and others (2014) studied about fuzzy optimization and linear programming approaches to minimize sum of access time and in-vehicle time in İzmir's urban bus lines organization [13]. They offered reduction of bus frequency and time cost. It also emphasized that cost function for both passengers and operators affects quality of public transportation services [13]. Murat and Demirkollu (2017) investigated daily headway of bus management to minimize cost and to provide social and environmental benefits [14]. Kavitha and Pandian (2015) studied the sensitivity analysis of the degeneracy interval transportation problem, which stems from a change in the cost coefficient [15]. Brenna and others (2020) draw attention to efficiency in the railway sector, and they investigated timetable optimization in their studies [1]. In addition to timetable optimization, Urbaniak and Kardas-Cinal (2022) contributed to the optimization of the electric energy recovered in railway stations in Poland [1]. Wang and others (2023) optimized the routes for minimizing transportation risk and cost [16]. Routes are investigated by Wang and others (2023) according to population density and building factors [16]. Also, in terms of optimization of routes, minimizing the cost of maintenance and repair of buses taking the route in a particular region took place through linear programming and sensitivity analysis by Latunde and others (2019) [17]. They (2019) recommended using these methods to determine the best ways of allocating vehicles by either increasing or decreasing the number of vehicles on a particular route [17].

Some technical parameters, such as weight, drag coefficient, rolling resistance, speed, and trip length, affect energy consumption as well [7]. These parameters are compared for buses and tramways in Figure 2. A tram car is heavier than a bus since 12000 kg weight is for a vehicle of the tram. In terms of drag coefficient, the value of the bus is 0.8 and the value of the tramway is 0.3, which means the loss of energy of the bus is greater than the tramway. Likewise, rolling resistance is closely related to energy consumption because of kinetic energy [18]. As the number of passengers increases, the need for kinetic energy will increase, too. When the number of stations is compared for buses and tramways, buses have disadvantages. For instance, buses must stop more frequently than trams, which means buses require more acceleration. Therefore, rolling resistance and aerodynamic drag coefficients lead to the loss of energy [19]. In terms of speed, buses are slightly faster than tramways because tramways have a 40 km/h speed [20], whereas buses have a 50 km/h speed [21]. Finally, their trip lengths are very close to each other. Briefly, tramways have lower energy consumption than buses because they have relatively light vehicles with low rolling resistance, drag coefficients, and a lower number of stations.

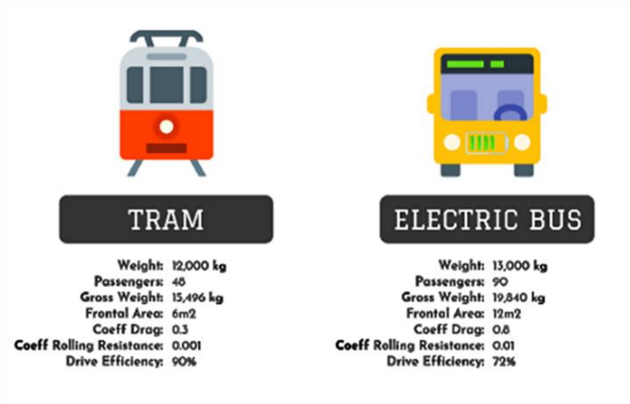

Figure 2: Parameters for a typical car of tram and electric bus [18]

This study draws attention to the lack of studies about perspectives other than monetary aims for optimality and feasibility of public transportation systems, and to the integration of public transportation modes and energy efficiency in public transportation. The study fills the gap in the literature by using the travel time matrix in optimization problems, and thus, it addresses optimization issue of social and environmental costs/benefits.

3 Data and Methods

Linear programming and sensitivity analysis were preferred in this study since the basic linear programming model (basic LP) model is used generally cost and line feasibility through sensitivity report output [22]. Origin-destination matrix (O-D matrix) is used frequently for the line planning model.

The optimization method is a mathematical model. This presents the optimal value to reach effective solutions. Linear programming is preferred to solve transportation problems. Transportation problems are separated from complex linear optimization problems. For optimization problems in transportation, a transport task was developed [23]. The task is called a classical transport task. Transport task is also a kind of method, and it was formulated by several authors in 1939 [23]. This method is used not only for transportation problems but also for computer networks, research management, working schedules, etc. The transport task method was first investigated by LV Kantorowicz in 1939 [23]. In this method, first, a transport table and matrix are formed (Table 1). Generally, this matrix is called the transport cost matrix (Figure 3) [23].

Table 1: Transport Table [23]

A_i \ B_j	B_1	B_2	…	B_n	a_i
A_1	c_{11}	c_{12}	…	c_{1n}	a_1
A_2	c_{21}	c_{22}	…	c_{2n}	a_2
…	…	…	…	…	…
A_m	c_{m1}	c_{m2}	…	c_{mn}	a_m
b_j	b_1	b_2	…	b_n	

The matrix

$$X = \begin{pmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{pmatrix}$$

is called ***matrix of transportations***.

Figure 3: Matrix of Transportations [23]

Generally, linear programming is used together with sensitivity analysis because they support each other. By using linear programming, optimum solutions can be obtained. Then, sensitivity analysis can be integrated into linear programming to obtain the right-hand side values and coefficients of the objective function [24]. Right-hand side values and objective coefficients can change according to the allowable increase and the allowable decrease. The change in right-hand side values determines the range of feasibility [24]. The sensitivity range for objective function coefficients is defined by the values of the upper and lower bounds [25]. It is also called a range of optimality. When linear programming is used with sensitivity analysis, it provides information on the sensitivity of the solution to certain changes in the data [26]. Sensitivity analysis puts forward the outcomes of changes. In line with this, how changing inputs affect the outputs of problems can be analysed. A new price policy and a new tax or subsidy system can be offered through linear programming for the optimization of costs [27]. The sensitivity analysis provides a reduction in the dimension of the problem, and it makes alternative options more understandable. Thus, it helps to evaluate alternative options.

Microsoft Excel® software utilized in this study presents a Solver tool to solve optimization problems, and it provides linear programming integrated with sensitivity reports. In operations research, the linear programming method provides to reach optimal and efficient results. Linear programming includes constraint values, decision values, and an objective function. For this study, general array was defined below (1).

Objective Function (Z) = $\sum_{v=0}^{n}(v * vd)$ (1)

v: Variable Cells in Optimization Tables

vd: Decision Variables

The objective functions, here, are minimization problems (2-4). Decision variables for the first and the second objective functions are the travel times, while in the third objective function, decision variable is passenger cost. The constraint variables of the decision variables in objective functions of this study are energy consumption (kWh) for the first objective function, speed (km/h) for the second objective function, and number of passengers (per/day) for the third objective function.

Objective Function ($Z_{1\,min}$) = $\sum_{v=0}^{n}(v * vd)$ (2)

v: Variable Cells in Minimization of Energy Consumption (Table 12)

vd: Decision Variables (Travel time) (Table 11)

Objective Function ($Z_{2\,min}$) = $\sum_{v=0}^{n}(v * vd)$ (3)

v: Variable Cells in Minimization of Route Length (Table 14)

vd: Decision Variables (Travel time) (Table 13)

Objective Function ($Z_{3\,min}$) = $\sum_{v=0}^{n}(v * vd)$ (4)

v: Variable Cells in Minimization of Passenger Costs (Table 20)

vd: Decision Variables (Passenger cost) (Table 19)

The method diagram of this study is located below (Figure 4).

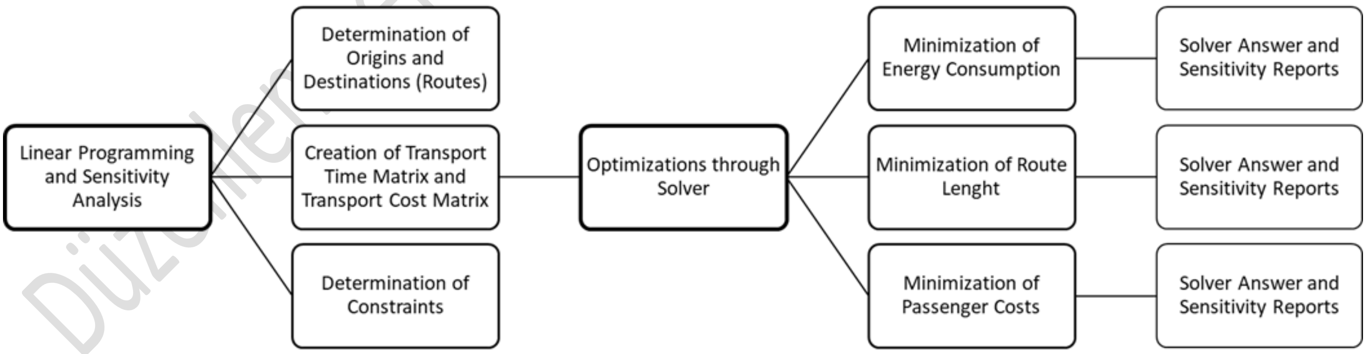

Figure 4: The Method Diagram

3.1 Case of İzmir

İzmir is a major import/export port city located west of Türkiye. One of the three largest cities in Türkiye is Izmir. In Izmir, wheeled public transportation systems, rail systems, and ferry systems are operated by İzmir Metropolitan Municipality

[ESHOT, 2012; 4]. This study focuses on bus and tramway modes. Trams are a relatively new transportation mode compared to bus systems. Figure 5 below shows the public transportation modes in İzmir. Bus lines (gray colour) and tram lines (green colour) intersect in both north and south part of İzmir.

