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Intelligent Urban Mobility and Traffic Management: A Case Study of Smart Intersection Implementation and E-Mobility Integration in Trabzon, Türkiye

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Abstract: In response to escalating urban traffic congestion, environmental degradation, and mobility inefficiencies, intelligent transportation systems (ITS) and sustainable mobility strategies have been increasingly recognised as vital components of smart city development. In this study, the city of Trabzon, Türkiye, was examined as a representative urban environment facing such challenges. Six major intersections exhibiting persistent traffic congestion were selected for conversion from conventional fixed-time signal control to adaptive, traffic-actuated signalisation systems. Detailed performance evaluations were conducted, incorporating microsimulation modelling and real-time traffic flow analysis. The implementation of adaptive signalisation was found to significantly reduce vehicular delay, queue lengths, and intersection-level emissions, while enhancing operational efficiency and traffic safety. A complementary analysis assessed the economic and environmental impacts of this intervention, revealing considerable annual savings in fuel consumption and marked reductions in carbon dioxide (CO_2) emissions, thereby underscoring the long-term sustainability and cost-effectiveness of the proposed system. In parallel, the integration of electric vehicles (EVs) and micromobility solutions—including electric buses, minibuses, passenger cars, bicycles, and scooters—was proposed to further promote sustainable urban mobility. Strategic placement of EV charging infrastructure was suggested, with spatial planning informed by expected demand distribution and intermodal connectivity. Economic modelling demonstrated a reduction in operational fuel expenditure, while environmental projections indicated a substantial decrease in transport-related greenhouse gas emissions. Furthermore, micromobility modes were proposed as critical for addressing first- and last-mile connectivity gaps, mitigating short-distance vehicular traffic, and alleviating urban parking demand. Policy recommendations emphasised the necessity of strong municipal leadership in facilitating infrastructure deployment, public adoption, and behavioural shifts towards low-emission transport alternatives. The findings position Trabzon as a viable model for medium-sized urban centres seeking to implement scalable and replicable smart mobility frameworks. By integrating adaptive traffic control with zero-emission mobility, this study provides actionable insights into the design of efficient, economically viable, and environmentally sustainable urban transportation ecosystems.

Keywords: Intelligent transportation systems (ITS); Urban mobility; Adaptive signalisation; Electric vehicles (EVs); Charging infrastructure; Micromobility; Sustainable urban development; Smart cities

1 Introduction

As the population of urban areas increases in number and density, the number of vehicles on the roads is also increasing. In addition, the increase in individuals' purchasing power and expectation of comfort has increased the number of private vehicles on the roads, while the social isolation and transmission risk associated with the COVID-19 pandemic has led people to turn to private vehicles [1]. This habit continues to this day. The increase in the number of vehicles brings traffic chaos and various difficulties in traffic management. In particular, effective planning is needed at intersections, where different traffic flows from different directions converge. Intersections can be categorised as either level or different-level depending on how traffic flows from different directions intersect [2]. Road sections where traffic moving in different directions intersect, with vehicles directed by traffic signs, are called uncontrolled intersections [3]. At intersections with high vehicle density, signalling systems are used to manage the intersection more safely and efficiently by eliminating conflicts. These intersections are called controlled intersections, where the sequence of vehicles using the intersection is managed by signalling systems [4]. At controlled intersections, the intersection of different traffic flows is eliminated and traffic is made to pass in a sequence. Thus, traffic safety is increased [5]. Signalling systems can be classified into four main categories: fixed-time, traffic-activated, pedestrian-activated and manually controlled [6]. In fixed-time systems, the phase order and green times for different directions are predetermined, as is the operating order. Given the changes in directional density at different times of day, different fixed times can be defined for different periods. Traffic warning signalling systems operate in a way that changes the phase order, leg-based green times and cycle time depending on the number of vehicles in the intersection legs. The number of vehicles in the legs is determined by cameras or detectors. In pedestrian-activated signalling systems, the signalling is set up according to the pedestrian's request. In manually controlled signalling systems, the signalling is regulated manually based on observations.

Nowadays, fixed-time traffic signals are more widely used than traffic-actuated signals because they are easier to implement and cheaper. However, traffic-actuated systems are becoming increasingly widespread, particularly in metropolitan areas and at busy city intersections. Fixed-time signalling systems operate with predetermined time assignments and are generally unable to adapt to changing traffic conditions. This results in increased traffic, especially during peak hours. In adaptive signalling systems, the aim is to ensure intersection operation with minimum delay and queue length and to maintain traffic flow by analysing real-time traffic density data to determine signal duration and phase plan. This approach can improve delay time, defined as the total time lost by a vehicle due to environmental effects, and queue length, defined as the total length of vehicles stopped due to red lights at signalised intersections. In addition to improving delay time and queue length, the aim is to reduce fuel consumption and minimise the negative environmental impact of fossil fuels accordingly. Adaptive traffic control systems improve traffic conditions by increasing lane capacity and travelling speed. Consequently, they reduce delays, the number of stops, queue lengths, fuel consumption and emissions resulting from fuel consumption. Effective intersection management also reduces the probability of accidents [7].

With adaptive signalling systems, traffic flow continuity can be ensured, reducing engine noise and brake sounds by decreasing the number of vehicle stops and starts, thereby reducing noise pollution. In addition, these systems can quickly adapt to unexpected traffic conditions, such as traffic accidents, social events (concerts, matches, etc.) and maintenance and repair works, and efficiently manage intersections. However, the higher cost of adaptive systems compared to fixed-term signalling systems due to infrastructure requirements has a slowing effect on their widespread adoption. An effective intersection management plan clearly contributes to environmentally friendly and sustainable transport. Alongside this planning approach, using zero-emission EVs to eliminate the negative effects of fossil fuels also contributes greatly to environmentally friendly and sustainable transport. To this end, electric alternatives have emerged in both public and private vehicles in recent years. Furthermore, micromobility solutions are becoming widespread due to traffic congestion and transport costs in urban areas.

In addition to international brands, electric cars have become widespread on the roads thanks to the domestic car brand TOGG. The incentives provided for electric cars and their low maintenance costs have been effective in this regard. As EVs become more widespread, infrastructure investments to meet their charging needs are also increasing. The aim of this is to reduce car consumers' concerns about running out of charge and being stranded on the road, and to encourage them to adopt electric vehicle technologies [8]. The lack of electric vehicle charging stations and the time taken for charging limit the use of EVs [9]. The widespread use of fast charging stations is an important factor in popularising EVs [10]. Many brands have made charging more accessible by installing charging units in shopping malls, urban recreation areas, public service buildings (especially hospitals and universities) and fuel stations. Ease of access to charging also positively affects the purchase and use of EVs. Additionally, electric public transport vehicles have also increased remarkably in recent years, especially in metropolises. This development is supported by policies and financed by national and international projects. The routes for electric public transport vehicles are determined by balancing performance with fuel consumption, and special charging stations are installed at the start and end stops. In Türkiye, many studies have been carried out on zero-emission sustainable public transport, particularly by local administrations. However, analysis of the number of public transport vehicles purchased by the public and private sectors, as well as the number in the inventory, shows that although the number of electric buses has increased rapidly in recent years, they remain at very low levels compared to fossil fuel vehicles. This is thought to be due to the high initial purchase cost of electric buses compared to fossil-fuelled buses, as well as uncertainties regarding their use [11–13]. Although electric public transport vehicles remain in the minority, the transport authorities' vision to transition from fossil fuel vehicles to electric, zero-emission vehicles is notable. The fact that charging times are shortening year on year thanks to developing charging technology will also help to make electric public transport vehicles more widespread in the future.

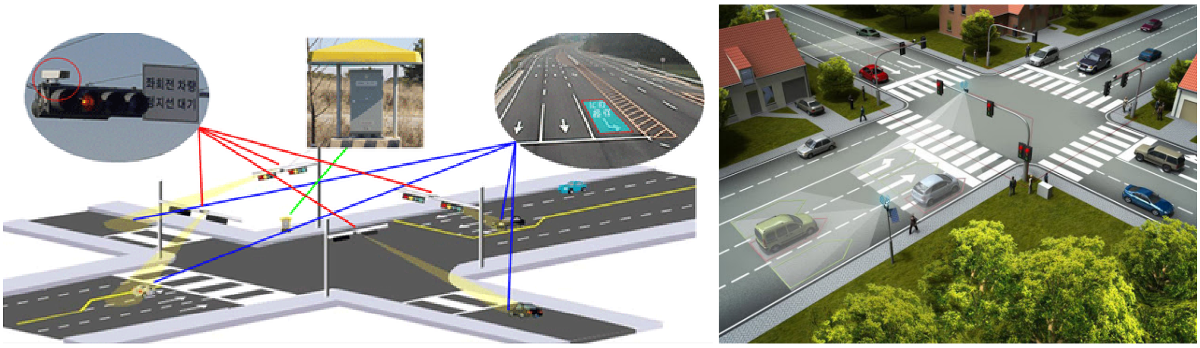
Micromobility refers to lightweight, mostly EVs used for short-distance travel. Electric scooters and shared bicycles are the main examples of micromobility vehicles. Micromobility solutions can provide an effective alternative for short journeys, offering a more environmentally friendly, economical and faster option than individual vehicles and public transport. The increasing popularity of micromobility systems can be attributed to the growing number of car-sharing systems, their affordability for short distances, their low susceptibility to traffic congestion and the perception that these systems are environmentally friendly [14]. Micromobility can facilitate access to public transport, increase mobility, reduce the need for car parking, reduce the number of vehicles on the road and reduce stops, thereby solving the first and last kilometre problem of public transport [15, 16]. Thanks to their ability to navigate heavy traffic more quickly than other vehicles, micromobility vehicles can make urban transport more efficient and facilitate integration with public transport systems [17]. However, the widespread use of micromobility vehicles may also lead to irregular parking [18]. Furthermore, the lack of appropriate infrastructure and legal regulations may result in negative situations in terms of traffic safety [19]. This study addresses traffic-activated signalling systems, electric bus and minibus applications, and micromobility solutions that could be implemented in Trabzon. Implementing the recommendations could reduce delay times and queue lengths at intersections, providing more efficient intersection management. Additionally, the use of EVs in public transport will create a more environmentally friendly transport infrastructure. The implementation of micromobility solutions will provide users with an efficient option for short-distance travel.

2 Intelligent Signalized Intersection Applications and E-Vehicle Utilization

In order for Trabzon to have the status of a smart city in terms of transportation characteristics and to offer mobility solutions, the systems that need to be implemented in the first place are examined under the titles of 'Signalised Intersections with Traffic Alert' and 'Electric Vehicles and Charging Stations', which are detailed below. Trabzon was selected as a pilot city from the research conducted within the scope of the study. To this end, the city's transport potential and the characteristics of its public transport vehicles were examined in detail. Thus, effective solution proposals that can improve traffic flow performance and micromobility in urban transport have been developed, taking into account economic costs and benefits.

2.1 Traffic Actuated (Intelligent) Signalized Intersections

Level and pedestrian crossings are controlled by signal lights at the intersection legs to control vehicle and pedestrian flows, increase safety, and ensure traffic moves in an orderly fashion. However, fixed-time signalisation systems may lose their effectiveness over time as the number of vehicles approaching the intersection increases. Dysfunction of the signalling system at intersections can cause long queues at the intersection and its branches and, consequently, accidents due to undisciplined driver behaviour. In addition to traffic accidents, long interruptions and delays to traffic flow can be seen due to chaos and queuing at intersections. This not only causes delays, but also increases fossil fuel consumption and transportation costs, triggering exhaust emissions and air pollution [20, 21].



(a) (b)

Figure 1. Examples of traffic-activated intersections (a) camera [22] and (b) traffic density detection with road surface sensors [23]

In recent years, technological developments have led to the creation of signal management systems such as Vehicle Excitation and Green Wave. These systems are designed to control delays at signalised intersections caused by signal durations. One of the most prominent of these systems is the dynamic signal system, which is one of the most effective. In Türkiye, intersections where such systems are applied are generally referred to as 'smart intersections' [24]. These intersections are also known as 'adaptive intersections', 'dynamic intersections', 'intersections with cameras', 'intersections with sensors', 'smart traffic management systems' or 'fully adaptive traffic management systems'. In summary, these are intersections where the times allocated to each direction change dynamically after vehicle density is determined using vehicle counting cameras or sensors at signalised intersections. In these systems, signal durations are automatically determined according to the instantaneous need by means of sensors that detect both main and secondary road vehicle flows, within the framework of pre-prepared signal plans (Figure 1).

These systems are defined as ‘actuated’ or ‘traffic-actuated’ in the literature, and are widely used in many countries, from Europe to the USA. Given the importance of ITS in Türkiye in recent years, traffic-actuated systems developed by many local technology companies have begun to be used effectively in the operation of signalised intersections in the General Directorate of Highways in Türkiye and in more than 50 cities (Figure 2).

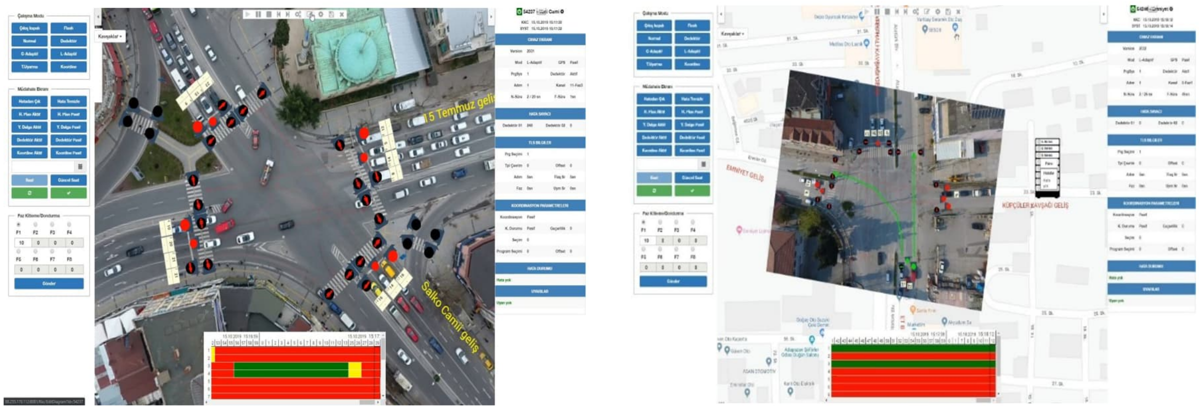


Figure 2. Example images of software used in the operation of traffic signalized intersections [25]

The basic logic of these systems is to adjust the length of the green phase at the intersection legs according to the number of vehicles (demand) at the intersection. In such systems, vehicle density at the intersection can be determined using cameras that cover all intersection legs and the intersection itself, or using a sensor that provides speed and volume data. This sensor is installed in the road pavement under the asphalt to create a magnetic field. In other words, these are systems in which the duration of the green light is automatically determined according to vehicle density. At normal signalised intersections, vehicles are manually counted for each hour of the day, and the optimal green times are determined and uploaded to the intersection control device. Since the times are fixed in these systems, they do not change with changes in vehicle density. In smart intersection applications, however, the green times change according to density, thereby minimising waiting times at the intersection. Reducing the waiting time for vehicles at intersections saves time and reduces environmental damage by saving fuel and reducing emissions. In Türkiye, applications show that ‘smart intersections’ reduce waiting times by an average of 20% to 35% (depending on the intersection’s structure and capacity, this can vary between 3% and 50%) [26]. Existing literature shows that the number of traffic accidents at these intersections decreases by between 10% and 25% [25]. The number and density of vehicles at the intersection legs can be obtained using two different methods. The first method involves processing images obtained with the help of a camera. The second method involves collecting data on the number of vehicles passing over the road using sensors (usually air-pressurised tubes) placed on the road surface (Figure 1). The most widely used technique in Türkiye is determining the number and density of vehicles with camera number one. The equipment required for each intersection in smart intersection applications designed using this technique is as follows:

‘Vehicle Counting Camera’ (smart camera): up to four directions.