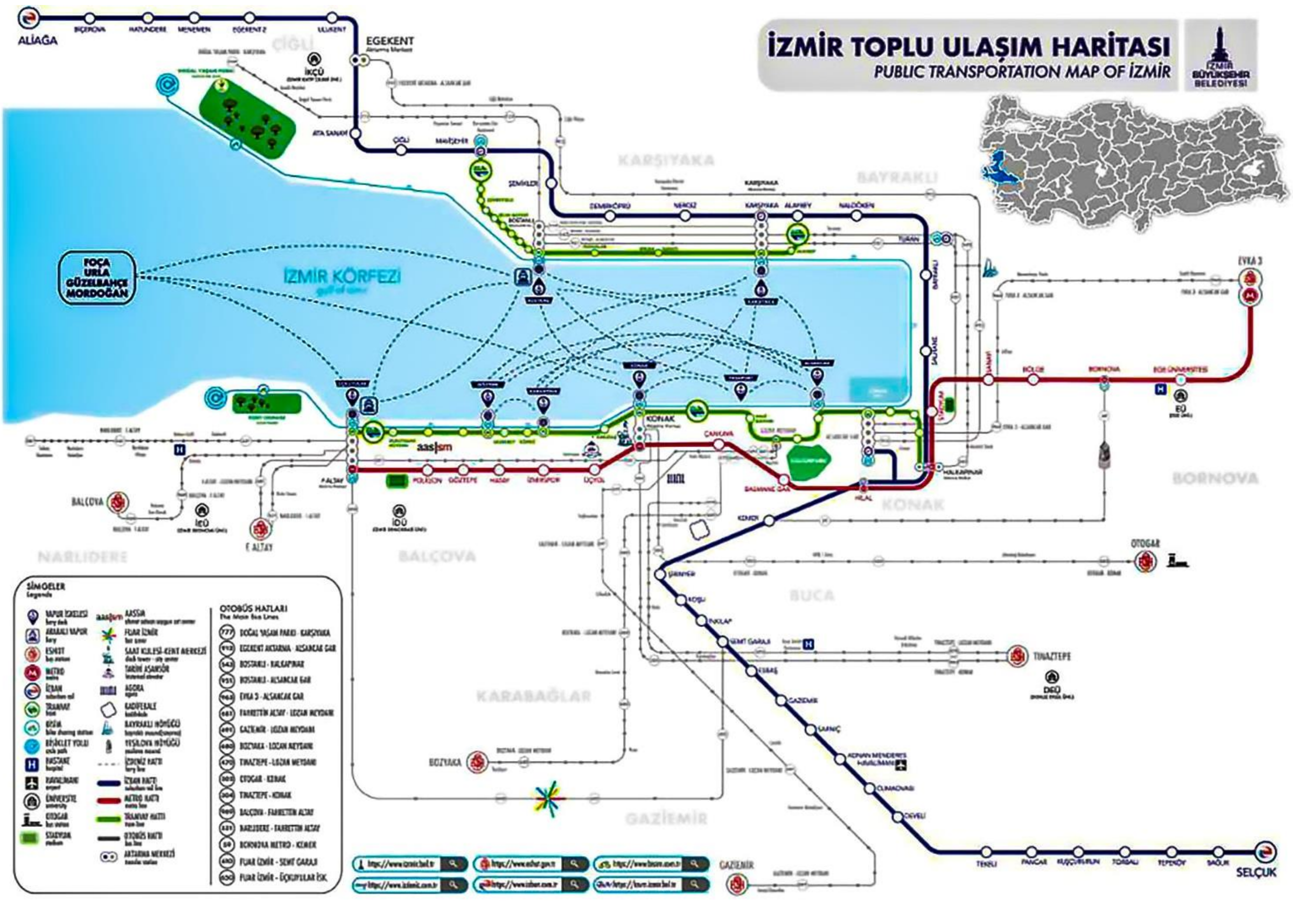

Figure 5: Public Transportation Maps in İzmir (Update 31.10.2022) [28]

There are two tramway lines, Halkapınar-Fahrettin Altay Line and Ataşehir-Alaybey Line. Izmir Metro and IZBAN are timed-transfer integrated rail system lines [29]. Ataşehir-Alaybey Line is called as Karşıyaka Tramway, and Halkapınar-Fahrettin Altay Line is called as Konak Tramway. Karşıyaka Tramway Line has an 8.8 km length and 14 stations, whereas Konak Tramway Line has a 12.6 km length and 19 stations [29]. According to the data from 2019, T1-Karşıkaya Tramway Line serves an average of 30000 passengers, whereas T2-Konak Tramway Line serves an average of 90000 passengers daily [30]. The vehicle capacity of the tram is 57, and the total capacity of the tram is 285 because it consists of five vehicles [31].

The bus capacity, on the other hand, is 100 passengers [32]. ESHOT has 1766 vehicles in 2020, and it targets to have 120 electric buses by 2022 [33]. For this study, five bus lines were used, and it was assumed that electric buses were used on these bus lines because the study focuses on the comparison of energy consumption between trams and buses. The numbers of these bus lines are 428, 543, 681, 821, and 921. Line 428 refers to Egekent 2-Bostanlı İskele and has 42 stations. Its daily frequency is 54. Line 543 refers to Bostanlı İskele-Halkapınar Metro and has 22 stations. Its daily frequency is 36. Line 681 refers to Fahrettin Altay-Lozan Meydanı and has 23 stations. Its daily frequency is 60. Line 821 refers to Mavişehir Aktarma Merkezi-Bostanlı İskele and has 19 stations. Its daily frequency is 42. The last one is Line 921, which refers to Bostanlı İskele-Alsancak Gar. It has 10 stations. Its daily frequency is 36 [33]. The daily frequencies of lines are for workdays. Table 2 shows the number and names of bus and tramway lines.

Table 2: Names of the Transportation Lines

BUSLINE NO
428-EGEKENT 2 - BOSTANLI İSKELE
543-BOSTANLI İSKELE - HALKAPINAR METRO
681-FAHRETTİN ALTAY - LOZAN MEYDANI
821-MAVİŞEHİR AKTARMA MERKEZİ - BOSTANLI İSKELE
921-BOSTANLI İSKELE - ALSANCAK GAR
TRAMLINE NO
T1-KARŞIYAKA TRAMWAY (Alaybey - Ataşehir)
T2-KONAK TRAMWAY (Fahrettin Altay - Halkapınar)

In the context of this study, nine routes were determined to apply the optimization method and sensitivity analysis. In the study, each route was evaluated in terms of two options bus and tramway. Therefore, the matrix of transportation has eighteen alternatives (Table 3). In table 3, the matrix was denoted as B for the bus and T for the tramway. On the bus routes, only buses were used apart from Fahrettin Altay-Halkapınar because there is no other bus option for this route. However, on the tramway routes, only tramways and the possible integration of buses and tramways are preferred because there are limited tramway lines. Egekent 2-Bostanlı route has no tramway line. Therefore, the bus option had to be used on this route. There are three origins: Fahrettin Altay, Egekent 2, and Mavişehir. At the same time, the origin points of routes are transfer points apart from Egekent 2. Lastly, these routes reach three destinations, which are also the transfer points: Bostanlı, Alsancak Gar, and Halkapınar. Routes were determined between transfer points to show integration and to measure the demand and capacity of passengers.