• Smart Intersection Management Module
• Intersection Monitoring Camera
• Smart Intersection Controller
• Smart Intersection Centre Software
• Camera poles, cables, routers, etc.

The steps to turn a signalized intersection into a smart intersection are as follows:

• If there is no fiber line to transfer the information at the intersection to the center, 1 4G data line should be purchased for each intersection.

• Camera poles at least 8 meters high should be erected for each direction, and a 220 V power cable should be installed on each camera pole to provide energy to the cameras.

• For data transfer, 1 CAT6 Ethernet cable should be installed on each camera pole.

• After the infrastructure and cabling works are completed, vehicle counting cameras, intersection monitoring camera, and smart intersection management modules should be installed.

• Commissioning should be completed with calibration and final controls.

2.2 EVs and Charging Stations

In recent years, many vehicle manufacturers, including those producing cars, buses, minibuses and tractors, have placed great importance on producing EVs as well as fossil fuel vehicles (such as cars, buses, motorcycles and bicycles) due to global warming and increasing fuel costs [27]. As automobiles are the most widely used type of vehicle for transportation, manufacturers have started to develop and market hybrid or electric versions due to their fuel-saving and environmentally friendly features. In fact, Tesla, which specialises in the direct production of EVs, has captured the electric vehicle market in a very short time and has become a pioneer in this field. Today, it is developing effectively to become the leader in the electric vehicle category as a whole, having recently started to produce electric trucks and SUVs. According to the 'Long-Term Electric Vehicle Outlook Report' published by the research company Bloomberg NEF (BNEF) in 2020 (Figure 3), it is predicted that electric cars will constitute approximately 60% of the global passenger car market by 2040 [28].

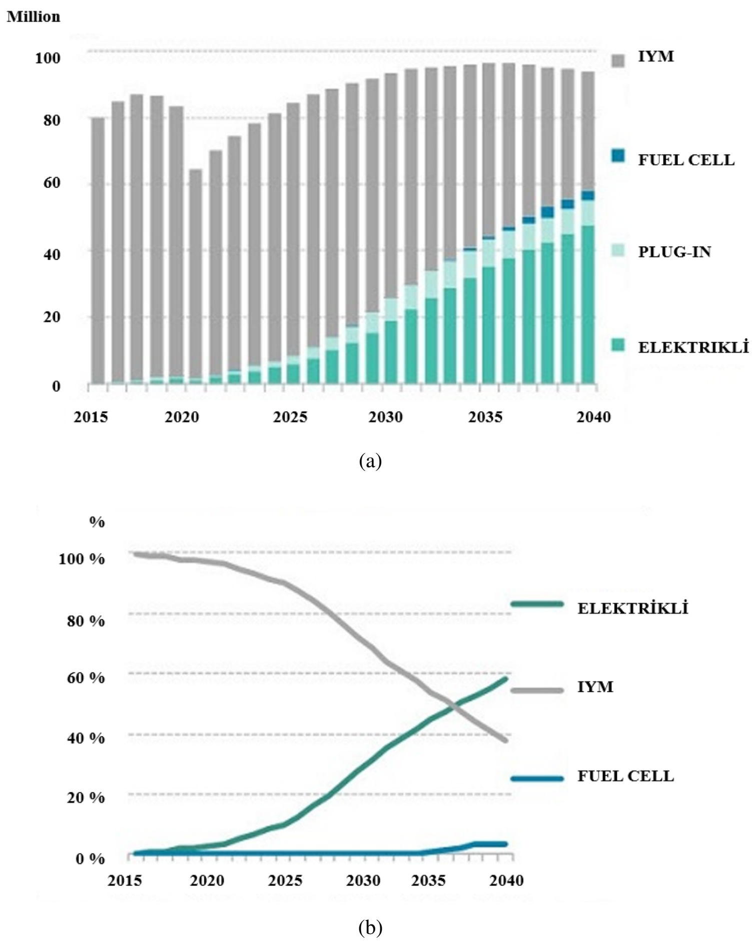


Figure 3. Change in the electric vehicle market by years (a) number of vehicles and (b) percentage distribution [28, 29]

Research results show that electric cars and other EVs, such as electric buses, minibuses, bicycles, scooters, mopeds, tractors and trucks, will soon become an integral part of our transport system and an important component of urban mobility. In line with these developments in Türkiye's electric vehicle market, the Türkiye Automobile Initiative Group (TOGG) was established in 2018 with the aim of becoming a major player in the future electric car and charging station market. Similarly, many vehicle manufacturers operating in Türkiye are involved in developing, producing and installing electric minibuses (e.g. Karsan), buses (e.g. Bozankaya, Temsa and BMC), bicycles (e.g. Volta, Salcano and Ümit), scooters (e.g. Volta and Martı) and tractors (Ministry of Agriculture and Forestry), as well as the required charging stations (Figure 4).

All this information suggests that Türkiye is set to become a key player in every aspect of EVs and charging stations, from design to manufacturing, within a very short timeframe. The key issue here is the adoption and effective use of these environmentally friendly, fuel-efficient vehicles by society. As is well known, the key issue with all EVs is their battery range and the availability of charging stations at accessible locations. According to research conducted by TEHAD (2020), as of May 2020, there were approximately 800 electric and plug-in hybrid charging stations in 61

Turkish cities (Figure 5). The study found that there are 3 electric car charging stations within the borders of Trabzon province (this number may vary according to updates).

(a)

(b)

(c)

(d)

(e)

(f)

Figure 4. Examples of EVs produced in Türkiye (a) e-car [30], (b) e-minibus [31], (c) e-tractor [32], (d) e-bike [33] (e) e-bus [34] and (f) e-scooter [35]

Figure 5. Map of available electric and plug-in hybrid charging stations in Türkiye for 2020 [29]

A significant need for charging stations is expected to emerge in Türkiye due to the widespread use of electric cars and other EVs. In recent years, many countries have begun conducting research into charging stations due to the increasing popularity of electric cars. In Türkiye, studies on the number and location of charging stations are currently being conducted based on the assumption that cities with registered fully electric cars are mostly big cities and that their routes are variable (not clearly defined). In a city like Trabzon, which attracts many local and foreign tourists from various cities for tourism purposes, it is challenging to anticipate the charging station requirements of electric car users who arrive in Trabzon with EVs or pass through the city on international routes. Nevertheless, it is crucial to address this need.

It is an undeniable fact that the use of EVs will increase significantly in Trabzon in a very short time. This city attaches importance to global warming, develops projects on this issue and is visited by millions of local and foreign tourists. It also has a high vehicle ownership rate of 24.2% [36]. Unfortunately, most transportation activities in Trabzon, which is renowned for its natural beauty and tourist attractions, are carried out by car. As a tourist city, a place where the Silk Road connects to the Black Sea, and with the port of Trabzon growing every year, as well as being located on the Black Sea coastal road and on the route connecting many countries and cities to Türkiye, and as an important tourist centre with its natural and historical attractions, Trabzon is expected to play a significant role in the electric car market. In the European Union's action plan to reduce air pollution and global warming caused by fossil fuel emissions, the widespread use of EVs and electricity generation from renewable sources is crucial. In this context, many EU countries have declared their intention to switch to the use of fully EVs in the next few decades. In Türkiye, the aim is to have one million electric cars on the roads by 2030, particularly through the mass production of domestic electric cars. One million charging stations are also planned [37]. Therefore, it is important for countries to announce their intention to switch to EVs, and to create a perception among users in cities that EVs will become widespread in the future. This can be achieved through exemplary projects carried out in this regard. Creating a positive perception of the importance and future of electric vehicle use, especially through exemplary projects carried out at important and busy locations in Trabzon, is crucial for users to quickly adopt and effectively utilise these systems in the future. Municipalities play an important role in the effective use and promotion of EVs, particularly electric cars, and their charging stations. With the financial support provided to different cities in many countries through the European Union's Horizon 2020 programme, municipalities are encouraged to set an example for citizens in using EVs and installing charging stations, and to take a leading role in planning and implementation. For Trabzon, a city that continues to develop by producing projects in line with the European Union's vision, being a pioneer in the planning and use of EVs and charging stations will be very important in terms of recognition and prominence in European Union-supported projects. Unfortunately, Türkiye has few studies and practices on issues such as electric vehicle use, charging station installation and operation, urban mobility, and short-distance intermodal access in public transport (micromobility), all of which are important to the European Union. Consequently, studies on this subject will establish Trabzon as a leader in ITS and urban micromobility, contributing significantly to its development as a smart city (Figure 6).