Table 3: Transport Table and Matrix

Origins	Destinations	Bostanlı	Alsancak Gar	Halkapınar
Bus 1	**Fahrettin Altay**	B_{11}	B_{12}	B_{13}
Tramway 1	**Fahrettin Altay**	T_{11}	T_{12}	T_{13}
Bus 2	**Egekent 2**	B_{21}	B_{22}	B_{23}
Tramway 2	**Egekent 2**	B_{21}	T_{22}	T_{23}
Bus 3	**Mavişehir**	B_{31}	B_{32}	B_{33}
Tramway 3	**Mavişehir**	T_{31}	T_{32}	T_{33}

Figure 6 represents the origins and destinations. Figure 6 was related to the transport table and matrix table above. Thus, nine routes were shown with their alternative options.

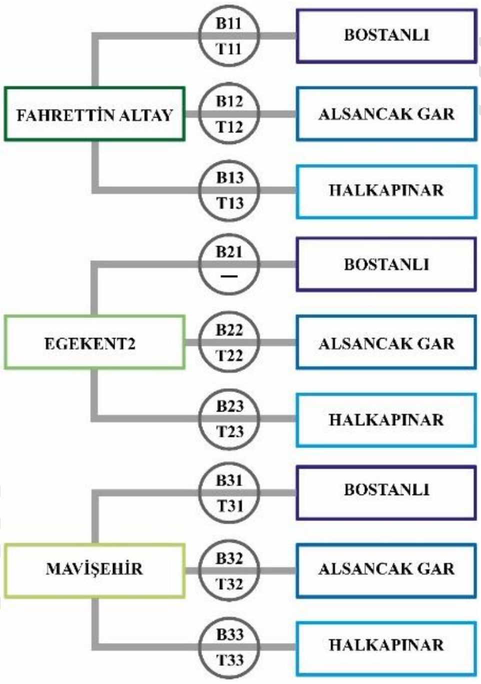

Figure 6: Origins and Destinations

Routes, which were already determined, are shown in Figures 7-8-9. Also, the number of lines according to transportation modes is demonstrated in Figures 7-8-9. Yellow points refer to transfer points. Blue lines are bus lines, and green lines are tramway lines.

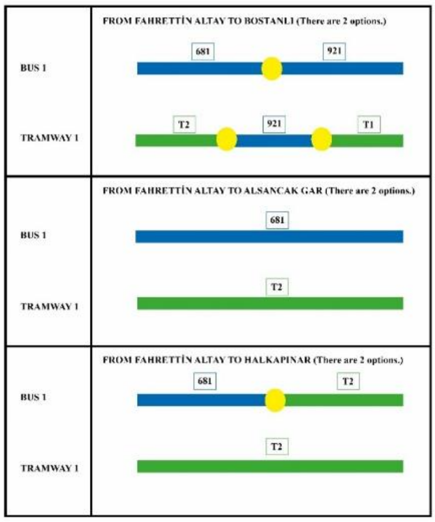

Figure 7: Routes of Bus and Tramway from Fahrettin Altay

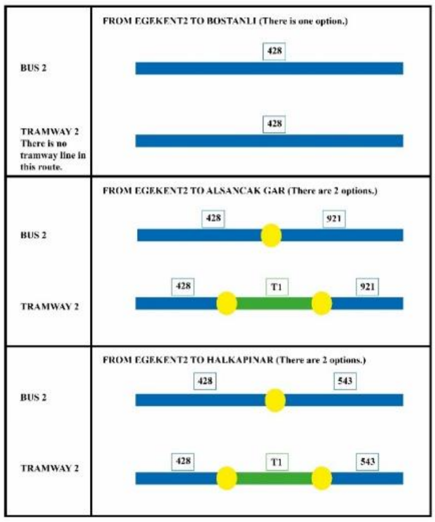

Figure 8: Routes of Bus and Tramway from Egekent 2

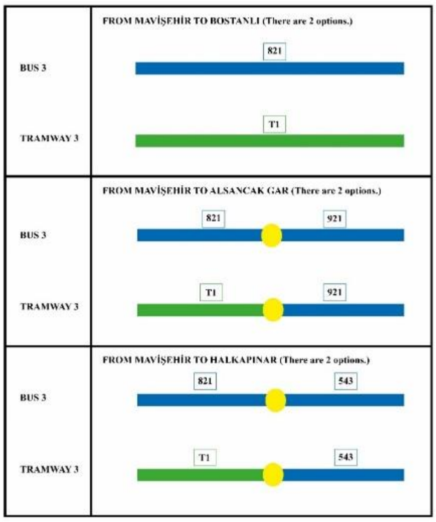

Figure 9: Routes of Bus and Tramway from Mavişehir

In this study, travel time was used as the primary data to be used in the optimization formula. In line with this, minimum travel time was preferred to minimize energy consumption and path length. This way, excessive travel time is to be prevented. Travel time and the number of lines are shown in Table 4 (See appendix table 24). For the same routes, both bus and tramway options were evaluated together. According to the use of buses and trams, line numbers were found, and their travel times were calculated. The calculation was done using the formula below (5).

$$\textbf{Travel Time (min.)} = t_v + t_s + t_t + t_w \qquad (5)$$

t_v: spending time in the vehicle without stopping ((km/V) * 60 min.)

t_s: spending time in stations ((**Ns***30 sec.) / 60 min.) **Ns** means the number of stations passed.

t_t: waiting time in transfer point(s) (min.)

t_w: walking time (min.)

The unit of travel time is in minutes. Examined travel time is around 2 p.m. in off-peak time. Integration between transportation modes or transferring time was determined by the following frequency table on the ESHOT website and TramIzmir website. According to the frequency table of transportation modes, travels for this study were started in the available time. Also, travel times were calculated according to kilometers taken in each mode of transportation. Speeds of transportation modes are 40 km/h for tramways and 50 km/h for buses. For each station, the waiting time of vehicle was assumed as 30 seconds. 30 seconds waiting time in each station was accepted according to the average data of İzmir Smart Transportation Card given in the study by Doğan and Ozuysal (2017) [10]. Each route has both tramway and bus options, except for Egekent 2-Bostanlı (Table 4). Thus, tramway and bus lines were compared in terms of travel time, energy consumption, path length, and passenger cost.

Table 4: Travel Time and Number of Lines Between the Destinations

Destinations		Bostanlı		Alsancak Gar		Halkapınar	
Origins		Line No	Travel Time	Line No	Travel Time	Line No	Travel Time
Bus 1	**Fahrettin Altay**	681-921	59 minutes	681	34 minutes	681-T2	35 minutes
Tramway 1	**Fahrettin Altay**	T2-921-T1	53 minutes	T2	22 minutes	T2	28 minutes
Bus 2	**Egekent 2**	428	46 minutes	428-921	72 minutes	428-543	94 minutes
Tramway 2	**Egekent 2**	428	46 minutes	428-T1-921	76 minutes	428-T1-543	95 minutes
Bus 3	**Mavişehir**	821	18 minutes	821-921	59 minutes	821-543	77 minutes
Tramway 3	**Mavişehir**	T1	22 minutes	T1-921	51 minutes	T1-543	74 minutes

In addition to travel time, passenger costs (fares) were calculated based on the number of transfers (Table 5). The first travel cost is 8.78 TL. The first transfer cost is 3.50 TL, and the second transfer cost is 2.00 TL (Table 6) [34].

Table 5: Number of Transfers

Destinations		Number of Transfers		
Origins		Bostanlı	Alsancak Gar	Halkapınar
Bus 1	**Fahrettin Altay**	1	–	1
Tramway 1	**Fahrettin Altay**	2	–	–
Bus 2	**Egekent 2**	–	1	1
Tramway 2	**Egekent 2**	–	2	2
Bus 3	**Mavişehir**	–	1	1
Tramway 3	**Mavişehir**	–	1	1

Table 6: Travel Fares

Fares (TL)	
First getting on	8.78
First transfer	3.50
Second transfer	2.00

Lastly, linear programming was applied to minimize energy consumption, path length, and passenger cost. The sensitivity analyses were interpreted through solver sensitivity reports of the data analysis software. These reports present a range of objective function values. Also, sensitivity analyses allow us to play with what-if scenarios that denote alternatives.

4 Findings

4.1 Linear programming solutions

For the optimization of three goals, linear programming and sensitivity analysis methods were applied. First of all, the tramway and bus were optimized and analyzed in terms of energy consumption. The table below shows the energy consumption of tramway lines in Izmir per passenger monthly (Table 7). As we can see in the table, energy consumption of trams changes according to seasonal passenger volume, frequency, headway, and even the weights of the passengers. In terms of frequency and headway, the frequency decreases if headway increases. Thus, it can be said that energy consumption decreases regardless of other parameters. If headway decreases, this will mean more energy consumption. Considering only working energy, Konak Tram Line has less energy consumption per passenger due to having more passengers than Karşıyaka Tram Line [30].