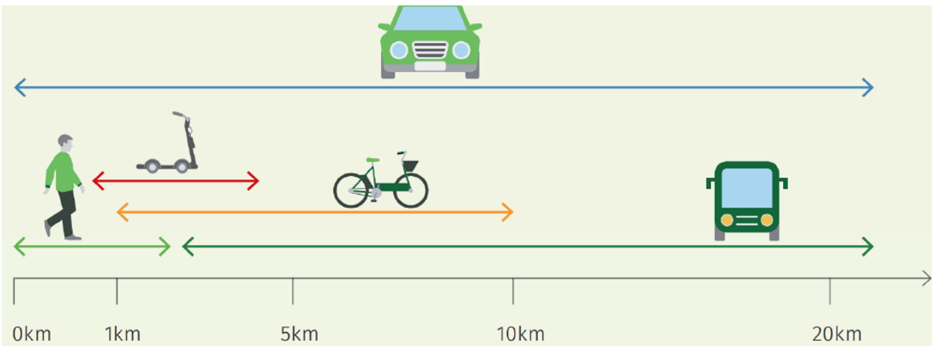


Figure 6. The relationship between transport modes and distance for micromobility in urban transport [38]

As EVs and their infrastructure develop, Trabzon will become a pioneering city in intelligent transportation and mobility, enabling it to develop rapidly. With the knowledge and benefits to be gained, more projects can be developed with support from domestic and foreign sources, and more knowledge and experience will be gained in developing solutions to the city's transportation problems. Therefore, this research has developed recommendations for the use of EVs and their charging stations to increase urban mobility through EVs. The study proposes electric versions of the most commonly used vehicles in Trabzon: cars, buses and minibuses (public transport), bicycles and scooters (tourism and short-distance travel), and road routes that can be used effectively in the initial phase.

3 Transformation of Signalized Intersections into Smart Intersections

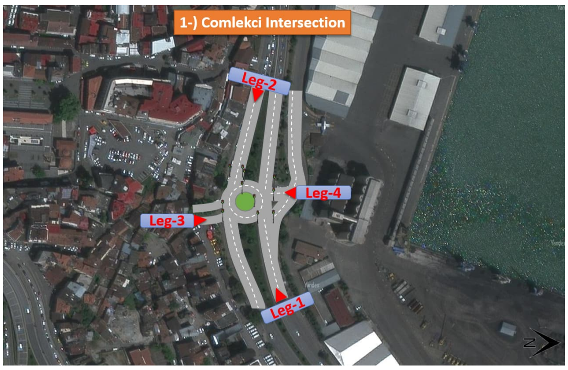
3.1 Technical Analysis for Transformation

Within the scope of the study, the intersections in Trabzon's central districts, where traffic density is high, were examined based on their congestion, delays and queuing conditions. Six intersections that require conversion to traffic-signalised intersections were identified. Field observations made at these intersections during peak hours (07:30–08:30 and 16:30–18:30) revealed the traffic volumes at the intersection arms and the service level of the intersections, as shown in Table 1.

Table 1. Traffic flow characteristics of the 6 problematic intersections

Intersection No.	Intersection Name	Volume (veh/hr) Leg-1	Leg-2	Leg-3	Leg-4	Control Delay (veh/sec)	Level of Service (A–F)
1	Comlekci	1980	2982	62	189	65	F
2	Macka	1052	1015	1101	–	72	F
3	Bus Terminal	1089	985	431	–	64	F
4	Hackalibaba	1203	1328	756	298	60	F
5	Trabzon University	1567	1395	352	–	55	E
6	Trabzon Fire Brigade	864	745	530	943	45	D

According to the obtained data, it was determined that the service levels at the intersections vary within the D–F range, according to the average control delay values specified in the 2010 Highway Capacity Manual [39]. Based on these results, it was concluded that implementing traffic-actuated intersection systems, or 'smart intersections', would be beneficial in order to prevent or reduce average control delays and queuing at these intersections. Based on the service levels and field observations obtained from the analyses, the intersections are ranked in order of importance for smart intersection transformation, as shown in Table 1. According to this ranking, the first intersection to be converted is the Comlekci intersection in front of the port, and the last is the Fire Brigade intersection. Figures 7-11 show schematic and actual images of the intersections in order of importance for transformation and in order of intersection leg.

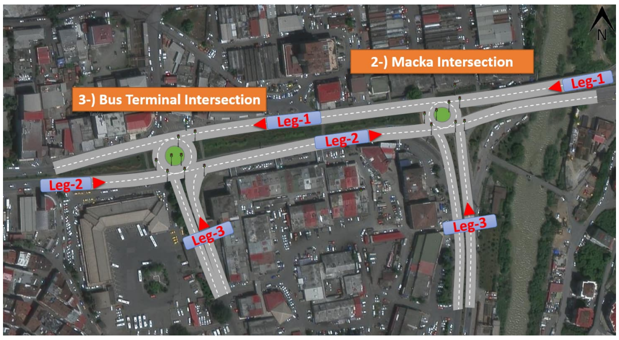


(a)

(b)

Figure 7. (a) Schematic and (b) field visual of Comlekci intersection

Note: This figure was prepared by the authors



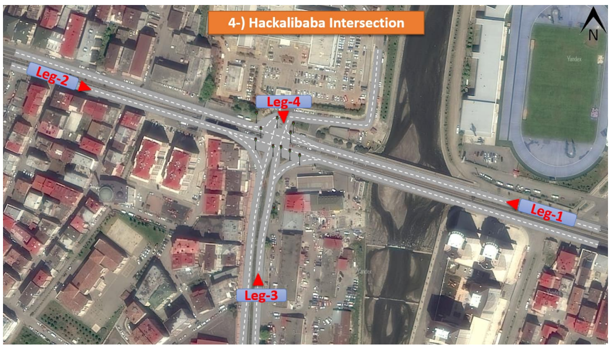
(a)

(b)

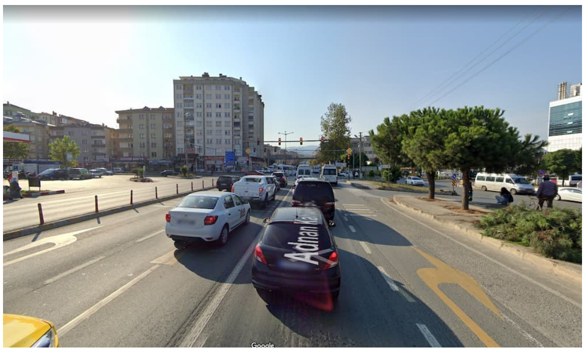
(c)

Figure 8. (a) Schematic of Macka and Bus Terminal intersection, (b) field visuals of Macka and (c) Terminal intersection

Note: This figure was prepared by the authors



(a)



(b)

Figure 9. (a) Schematic and (b) field visual of Akcaabat Hackalibaba State Hospital intersection

Note: This figure was prepared by the authors

Field investigations have revealed that the Comlekci intersection in front of Trabzon Port, suggested for transformation into a smart intersection, is heavily used by vehicles accessing the port. It has been determined that this frequent use causes significant losses in the intersection's safety and operational performance. To address this issue, the proposal includes the addition of an extra gate and a new road route adjacent to the car park in front of the port. This route would enable heavy vehicles to enter and exit the port. Figure 12 illustrates this proposed route.