Table 7: Energy Consumption of Tramway in Izmir [35]

Energy Consumption of Tramway (kWh/per passenger)			
Year	Months	Karşıyaka	Konak
2022	1	0.68	0.47
2022	2	0.55	0.38
2022	3	0.52	0.35
2022	4	0.44	0.29
2022	5	0.49	0.32
2022	6	0.49	0.34
2022	7	0.66	0.47
2022	8	0.56	0.40
2022	9	0.35	0.30
2022	10	0.40	0.25
2022	11	0.40	0.26
2022	12	0.41	0.27

In table 8, trams' energy consumptions are located. Trams' energy consumptions were calculated according to energy consumption per passenger, frequency and tram capacity (person). kWh/per passenger were found in accordance with average of data above table for each tram line. In line with these, energy consumption of Karşıyaka Tram per hour was accepted as 1130 kWh, and Konak Tram' energy consumption was accepted as 1170 kWh per hour.

Table 8: Energy Consumption of Trams

For Tramways	kWh/per passenger	Frequency	Tram Capacity	Energy Consumption (kWh)
Karşıyaka Tram	0.50	8	285	1130
Konak Tram	0.34	12	285	1170

Table 9 shows passenger weight, bus frequency and bus capacity, and also bus weight. Passenger weight in one hour was found by multiplying average passenger weight [36], frequency and bus capacity. Energy consumption of buses was calculated according to sum of passenger weights and bus weights [37]. Table 9 also expresses effect of passenger weight on buses' energy consumption. Buses work with 230 kWh but buses carrying passengers per hour consume 690 kWh.

Table 9: Energy Consumption of Buses

For Buses	Passenger Weight	Frequency	Bus Capacity	Weight (kg)	Energy Consumption (kWh)
Passengers per hour	80	3	100	24000	
Bus				12000	230
Bus carrying passengers				36000	690

For integrated routes, where both tram and bus are used, energy consumption was assumed as sum of trams and bus energy consumptions (Table 10).

Table 10: Energy Consumption for Integrated Modes

For Integrated Modes	Energy Consumption (kWh)	Total Energy Consumption (kWh)
Buses-T1 Karşıyaka Tram	690+1130	1820
Buses-T2 Konak Tram	690+1170	1860

The matrix, which shows travel time (hour unit), was formed in the datasheet (Table 11). This matrix presents decision variables for optimization of minimum energy consumption. Constraints were accepted as energy consumption (kW/h). An electric bus works with 230 kW/h [38], and bus carrying passengers consumes 690 kWh per hour. Karşıyaka Tram' energy consumption is 1130, while Konak Tram' energy consumption is 1170. When both transportation modes have to be utilized, the sum of their energy consumption was taken as the constraint. Energy consumption of integrated mode is 1820 kW/h for Karşıyaka and 1860 kW/h for Konak. Generally, tramway routes are integrated by bus. Also, only the Fahrettin Altay Bus route has 1860 kW/h constraint because there is an integration of tramway and bus on this bus route.

Table 11: Travel Time and Energy Consumption of Transportation Modes

Modes	Origins \ Destinations	Bostanlı	Alsancak Gar	Halkapınar	Constraint (kW/h)
Bus	Fahrettin Altay	0.98	0.57	0.58	1860
Tramway	Fahrettin Altay	0.88	0.37	0.47	1860
Bus	Egekent	0.77	1.20	1.57	690
Tramway	Egekent	0.77	1.27	1.58	1820
Bus	Mavişehir	0.30	0.98	1.28	690
Tramway	Mavişehir	0.37	0.85	1.23	1820
	Constraint (kW/h)	1860	1860	1860	

Table 12 presents minimum energy consumption according to the constraints. Variable cells reflect optimum routes to minimize energy consumption. Optimum routes are Bus 1- from Fahrettin Altay to Halkapınar; Tramway 1- from Fahrettin Altay to Alsancak Gar; and Bus 3 and Tramway 3- from Mavişehir to Bostanlı. Green cells refer to the sum of energy consumption in variable cells. The objective function represents the sum of multiplying kW/h and time in these locations. It gives us the minimum total energy consumption through optimum choices. At 2403 kW/h, minimum energy consumption is seen when these optimum routes are used.

Table 12: Optimization of Minimum Energy Consumption for Transportation Modes

Origins	Destinations	Bostanlı	Alsancak Gar	Halkapınar	Constraint (kW/h)	Sign	Constraint (kW/h)
Bus 1	Fahrettin Altay	0	0	1860	1860	<=	1860
Tramway 1	Fahrettin Altay	0	1860	0	1860	<=	1860
Bus 2	Egekent	0	0	0	0	<=	690
Tramway 2	Egekent	0	0	0	0	<=	1820
Bus 3	Mavişehir	690	0	0	690	<=	690
Tramway 3	Mavişehir	1170	0	0	1170	<=	1820
	Constraint (kW/h)	1860	1860	1860			
	Sign	=	=	=			
	Constraint (kW/h)	1860	1860	1860			
	Objective Function	**2403**					

The second optimization was applied to define optimal route (path) lengths through speeds and travel time (Table 13). The route length varies according to the lines of public transportation modes. Public transportation modes highly affect travel time according to their speeds which are constraint, number of stations, headways, and frequencies. Finding minimum route length provides minimization of energy consumption. Constraints are speed (V). The formula of speed is V=x/t. x refers to the path taken (kilometer), and t refers to the time (hour). The speed (V) is defined as the km/h unit. The tramway works at 40 km/h, and the bus works at 50 km/h. The average of both modes is 45 km/h. Therefore, 45 km/h was accepted for integrated routes. 50 km/h was accepted for bus routes. Table 13 presents the travel time (hour) for each route. To find the optimum route in line with speed, the formula of x=V*t was used.

Table 13: Travel Time and Speed of Transportation Modes

Modes	Origins / Destinations	Bostanlı	Alsancak Gar	Halkapınar	Constraint (km/h)
Bus	**Fahrettin Altay**	0.98	0.57	0.58	50
Tramway	**Fahrettin Altay**	0.88	0.37	0.47	45
Bus	**Egekent**	0.77	1.20	1.57	50
Tramway	**Egekent**	0.77	1.27	1.58	45
Bus	**Mavişehir**	0.30	0.98	1.28	50
Tramway	**Mavişehir**	0.37	0.85	1.23	45
	Constraint (km/h)	45	45	45	

Optimum routes are Bus 1- from Fahrettin Altay to Halkapınar; Tramway 1- from Fahrettin Altay to Alsancak Gar; Bus 3- from Mavişehir to Bostanlı. The objective function is calculated by using the formulation of the sum-product of optimum cells in the variable cells area (Table 14) and travel time, which is related to these cells in Table 13, as the multiplication of speed and time gives the length of the path. That means the objective function is the sum of minimum path lengths.

Table 14: Optimization of Minimum Path Length for Transportation Modes

Origins	Destinations	Bostanlı	Alsancak Gar	Halkapınar	Constraint (km/h)	Sign	Constraint (km/h)
Bus 1	Fahrettin Altay	0	0	45	45	<=	50
Tramway 1	Fahrettin Altay	0	45	0	45	<=	45
Bus 2	Egekent	0	0	0	0	<=	50
Tramway 2	Egekent	0	0	0	0	<=	45
Bus 3	Mavişehir	45	0	0	45	<=	50
Tramway 3	Mavişehir	0	0	0	0	<=	45
	Constraint (km/h)	45	45	45			
	Sign	=	=	=			
	Constraint (km/h)	45	45	45			
	Objective Function	**56**					

The third optimization was applied to minimize passenger costs (fares). In other words, the result of optimization will give operators the minimum revenue because of the minimum fares. Constraints are passenger volume (per/day). Passenger volume can be estimated through adjustments of service capacity like the number of stations, length of runs, variation in headways, and number of vehicles in TU [2]. In literature, average passenger volume (P_{av}) is computed [2] by dividing on the line the total passenger km by line length (L) (6).

$$\text{Average Passenger Volume} = P_{av} = \frac{\sum_{i=1}^{n} pi*li}{L} \; [2] \qquad (6)$$

P: total number of passengers (prs/h)

p: number of passengers (prs/h)

L: line length (km)

l: interstation distance or spacing (km)

In the study, data set about boarding on the public transportation in 2022 were used to compute passenger volume [39]. Data set, which are used, shows daily passenger demand on public transport for 7 months. Therefore, the data set was reduced to the average of a month and then the average monthly passenger demand was calculated. These data were segregated according to transportation modes (Table 15).

Table 15: Passenger Demand in Public Transportation Modes

Public Transportation Modes	Eshot	İzban	İzdeniz	İzulaş	Metro	Tramvay Karşıyaka	Tramvay Konak	Total Demand
Number of Passengers who get on public transport	705619	204502	38030	171172	237577	23352	59767	1440019

Bus mode has two transport firms as ESHOT and İZULAŞ. Total passenger volume in bus mode was divided number of bus lines, and thus average a bus line demand was found. For 5 bus lines selected in the study, demand was computed by multiplying 5 times (Table 16).

Table 16: Passenger Demand in Bus Mode

Eshot	İzulaş	Sum of Bus Demands	Number of Bus Lines	Average a Bus Line Demand	Demand of Selected 5 Bus Lines
705619	171172	876791	380	2307	11537

For sea transportation, Fahrettin Altay-Halkapınar Line has 6 ferry docks, and Karşıyaka-Bostanlı Line has 2 ferry docks (Table 17). This information was used as ratio for estimation of passenger demand for each line. Table 17 shows passenger demand for İZDENİZ mode for both Fahrettin Altay-Halkapınar Line and Karşıyaka-Bostanlı Line according to their number of ferry docks.

Table 17: Passenger Demand for İZDENİZ

Routes	İzdeniz	Number of Ferry Docks	Average a Ferry Dock Demand	Demand for İzdeniz
Total	38030	8	4754	
Line between Fahrettin Altay-Halkapınar		6		28522
Line between Karşıyaka-Bostanlı		2		9507

The table below denotes total public transport demand. Passenger volume was calculated in accordance with mode options like bus, tram, metro, İZBAN and İZDENİZ in these lines (Table 18).

Table 18: Passenger Volume

Routes \ Modes	Bus	Tramvay Konak	Metro	İzban	İzdeniz	Total Public Transport Demand
Fahrettin Altay-Halkapınar	11537	59767	237577	204502	28522	**541906**
		Tramvay Karşıyaka				
Karşıyaka-Bostanlı	11537	23352		204502	9507	**248898**

Table 19 shows daily passenger volume on routes, and the matrix defines passenger cost computed according to number of transfers (TL). Considering passenger volume on lines constraints were determined. Mavişehir destination has less passenger volume relatively. Because of that, its constraint was assumed as 240000 (Table 19).

Table 19: Passenger Costs (Fares) and Passenger Volume of Transportation Modes

Modes	Origins \ Destinations	Bostanlı	Alsancak Gar	Halkapınar	Constraint (per/day)
Bus	Fahrettin Altay	12.28	8.78	12.28	541906
Tramway	Fahrettin Altay	14.28	8.78	8.78	541906
Bus	Egekent	8.78	12.28	12.28	248898
Tramway	Egekent	8.78	14.28	14.28	248898
Bus	Mavişehir	8.78	12.28	12.28	240000
Tramway	Mavişehir	8.78	12.28	12.28	240000
	Constraint (per/day)	248898	541906	541906	

Table 20 shows optimum routes for minimum passenger cost. The values in variable cells refer to optimum passenger volume for minimum fares. Multiplication of passenger volume and fares, which are in the above table, gives minimum fares for each route. The sum of these gives an objective function. Namely, for operators, minimum revenue can be found by using the minimum passenger cost. Optimum routes are Bus 1- from Fahrettin Altay to Alsancak Gar; Tramway 1- from Fahrettin Altay to Halkapınar; Bus 2- from Egekent to Bostanlı.

Table 20: Optimization of Minimum Passenger Costs (Fares) for Transportation Modes

Origins	Destinations	Bostanlı	Alsancak Gar	Halkapınar	Constraint (per/day)	Sign	Constraint (per/day)
Bus 1	Fahrettin Altay	0	541906	0	541906	<=	541906
Tramway 1	Fahrettin Altay	0	0	541906	541906	<=	541906
Bus 2	Egekent	248898	0	0	248898	<=	248898
Tramway 2	Egekent	0	0	0	0	<=	248898
Bus 3	Mavişehir	0	0	0	0	<=	240000
Tramway 3	Mavişehir	0	0	0	0	<=	240000
	Constraint (per/day)	248898	541906	541906			
	Sign	=	=	=			
	Constraint (per/day)	248898	541906	541906			
	Objective Function	11701189					

4.2 Sensitivity analysis by solver tool

Sensitivity analyses took place in the Solver Tool of the data analysis software. The solver sensitivity outputs are located below (Table 23-24-25). The variables part of the table denotes the range of optimality. Namely, adding the allowable increase value to the objective coefficient gives us an upper limit, whereas subtracting the allowable decrease value from the objective coefficient gives us a lower limit. Interpreting the constraints part of the table means a range of feasibility. Similar to defining the range of optimality, the range of feasibility is found according to allowable increase and allowable decrease. The upper limit is calculated by adding an allowable increase value to the constraint right-hand side. The lower limit is found by subtracting the allowable decrease value from the constraint right-hand side. The shadow price shows the increase or decrease value for each unit. Also, the shadow price determines critical constraints. It is calculated according to the differentiation between decision variables of optimal solutions and their constraint values. Solver sensitivity reports in the study were evaluated according to the constraints and their feasibility.

Solver sensitivity analysis of minimum energy consumption is seen in Table 21. Objective coefficient values refer to travel time (hour). Also, the shadow time in this analysis is denoted as one hour unit. Shadow time shows a change value for each unit. For Bus 1- from Fahrettin Altay to Halkapınar and Tramway 3- from Mavişehir to Bostanlı, the shadow time is not effective because it is 0. Their allowable increases are infinity. Allowable decrease of Bus 1- from Fahrettin Altay to Halkapınar is 0. Therefore, the lower limit does not change. Allowable decrease of Tramway 3- from Mavişehir to Bostanlı is 650 kW/h. Tramway 1- from Fahrettin Altay to Alsancak Gar is the most critical constraint because shadow time on this route leads to the most significant change. For Bus 3- from Mavişehir to Bostanlı, the constraint right-hand side can raise to 1860 kW/h because the allowable increase is 1170 kW/h. Also, the constraint right-hand side can show a decrease of as much as 650 kW/h. Namely, the range of feasibility is between 40 and 1860 kW/h. In Tramway 3- from Mavişehir to Bostanlı, the final value is 1170 kW/h. Its constraint right-hand side is 1820 kW/h. Because of that, it can be changed by an allowable decrease of as far as 650 kW/h.

Table 21: Solver Sensitivity Analysis of Minimum Energy Consumption

Variable Cells

Cell	Name	Final Value	Reduced Time (h)	Objective Coefficient	Allowable Increase	Allowable Decrease
$N$32	Fahrettin Altay Bostanlı	0	0.62	0.98	Infinity	0.62
$O$32	Fahrettin Altay Alsancak Gar	0	0.00	0.57	0.28	0.08
$P$32	Fahrettin Altay Halkapınar	1860	0.00	0.58	0.08	Infinity
$N$33	Fahrettin Altay Bostanlı	0	0.72	0.88	Infinity	0.72
$O$33	Fahrettin Altay Alsancak Gar	1860	0.00	0.37	0.08	Infinity
$P$33	Fahrettin Altay Halkapınar	0	0.08	0.47	Infinity	0.08
$N$34	Egekent Bostanlı	0	0.40	0.77	Infinity	0.40
$O$34	Egekent Alsancak Gar	0	0.63	1.20	Infinity	0.63
$P$34	Egekent Halkapınar	0	0.98	1.57	Infinity	0.98
$N$35	Egekent Bostanlı	0	0.40	0.77	Infinity	0.40
$O$35	Egekent Alsancak Gar	0	0.70	1.27	Infinity	0.70
$P$35	Egekent Halkapınar	0	1.00	1.58	Infinity	1.00
$N$36	Mavişehir Bostanlı	690	0.00	0.30	0.07	Infinity
$O$36	Mavişehir Alsancak Gar	0	0.48	0.98	Infinity	0.48
$P$36	Mavişehir Halkapınar	0	0.77	1.28	Infinity	0.77
$N$37	Mavişehir Bostanlı	1170	0.00	0.37	0.40	0.07
$O$37	Mavişehir Alsancak Gar	0	0.28	0.85	Infinity	0.28
$P$37	Mavişehir Halkapınar	0	0.65	1.23	Infinity	0.65