With the proposed new gate and entrance/exit route to the port, heavy vehicles will be able to wait in the car park. When it is their turn, they can enter the port to unload or pick up their cargo, then continue on their way without causing traffic chaos. This will prevent unnecessary heavy vehicle traffic on the Black Sea coastal road in front of the port. Significant reductions will be achieved, especially in the number of heavy vehicles using the Comlekci junction. This will improve both junction safety and performance. Alongside the opening of this alternative route and gate, improvements to the existing car park will contribute significantly to the port's growth and operational performance.

(a) (b)

Figure 10. (a) Schematic and (b) field visual of Trabzon University intersection
Note: This figure was prepared by the authors

(a) (b)

Figure 11. (a) Schematic and (b) field visual of Trabzon Fire Brigade intersection
Note: This figure was prepared by the authors

Figure 12. Alternative entry and exit gates and routes to Trabzon Port were suggested
Note: This figure was prepared by the authors

3.2 The Economic Costs and Benefits of Transformation

A market research study was carried out within the scope of the project to investigate the transformation of signalised intersections into smart intersections (intersections with traffic warnings). It was determined that the price range varies between 80,000.00 TL and 100,000.00 TL, depending on factors such as the number of intersections and system quality. For the economic analyses, an average installation cost of 90,000.00 TL per intersection was used (Table 2). According to the results of the analyses, the total installation and maintenance cost for the first year, including installation and one year of maintenance, was calculated as 594,000.00 TL.

Table 2. Calculated installation cost for the proposed intersections

Intersection No.	Intersection Name	Average Installation Cost (TL)	Yearly Average Maintenance Cost (TL)	Total Cost (TL)
1	Comlekci	90,000.00	9,000.00	594,000.00
2	Macka	90,000.00	9,000.00	
3	Bus Terminal	90,000.00	9,000.00	
4	Hackalibaba	90,000.00	9,000.00	
5	Trabzon University	90,000.00	9,000.00	
6	Trabzon Fire Brigade	90,000.00	9,000.00	

In order to calculate the total benefit (economic and exhaust emission), 'daily fuel consumption savings' given in Eq. (1) and 'daily carbon emission gain' given in Eq. (2) were used.

$$\alpha = \frac{AADT \times \theta \times \omega}{360} \times [(x_1 * y_1) + (x_2 * y_2) + (x_3 * y_3)] \tag{1}$$

In this equation:
α: Daily fuel consumption savings (TL/day),
$AADT$: Annual average daily traffic (vehicles/day),
θ: Waiting time improvement per vehicle (sec/vehicle),
ω: Standby fuel consumption per vehicle (lt/h),
x_1: Proportion of vehicles with gasoline as fuel type,
x_2: Proportion of vehicles whose fuel type is diesel,
x_3: Proportion of vehicles fuelled by LPG,
y_1: Gasoline price fiyatı (TL/liter),
y_2: Diesel price (TL/liter),
y_3: LPG price (TL/liter).

$$\beta = \frac{AADT \times \theta \times \tau}{60 \times 10^6} \tag{2}$$

In this equation:
β: Daily carbon emission emission gain (tonnes/day),
$AADT$: Annual average daily traffic (vehicles/day),
θ: Waiting time improvement per vehicle (sec/vehicle),
τ: Carbon emission value during waiting time per vehicle (gr/min).
To be used in both equations, firstly the post-improvement delay (waiting) values given in Table 3 were calculated.

Table 3. Expected average improvement after smart intersection installation and post-improvement delay (wait) values (sec)

Intersection No.	Intersection Name	Control Delay (veh/sec)	Average Delay Improvement for 30% (sec)	Delay after Improvement (sec)
1	Comlekci	65	15.5	49.5
2	Macka	72	21.6	50.4
3	Bus Terminal	64	19.2	44.8
4	Hackalibaba	60	18.0	42.0
5	Trabzon University	55	16.5	38.5
6	Trabzon Fire Brigade	45	13.5	31.5

To be used in the analyses, the KGM's 2019 annual average daily traffic (AADT) values for intersections 1, 2, 3, 4 and 5, and the average daily traffic (ADT) values for intersection 6, were determined using the observation values [40]. Using data from the Turkish Statistical Institute for 2020, the composition of fuel types of vehicles likely to pass through these intersections was determined, as was the number of AADT vehicles according to these ratios (Table 4) [41].

Table 4. AADT values for recommended intersections by fuel type

Intersection No.	Intersection Name	Annual Average Daily Vehicle Number	Vehicle Composition (%)		
			Gasoline (37%)	Diesel (25%)	LPG (38%)
1	Comlekci	75383	27892	18846	28646
2	Macka	36450	13487	9113	13851
3	Bus Terminal	32118	11884	8030	12205
4	Hackalibaba	53523	19804	13381	20339
5	Trabzon University	54218	20061	13555	20603
6	Trabzon Fire Brigade	11384	4212	2846	4326

The analyses took into consideration the average prices of Türkiye Petrolleri Anonim Ortaklığı A.Ş. for 2020. The analyses used fuel costs of 6.84 TL/litre for petrol, 6.22 TL/litre for diesel and 3.64 TL/litre for LPG [42]. The average fuel consumption value of the vehicles during waiting time was set at 0.9 l/h, with CO_2 emissions set at 25 g/min [43, 44]. The results obtained from the analyses regarding the daily and annual economic benefits and CO_2 gas emission reductions are given in Table 5.

Table 5. Economic and carbon emission gains obtained with smart intersection solutions

Intersection No.	Intersection Name	Fuel Consumption Saving		Carbon Emission Saving	
		TL/day	TL/year	tonne/day	tonne/year
1	Comlekci	1,597.54	583,103.85	0.49	177.70
2	Macka	1,076.42	392,909.09	0.33	119.74
3	Bus Terminal	843.14	307,744.66	0.26	93.78
4	Hackalibaba	1,317.23	480,788.14	0.40	146.52
5	Trabzon University	1,223.14	446,445.28	0.37	136.05
6	Trabzon Fire Brigade	210.12	76,695.42	0.06	23.37
Total Saving (Σ)		6,267.59	2,287,686.45	1.91	697.17

Analysis of Table 5 predicts that, by the end of the first year of smart system installation at intersections, the national economy will benefit to the tune of approximately four times the sum of the initial installation and operating costs. Additionally, it is determined that there will be an undeniable reduction in carbon emissions thanks to these intersections. The results show that all of the proposed intersections are feasible. It is clear that they will provide a range of benefits, from economic to environmental. In addition to these benefits, implementing these intersections will significantly contribute to Trabzon's goal of becoming a smart city with smart intersection applications. The spread of such applications will be an important driving force for R&D studies on smart transport in Türkiye.

4 Electric Vehicle Usage and Charging Station Installation

4.1 Electric Cars and Charging Stations

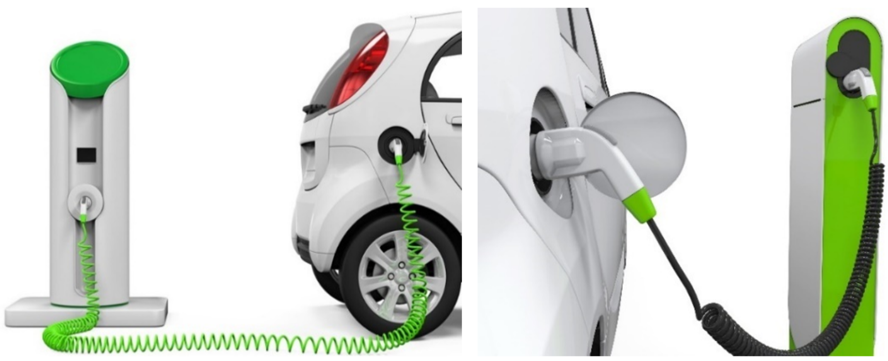


Figure 13. An example image of EVs and charging stations [45]

Unfortunately, the use of electric cars and charging stations in Türkiye is not yet where it should be. It is an undeniable fact that EVs, which have seen significant development in recent years, will replace fossil-fuelled cars in the future. Municipalities have a significant role to play in the effective and widespread adoption of EVs. Many

European municipalities are carrying out major projects supported by the European Union to promote the use of all types of EVs and prepare the necessary infrastructure. Some Türkiye cities are also carrying out projects in this regard (e.g. Antalya). In this context, it is important that Trabzon, one of the most dynamic and forward-thinking cities in Türkiye, is a pioneer in this area. To this end, establishing an electric car fleet within Trabzon Metropolitan Municipality is crucial. Using electric cars instead of fossil-fuelled cars for field missions will raise awareness among municipality staff and the city about fuel consumption, environmental benefits, and, most importantly, e-car use (Figure 13).