Constraints

Cell	Name	Final Value	Shadow Time (h)	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$N$38	Constraint (kW/h) Bostanlı	1860	0.37	1860	650	1170
$O$38	Constraint (kW/h) Alsancak Gar	1860	0.57	1860	0	0
$P$38	Constraint (kW/h) Halkapınar	1860	0.58	1860	0	1860
$Q$32	Fahrettin Altay Constraint (kW/h)	1860	0.00	1860	Infinity	0
$Q$33	Fahrettin Altay Constraint (kW/h)	1860	-0.20	1860	0	0
$Q$34	Egekent Constraint (kW/h)	0	0.00	690	Infinity	690
$Q$35	Egekent Constraint (kW/h)	0	0.00	1820	Infinity	1820
$Q$36	Mavişehir Constraint (kW/h)	690	-0.07	690	1170	650
$Q$37	Mavişehir Constraint (kW/h)	1170	0.00	1820	Infinity	650

Solver sensitivity analysis of minimum path length is seen in Table 22. Objective coefficient values refer to travel time (hour). The shadow time also refers to hour unit because the decision variables of analysis are travel time. Bus 1- from Fahrettin Altay to Halkapınar; Tramway 1- from Fahrettin Altay to Alsancak Gar; Bus 3- from Mavişehir to Bostanlı are optimal routes. In Bus 1- from Fahrettin Altay to Halkapınar, the allowable decrease is 5 km/h. Tramway 1- from Fahrettin Altay to Alsancak Gar has the most determinative shadow time. Its shadow time is -0.20, and it has a 5 km/h allowable decrease. Thus, the lower limit becomes 40 km/h. That means the change value for each unit is 0.20 h. Namely, if speed decreases 1 km/h, travel time will increase 12 minutes. Bus 3- from Mavişehir to Bostanlı has the same range of feasibility as the first optimal route.

Table 22: Solver Sensitivity Analysis of Minimum Path Length

Variable Cells

Cell	Name	Final Value	Reduced Time (h)	Objective Coefficient	Allowable Increase	Allowable Decrease
$N$19	Fahrettin Altay Bostanlı	0	0.68	0.98	Infinity	0.68
$O$19	Fahrettin Altay Alsancak Gar	0	0.00	0.57	0.28	0.08
$P$19	Fahrettin Altay Halkapınar	45	0.00	0.58	0.08	Infinity
$N$20	Fahrettin Altay Bostanlı	0	0.78	0.88	Infinity	0.78
$O$20	Fahrettin Altay Alsancak Gar	45	0.00	0.37	0.08	Infinity
$P$20	Fahrettin Altay Halkapınar	0	0.08	0.47	Infinity	0.08
$N$21	Egekent Bostanlı	0	0.47	0.77	Infinity	0.47
$O$21	Egekent Alsancak Gar	0	0.63	1.20	Infinity	0.63
$P$21	Egekent Halkapınar	0	0.98	1.57	Infinity	0.98
$N$22	Egekent Bostanlı	0	0.47	0.77	Infinity	0.47
$O$22	Egekent Alsancak Gar	0	0.70	1.27	Infinity	0.70
$P$22	Egekent Halkapınar	0	1.00	1.58	Infinity	1.00
$N$23	Mavişehir Bostanlı	45	0.00	0.30	0.07	Infinity
$O$23	Mavişehir Alsancak Gar	0	0.42	0.98	Infinity	0.42
$P$23	Mavişehir Halkapınar	0	0.70	1.28	Infinity	0.70
$N$24	Mavişehir Bostanlı	0	0.07	0.37	Infinity	0.07
$O$24	Mavişehir Alsancak Gar	0	0.28	0.85	Infinity	0.28
$P$24	Mavişehir Halkapınar	0	0.65	1.23	Infinity	0.65

Constraints

Cell	Name	Final Value	Shadow Time (h)	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$N$25	Constraint (km/h) Bostanlı	45	0.30	45	5	45
$O$25	Constraint (km/h) Alsancak Gar	45	0.57	45	5	0
$P$25	Constraint (km/h) Halkapınar	45	0.58	45	5	45
$Q$19	Fahrettin Altay Constraint (km/h)	45	0.00	50	Infinity	5
$Q$20	Fahrettin Altay Constraint (km/h)	45	-0.20	45	0	5
$Q$21	Egekent Constraint (km/h)	0	0.00	50	Infinity	50
$Q$22	Egekent Constraint (km/h)	0	0.00	45	Infinity	45
$Q$23	Mavişehir Constraint (km/h)	45	0.00	50	Infinity	5
$Q$24	Mavişehir Constraint (km/h)	0	0.00	45	Infinity	45

Solver sensitivity analysis of minimum passenger costs (fares) is seen in Table 23. Objective coefficient values and shadow price values represent passenger costs (TL). For Bus 1- from Fahrettin Altay to Alsancak Gar, the final value is 541906 per/day. For Tramway 1- from Fahrettin Altay to Halkapınar, the final value is 541906 per/day, and it has a 240000 per/day allowable decrease value. Its shadow price is the most effective because fares 3.50 TL increase if constraint right-hand side decrease a unit. For Bus 2- from Egekent to Bostanlı, final value is 248898 per/day. Lastly, it has a 240000 per/day allowable decrease value.

Table 23: Solver Sensitivity Analysis of Minimum Passenger Costs (Fares)

Variable Cells

Cell	Name	Final Value	Reduced Cost (TL)	Objective Coefficient	Allowable Increase	Allowable Decrease
$D$13	Fahrettin Altay Bostanlı	0	3.50	12.28	Infinity	3.50
$E$13	Fahrettin Altay Alsancak Gar	541906	0.00	8.78	3.50	Infinity
$F$13	Fahrettin Altay Halkapınar	0	0.00	12.28	0.00	3.50
$D$14	Fahrettin Altay Bostanlı	0	9.00	14.28	Infinity	9.00
$E$14	Fahrettin Altay Alsancak Gar	0	3.50	8.78	Infinity	3.50
$F$14	Fahrettin Altay Halkapınar	541906	0.00	8.78	3.50	Infinity
$D$15	Egekent Bostanlı	248898	0.00	8.78	0.00	Infinity
$E$15	Egekent Alsancak Gar	0	3.50	12.28	Infinity	3.50
$F$15	Egekent Halkapınar	0	0.00	12.28	Infinity	0.00
$D$16	Egekent Bostanlı	0	0.00	8.78	Infinity	0.00
$E$16	Egekent Alsancak Gar	0	5.50	14.28	Infinity	5.50
$F$16	Egekent Halkapınar	0	2.00	14.28	Infinity	2.00
$D$17	Mavişehir Bostanlı	0	0.00	8.78	Infinity	0.00
$E$17	Mavişehir Alsancak Gar	0	3.50	12.28	Infinity	3.50
$F$17	Mavişehir Halkapınar	0	0.00	12.28	Infinity	0.00
$D$18	Mavişehir Bostanlı	0	0.00	8.78	0.00	0.00
$E$18	Mavişehir Alsancak Gar	0	3.50	12.28	Infinity	3.50
$F$18	Mavişehir Halkapınar	0	0.00	12.28	0.00	0.00

Constraints

Cell	Name	Final Value	Shadow Price (TL)	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$D$19	Constraint (per/day) Bostanlı	248898	8.78	248898	240000	0
$E$19	Constraint (per/day) Alsancak Gar	541906	8.78	541906	0	0
$F$19	Constraint (per/day) Halkapınar	541906	12.28	541906	240000	0
$G$13	Fahrettin Altay Constraint (per/day)	541906	0.00	541906	0	0
$G$14	Fahrettin Altay Constraint (per/day)	541906	-3.50	541906	0	240000
$G$15	Egekent Constraint (per/day)	248898	0.00	248898	0	240000
$G$16	Egekent Constraint (per/day)	0	0.00	248898	Infinity	248898
$G$17	Mavişehir Constraint (per/day)	0	0.00	240000	Infinity	240000
$G$18	Mavişehir Constraint (per/day)	0	0.00	240000	Infinity	240000

According to linear programming and solver sensitivity analysis, the final findings have put forward results below. Optimal routes are shown in Figure 10. For energy consumption, the optimum routes are as below:

- Bus 1- from Fahrettin Altay to Halkapınar
- Tramway 1- from Fahrettin Altay to Alsancak Gar
- Bus 3- from Mavişehir to Bostanlı
- Tramway 3- from Mavişehir to Bostanlı

In terms of energy consumption, the origins of Fahrettin Altay and Mavişehir have optimum routes. For the Mavişehir-Bostanlı route, both two options are optimum. When their sensitivity analyses are compared, Bus 3- from Mavişehir to Bostanlı offers the lowest final value for energy consumption.

For minimum path length, the optimum routes are as follows:

- Bus 1- from Fahrettin Altay to Halkapınar
- Tramway 1- from Fahrettin Altay to Alsancak Gar
- Bus 3- from Mavişehir to Bostanlı

The origins of Fahrettin Altay and Mavişehir have minimum path length. These origins reach different destinations. Findings show that bus mode offers more options than tramways. This result proves that travel time has been effective for results according to the formula of x=V*t despite the speed of 50 km/h bus has.

For minimum passenger cost, optimum routes are as below:

- Bus 1- from Fahrettin Altay to Alsancak Gar
- Tramway 1- from Fahrettin Altay to Halkapınar

- Bus 2- from Egekent to Bostanlı

The start points of Fahrettin Altay and Egekent are convenient in terms of minimum passenger costs. In the study, tramway options were generally used as the integrated by bus. Thus, passenger costs can increase due to the number of transfers. However, the tramway option has continuity in Fahrettin Altay-Halkapınar. Therefore, optimal routes have same fares.

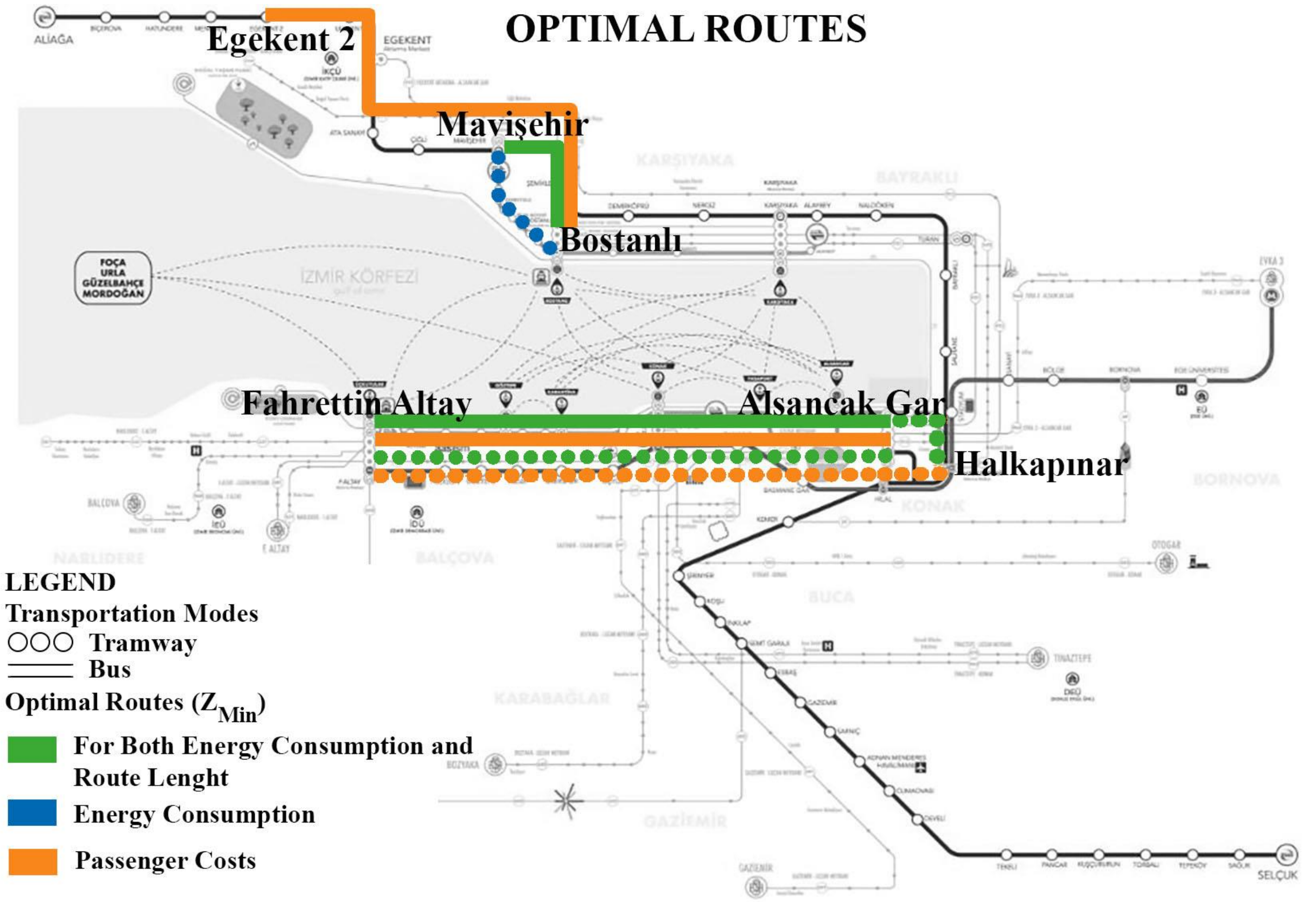

Figure 10: Optimal Routes

5 Conclusions

Energy efficiency in public transportation systems is very important for the sustainability and protection of the environment. Novel approaches are being developed in transportation systems with the newly arisen technologies as cures to the protection of nature and resources, such as electric buses, and light rail transit (LRT) which operates on electric power, etc. However, there might still be novel optimization approaches for the operations of the systems. This study focused on Izmir's public transportation problems in terms of energy consumption, travel time, and passenger cost. Also, the study is interested in route lengths in order to reduce energy consumption levels. Two transportation modes, the bus and the tramway, with paralleling routes, as complementary to each other, were compared and analysed to reach optimal solutions. Five bus lines and two tramway lines were used in forming the routes. The methods of the study are linear programming and sensitivity analysis. These methods were applied in the analysis tool called "Solver" within a commercial data analysis software.

For three transportation problems observed in Izmir, three optimizations were done to minimize energy consumption, route (path) length, and passenger cost (fare). Travel time was used as relevant decision variable for the minimization of energy consumption levels and route lengths. For the minimization of passenger costs, fares were used as decision variable.

Routes were evaluated through solver answer reports (See appendix table 25-26-27) and solver sensitivity analysis. As a result of the evaluation, some of the routes reach optimality for two optimizations. Briefly, Bus 1- from Fahrettin Altay to Halkapınar (integrated route); Tramway 1- from Fahrettin Altay to Alsancak Gar; Bus 3- from Mavişehir to Bostanlı are the most seen optimum routes since they are optimum in terms of both minimization of energy consumption and route length. In addition, Tramway 3- from Mavişehir to Bostanlı is optimal route for minimum energy consumption. Bus 1- from Fahrettin Altay to Alsancak Gar; Tramway 1- from Fahrettin Altay to Halkapınar and Bus 2- from Egekent to Bostanlı are optimal routes to minimize passenger cost. According to the gains obtained, although Bus 1- from Fahrettin Altay to Halkapınar (integrated route) is costly due to the transfers, it is preferable in terms of less energy consumption and path length. Also, Tramway 3 and Bus 3 from Mavişehir to Bostanlı present optimal solutions for minimization of energy consumption. Here, bus option is more energy-efficient because it has less travel time. Therefore, the results encourage passengers to select these routes and transportation modes to reduce energy consumption, travel time, and fares. Tramway, which is generally integrated by bus, solutions show that integrated transportation systems can also be the best solution for transportation problems.

In conclusion, linear programming and sensitivity analysis can be used in transportation problems to reduce energy consumption, excessive travel time, passenger cost, and path length. In other words, linear programming with such a simplistic approach can practically offer sort of time-saver solutions for transportation problems if the most basic data are gathered. In the study, some of the solutions offered are sometimes suitable for buses, sometimes for trams, and sometimes for integrated transit systems. We can say that on optimal routes, bus options are more dominant in terms of minimum route length and minimum passenger costs optimization. For energy consumption, optimal routes offer mode options in equal numbers. Briefly, linear programming provides many alternatives. Similarly, sensitivity analysis can ease the decision-making for both passengers and operators in the choice of transportation modes. In order to do that, the process proposed shows a wide range of optimality and feasibility. As a result, this study presents cost-effective and energy-efficient routes with their related transportation modes. The study contributes to the literature using the time matrix instead of the transport cost matrix. The travel time matrix can adapt to future optimization problems. Constraints and decision variable matrices should change according to the formula of the objective function offered. Thus, optimality and feasibility can be provided not only for fiscal aims but also for environmental and social aims. This study may lead to other future studies in achieving environmentally friendly transportation solutions.