Similar applications have been implemented in many European cities, with positive feedback received. In this context, it is recommended that an e-car fleet of 22 EVs (one for each department) be created for the 22 different departments within Trabzon Metropolitan Municipality. Using electric cars at Trabzon Metropolitan Municipality, where the city's practitioners are located, will contribute to the development of effective projects and inform future decisions regarding the increase in the number of these cars. Many projects carried out today (e.g., European Union Horizon 2020 Programme, Smart Cities and Communities (SCC-1-2017) Match-Up Project [46]) have determined that four charging stations for 22 vehicles would be sufficient, taking into account the initial phase's requirement of one charging station for every five vehicles. A total of 20 e-car charging stations (four for municipal vehicles and 16 for city users) are proposed for installation throughout the city, bearing in mind that other vehicles will also use electric cars. The locations of these 20 charging stations were determined by evaluating traffic density and parking facilities throughout the city, as shown in Figure 14.

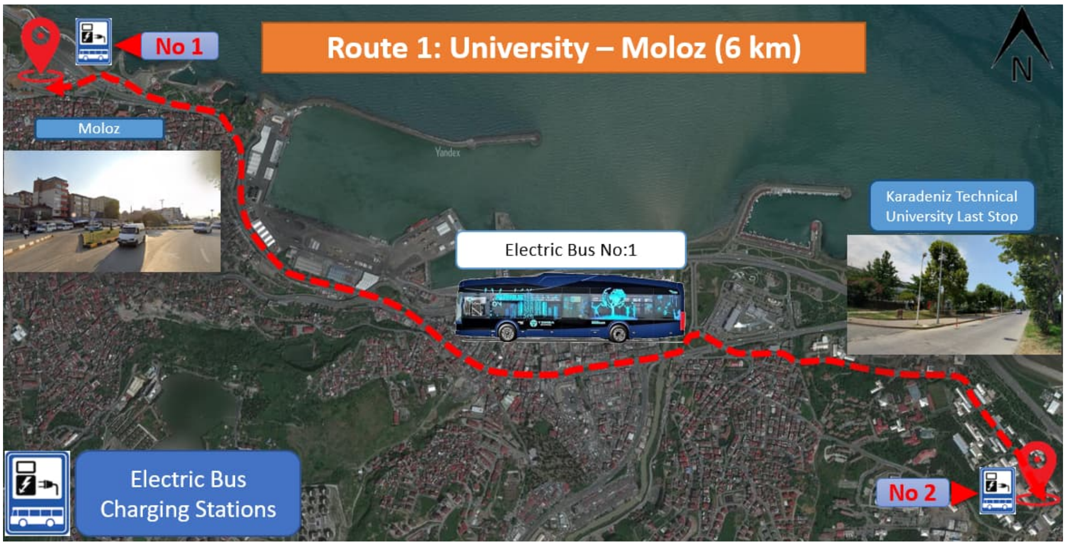
Figure 14. Suggested locations for electric vehicle charging stations in Trabzon

Note: This figure was prepared by the authors

4.2 Electric Buses, Minibuses and Charging Stations

Public transport in Trabzon largely consists of buses and minibuses. For this reason, the transition to EVs is important not only for cars, but also for these two types of public transport. Unfortunately, Trabzon's mountainous terrain has a negative effect on electric buses and minibuses. With current battery technology, EVs are not effective on long uphill routes. Therefore, until battery technology advances and charging stations become widespread, using electric buses and minibuses on flat routes will greatly improve performance. The main purpose of this study is to ensure that the introduction of electric buses and minibuses to Trabzon province, where they are currently absent, is planned and spreads quickly and effectively through awareness-raising. Since electric buses are expensive, they can be used effectively on main routes in the initial phase, which will help them to be accepted by society and create a positive perception. To this end, three different routes have been proposed for three different electric buses (Figure 15). According to the buses' charging status on these routes, four different charging stations have been proposed so that the buses can be charged when needed.

Three different routes and three charging stations were proposed for three electric minibuses to raise awareness of the conversion of minibuses to EVs. Minibuses play an important role in Trabzon's public transport network and are widely used by the city's residents (Figure 16). Within the scope of the study, electric bus and minibus routes were proposed on frequently travelled routes that attract the attention of potential passengers and city dwellers alike. It is important for the city to become familiar with these electric public transport vehicles and to develop a positive attitude towards them.



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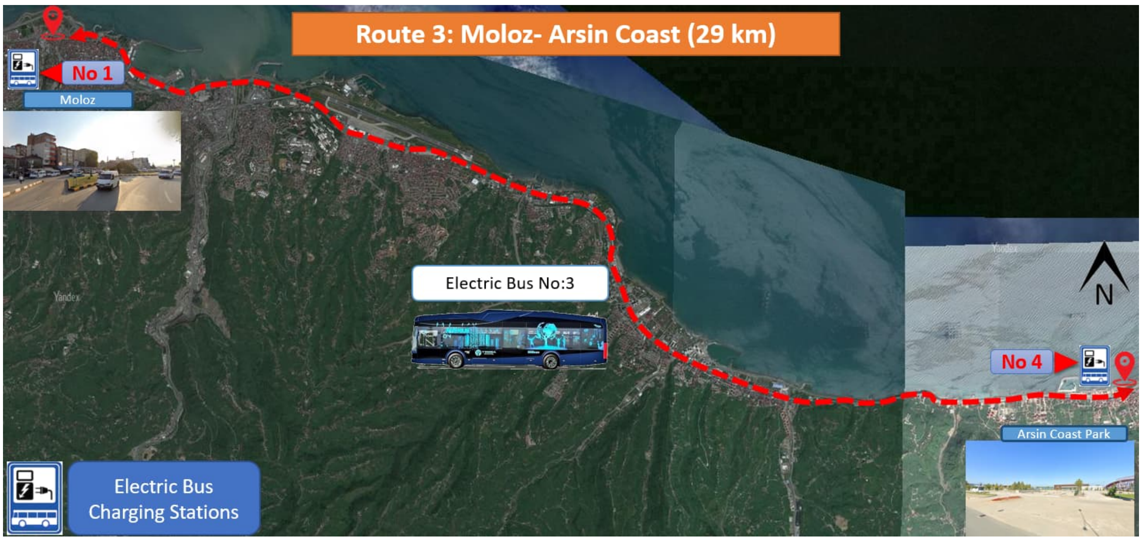
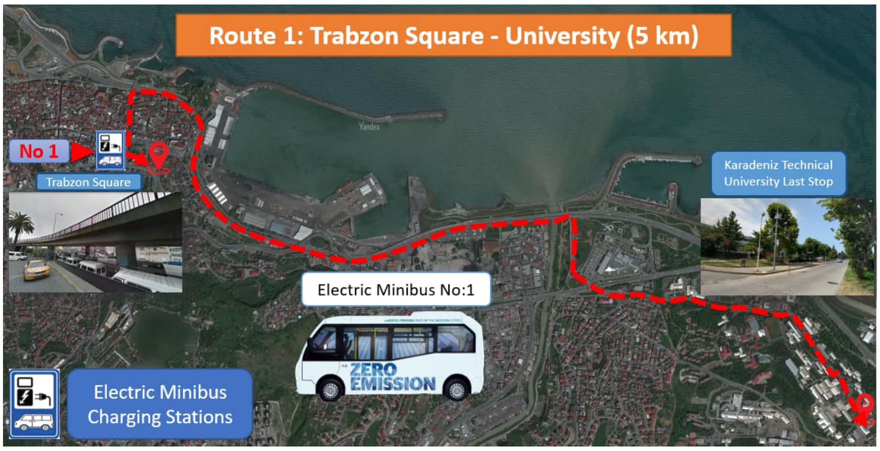