6 Declaration of authors' contribution

All authors contributed to the study's conception and design. Conceptualization, methodology, formal analysis and investigation, writing - original draft preparation: [Author 1 and Author 2]; writing - review – editing, supervision: [Author 3]. All authors read and approved the final manuscript.

7 Declaration of ethics committee approval and conflict of interest

"The article does not necessitate a research ethics commitee approval".

"There is no conflict of interest issue with any person/institution throughout this paper work".

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9 Appendix

Table 24: Details of Travel Time for each Route in both Transportation Modes

Origins	Destinations	Bostanlı		Alsancak Gar		Halkapınar	
		Line No	Travel Time	Line No	Travel Time	Line No	Travel Time
Bus 1	**Fahrettin Altay**	681-921	20 min.+20 min. waiting+19 min.	681	20 min.+14 min. walking	681-T2	20 min.+4 min. waiting+11 min.
Tramway 1	**Fahrettin Altay**	T2-921-T1	22 min.+8 min. waiting+15 min.+8 min.	T2	22 min.	T2	28 min.
Bus 2	**Egekent 2**	428	46 min.	428-921	46 min.+7 min. waiting+19 min.	428-543	46 min.+21 min. waiting+27 min.
Tramway 2	**Egekent 2**	428	46 min.	428-T1-921	46 min.+7 min. waiting+8 min.+15 min.	428-T1-543	46 min.+7 min. waiting+8 min.+12 min. waiting+22 min.
Bus 3	**Mavişehir**	821	18 min.	821-921	18 min.+22 min. waiting+19 min.	821-543	18 min.+32 min. waiting+27 min.
Tramway 3	**Mavişehir**	T1	22 min.	T1-921	21 min.+15 min. waiting+15 min.	T1-543	22 min.+25 min. waiting+27 min.

Table 25: Solver Answer Report for Optimization of Minimum Energy Consumption

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$N$42	Objective Function =	0	2403

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$N$32	Fahrettin Altay Bostanlı	0	0	Contin
$O$32	Fahrettin Altay Alsancak Gar	0	0	Contin
$P$32	Fahrettin Altay Halkapınar	0	1860	Contin
$N$33	Fahrettin Altay Bostanlı	0	0	Contin
$O$33	Fahrettin Altay Alsancak Gar	0	1860	Contin
$P$33	Fahrettin Altay Halkapınar	0	0	Contin
$N$34	Egekent Bostanlı	0	0	Contin
$O$34	Egekent Alsancak Gar	0	0	Contin
$P$34	Egekent Halkapınar	0	0	Contin
$N$35	Egekent Bostanlı	0	0	Contin
$O$35	Egekent Alsancak Gar	0	0	Contin
$P$35	Egekent Halkapınar	0	0	Contin
$N$36	Mavişehir Bostanlı	0	690	Contin
$O$36	Mavişehir Alsancak Gar	0	0	Contin
$P$36	Mavişehir Halkapınar	0	0	Contin
$N$37	Mavişehir Bostanlı	0	1170	Contin
$O$37	Mavişehir Alsancak Gar	0	0	Contin
$P$37	Mavişehir Halkapınar	0	0	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$N$38	Constraint (kW/h) Bostanlı	1860	$N$38=$N$40	Binding	0
$O$38	Constraint (kW/h) Alsancak Gar	1860	$O$38=$O$40	Binding	0
$P$38	Constraint (kW/h) Halkapınar	1860	$P$38=$P$40	Binding	0
$Q$32	Fahrettin Altay Constraint (kW/h)	1860	$Q$32<=$S$32	Binding	0
$Q$33	Fahrettin Altay Constraint (kW/h)	1860	$Q$33<=$S$33	Binding	0
$Q$34	Egekent Constraint (kW/h)	0	$Q$34<=$S$34	Not Binding	690
$Q$35	Egekent Constraint (kW/h)	0	$Q$35<=$S$35	Not Binding	1820
$Q$36	Mavişehir Constraint (kW/h)	690	$Q$36<=$S$36	Binding	0
$Q$37	Mavişehir Constraint (kW/h)	1170	$Q$37<=$S$37	Not Binding	650

Table 26: Solver Answer Report for Optimization of Minimum Path Length

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$N$29	Objective Function =	0	56

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$N$19	Fahrettin Altay Bostanlı	0	0	Contin
$O$19	Fahrettin Altay Alsancak Gar	0	0	Contin
$P$19	Fahrettin Altay Halkapınar	0	45	Contin
$N$20	Fahrettin Altay Bostanlı	0	0	Contin
$O$20	Fahrettin Altay Alsancak Gar	0	45	Contin
$P$20	Fahrettin Altay Halkapınar	0	0	Contin
$N$21	Egekent Bostanlı	0	0	Contin
$O$21	Egekent Alsancak Gar	0	0	Contin
$P$21	Egekent Halkapınar	0	0	Contin
$N$22	Egekent Bostanlı	0	0	Contin
$O$22	Egekent Alsancak Gar	0	0	Contin
$P$22	Egekent Halkapınar	0	0	Contin
$N$23	Mavişehir Bostanlı	0	45	Contin
$O$23	Mavişehir Alsancak Gar	0	0	Contin
$P$23	Mavişehir Halkapınar	0	0	Contin
$N$24	Mavişehir Bostanlı	0	0	Contin
$O$24	Mavişehir Alsancak Gar	0	0	Contin
$P$24	Mavişehir Halkapınar	0	0	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$N$25	Constraint (km/h) Bostanlı	45	$N$25=$N$27	Binding	0
$O$25	Constraint (km/h) Alsancak Gar	45	$O$25=$O$27	Binding	0
$P$25	Constraint (km/h) Halkapınar	45	$P$25=$P$27	Binding	0
$Q$19	Fahrettin Altay Constraint (km/h)	45	$Q$19<=$S$19	Not Binding	5
$Q$20	Fahrettin Altay Constraint (km/h)	45	$Q$20<=$S$20	Binding	0
$Q$21	Egekent Constraint (km/h)	0	$Q$21<=$S$21	Not Binding	50
$Q$22	Egekent Constraint (km/h)	0	$Q$22<=$S$22	Not Binding	45
$Q$23	Mavişehir Constraint (km/h)	45	$Q$23<=$S$23	Not Binding	5
$Q$24	Mavişehir Constraint (km/h)	0	$Q$24<=$S$24	Not Binding	45

Table 27: Solver Answer Report for Optimization of Minimum Passenger Costs (Fares)

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$23	Objective Function =	0	11701189

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$D$13	Fahrettin Altay Bostanlı	0	0	Contin
$E$13	Fahrettin Altay Alsancak Gar	0	541906	Contin
$F$13	Fahrettin Altay Halkapınar	0	0	Contin
$D$14	Fahrettin Altay Bostanlı	0	0	Contin
$E$14	Fahrettin Altay Alsancak Gar	0	0	Contin
$F$14	Fahrettin Altay Halkapınar	0	541906	Contin
$D$15	Egekent Bostanlı	0	248898	Contin
$E$15	Egekent Alsancak Gar	0	0	Contin
$F$15	Egekent Halkapınar	0	0	Contin
$D$16	Egekent Bostanlı	0	0	Contin
$E$16	Egekent Alsancak Gar	0	0	Contin
$F$16	Egekent Halkapınar	0	0	Contin
$D$17	Mavişehir Bostanlı	0	0	Contin
$E$17	Mavişehir Alsancak Gar	0	0	Contin
$F$17	Mavişehir Halkapınar	0	0	Contin
$D$18	Mavişehir Bostanlı	0	0	Contin
$E$18	Mavişehir Alsancak Gar	0	0	Contin
$F$18	Mavişehir Halkapınar	0	0	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$D$19	Constraint (per/day) Bostanlı	248898	$D$19=$D$21	Binding	0
$E$19	Constraint (per/day) Alsancak Gar	541906	$E$19=$E$21	Binding	0
$F$19	Constraint (per/day) Halkapınar	541906	$F$19=$F$21	Binding	0
$G$13	Fahrettin Altay Constraint (per/day)	541906	$G$13<=$I$13	Binding	0
$G$14	Fahrettin Altay Constraint (per/day)	541906	$G$14<=$I$14	Binding	0
$G$15	Egekent Constraint (per/day)	248898	$G$15<=$I$15	Binding	0
$G$16	Egekent Constraint (per/day)	0	$G$16<=$I$16	Not Binding	248898
$G$17	Mavişehir Constraint (per/day)	0	$G$17<=$I$17	Not Binding	240000
$G$18	Mavişehir Constraint (per/day)	0	$G$18<=$I$18	Not Binding	240000