(c)

Figure 15. Suggested routes for electric buses are (a) 1, (b) 2 and (c) 3

Note: This figure was prepared by the authors



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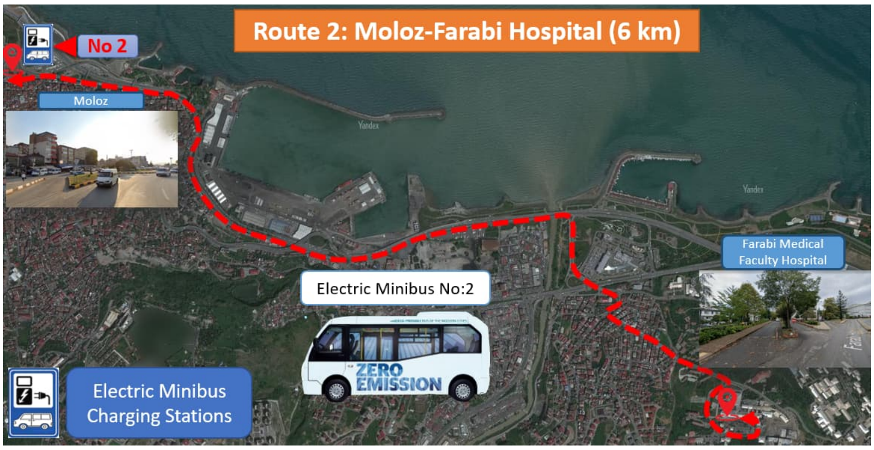

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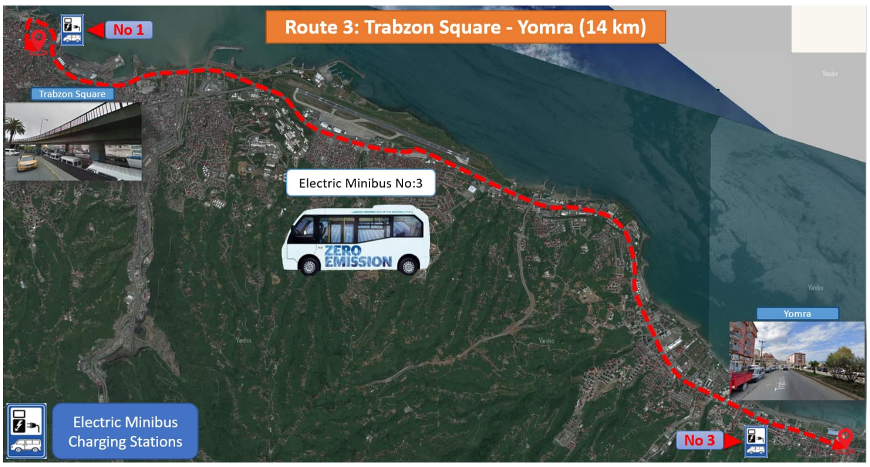


(c)

Figure 16. Suggested routes for electric minibuses are (a) 1, (b) 2 and (c) 3
Note: This figure was prepared by the authors

4.3 Electric Buses, Minibuses and Charging Stations

Due to its location on the Black Sea coast, Trabzon city has significant potential for tourism and transport activities along the coast. Beşirli Beach, located in the city centre, is a popular walking and sightseeing destination for both local and international visitors. For this reason, there is significant potential for the use of bicycles and scooters. Currently, there is heavy use of the existing 8 km of bicycle paths with Trabis or users' own bicycles. The widespread use of e-bikes and e-scooters in recent years shows that these vehicles can be used effectively in coastal cities with cycle paths. In many cities around the world, such as London, Washington, Copenhagen and Barcelona, the use of e-bikes and e-scooters has become widespread due to their ease of use and the opportunity to travel without consuming energy. They have started to replace existing non-electric bicycles and scooters. These types of e-bikes and e-scooters are actively used to connect to public transport stops and for short distances between modes. They can provide micromobility in public transport systems (Figure 12). With the increased recognition and effective use of these two types of electric vehicle, it is an undeniable fact that they will play an important role in providing micromobility in Trabzon's public transport system. In the current situation, the careless and non-compliant use of e-scooters on all types of roads makes it mandatory to use them on cycle paths for the time being. To control the use of e-scooters and e-bicycles, the Ministry of Transport and Infrastructure is preparing a regulation, but there is no finalised regulation yet. For this reason, this study proposes a total of 35 e-bikes and 15 charging stations for them, as well as 65 e-scooters and 19 charging stations for them, on two different routes along existing and proposed cycle paths. The first of these routes is the 9 km Besirli coastal route, which includes an 8 km cycle path (Figure 17).

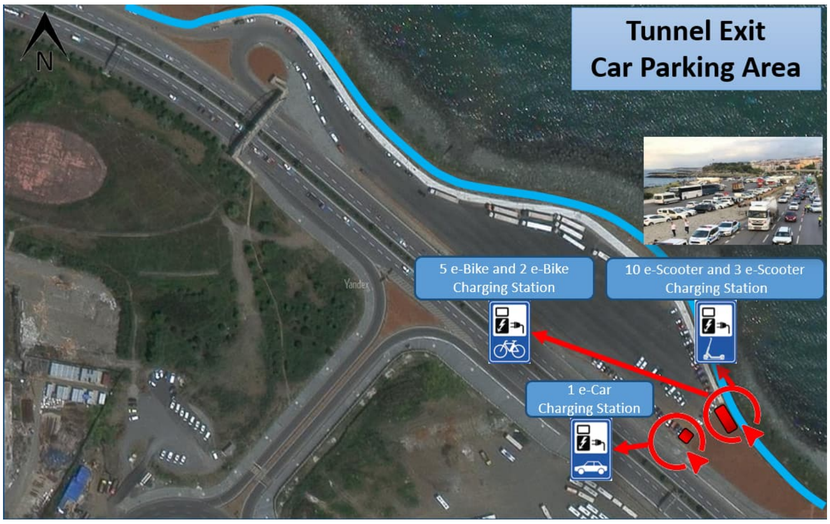
Figure 17. Suggested route number 1 for e-bikes and e-scooters
Note: This figure was prepared by the authors

Route 1 in Figure 17 begins at the car park by the tunnel exit and ends at the Şenol Güneş Sports Complex. Anyone wanting to visit the coastal area, access important attractions (such as the Ayasofya Mosque and Museum, the Dental Hospital and the Ecopark) or watch a Trabzonspor match can park their car in any suitable car park after exiting the tunnel and enjoy walking along the coast and commuting to the attractions and match venue comfortably, without getting stuck in traffic on match days. Thus, the proposed route provides a comfortable transport option, eliminating the need to search for a parking space. In addition, the issuance of the regulation on the circulation of e-scooters in the city will enable the coastal area to be connected to the city centre via new e-scooter and e-bike routes. The new car parks to be built in the coastal area will facilitate the Park & Ride scheme, providing car-free access to the city centre. Therefore, the disadvantage of the city centre being higher than the coast can be offset by the electric power of e-bikes and e-scooters, making access to the centre with these vehicles attractive. Figure 18 shows the detailed view of the start, end and intermediate station points on route number 1, as proposed within the scope of this study, together with the number of EVs and charging stations.

The route number 2 proposed within the scope of the study is the Akçaabat coastal area, the route of which is shown on Figure 19.

Although there is high pedestrian mobility on this coastal section, which is as active as the Besirli coast, unfortunately, there is no long-distance cycle path for e-bikes and e-scooters. Within the scope of this study, it is proposed that a 3 km long cycle path be constructed along this route, starting in front of Hackalibaba State Hospital and ending in front of Akcaabat Municipality Fish Market, where pedestrian mobility and demand will be high. This will provide an environmentally friendly and economical means of transport between Akcaabat city centre and the state hospital. Additionally, this new route will provide easy access to the Sogutlu Athletics Stadium for those who wish to exercise.

This route will provide an alternative walking and sightseeing route along the coast, creating a new tourist attraction for Akçaabat, which is famous for its coastal restaurants, and further increasing the city's appeal. In future projects, this bicycle route will also be connected to the route on the Besirli coastal road, enabling direct transportation from the Ortahisar district to the Akçaabat district by e-bikes and e-scooters. Figure 20 shows the start and end points of route number 2, together with the number of EVs and charging stations.



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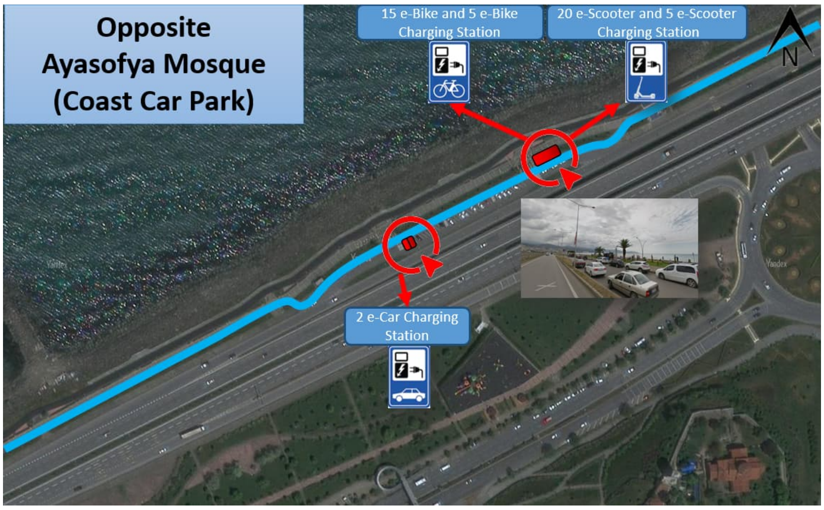

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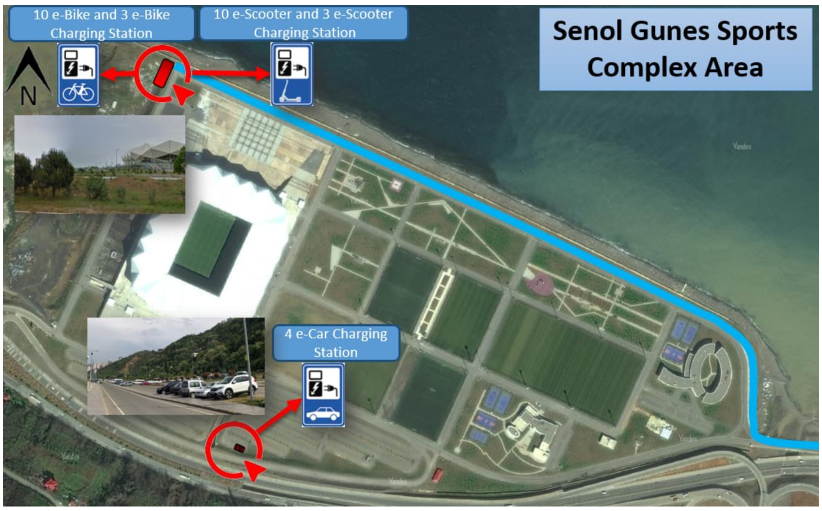

(c)

Figure 18. Route 1 (a) starting point (Tunnel exit car park) (b) intermediate station (opposite Ayasofya Mosque) and (c) end point (Akyazi stadium area)

Note: This figure was prepared by the authors

Figure 19. Suggested route number 2 for e-bikes and e-scooters

Note: This figure was prepared by the authors

(a)

(b)

Figure 20. Route number 2 (a) starting point (next to Haçkalıbaba State Hospital) and (b) end point (in front of Akcaabat Municipality Fish Market)

Note: This figure was prepared by the authors

5 Economic Costs and Benefits of EVs and Charging Stations

The study has involved cost and environmental impact analyses to demonstrate the economic and environmental effectiveness of all proposed EVs and charging stations. The results obtained are presented in the sections below. The parameter values used in the analyses were taken from sources that had conducted economic and environmental evaluations [47–63].

5.1 Economic Costs and Benefits for an Electric Car Fleet and Charging Stations Installation

As mentioned in previous sections, the study proposes creating an electric vehicle fleet of 22 e-cars for use by each department within Trabzon Metropolitan Municipality. Economic and environmental analyses have been conducted to determine the cost of the proposed B or C class e-car, which is frequently used for municipal works. The results are presented in Table 6. Table 6 also shows the total cost of the four e-charging stations proposed for the 22 electric cars in the municipal fleet, as well as the sixteen e-charging stations proposed for use by city residents and tourists. The total cost of purchasing the EVs and e-charging infrastructure is estimated at approximately 6 million TL.

Table 6. Total procurement cost of e-car and e-charging stations (TL)

Product Name	Unit Cost (TL)	Unit (Number)	Cost (TL)
e-Car	235,000.00	22	5,170,000.00
e-Car Charging Station	45,000.00	20	900,000.00
	Total (Σ)		6,070,000.00

If Trabzon Metropolitan Municipality were to cover an average daily distance of 100 km without purchasing any electric cars, but instead using cars in the same segment with normal diesel fuel, the fuel cost would be calculated as approximately 22 million TL per year. Using e-cars in the same segment instead of fossil-fuelled cars will reduce this expense to approximately 11 million TL, i.e., the fuel cost will be halved. Furthermore, the amount gained from fuel savings will more than cover the cost of the installed system in the first year (Table 7). Economic benefit analyses revealed that investing in electric cars is feasible for the municipality.

Table 7. Comparison of fuel costs of fossil fuelled and electric cars

Fuel Consumption Type	Vehicle Number (Pieces)	Average Daily Usage (km)	Fuel Consumption (per 100 km)	Unit Fuel Cost	Fuel Cost (TL)	
					Daily	Yearly ($\sim$ 264 work days)
Fossil Oil (Diesel)	22	100	6 lt	6.22 TL/lt	82,104.00	21,675,456.00
Electric	22	100	18 kwh	1.03 TL/kwh	40,788.00	10,768,032.00
		Difference (TL)			41,316.00	10,907,424.00

In addition to the economic benefits of e-cars, the study also obtained environmental benefits by comparing carbon dioxide emissions with those of fossil fuel vehicles. The results are given in Table 8.

Table 8. Environmental benefits of e-car use

Fuel Consumption Type	Vehicle Number (Pieces)	Average Daily Utilization (km)	CO_2 Emissions per km (gr)	CO_2 Emission (tonne)	
				Daily	Yearly ($\sim$ 264 work days)
Fossil Oil (Diesel)	22	100	130	0.286	75.50
Electric	22	100	86.7	0.191	50.42
	Difference (Tonne)			0.095	25.08

When Table 8 is examined in detail, it shows that the use of electric cars instead of fossil fuel (diesel) cars in the municipal vehicle fleet will reduce carbon emissions by approximately 25 tonnes per year (for 22 cars). This result shows that the use of e-cars will make a significant contribution not only economically but also environmentally, especially in terms of having an environmentalist municipality identity.

5.2 Economic Costs and Benefits for Electric Bus/Minibus Fleet and Charging Station Installation

Another innovative approach proposed within the scope of the study was on buses and minibuses, which are the main pillars of public transport in Trabzon province. Within the scope of the study, considering the existing electric bus and minibus battery technology, it was proposed to purchase 3 e-buses and 4 e-chargers for them and 3 e-minibuses and 3 e-charging stations to charge them. The total cost of purchasing all these EVs and their charging stations is given in Table 9.

Table 9. Total procurement cost of e-bus/e-minibus and e-charging stations (TL)

Vehicle Type	Product Name	Unit Cost (TL)	Unit (Pieces)	Cost (TL)
Bus	e-Bus	1,600,000.00	3	4,800,000.00
	e-Bus charging stations	170,000.00	4	680,000.00
Minibus	e-Minibus	373,800.00	3	1,121,400.00
	e-Minibus charging stations	95,000.00	3	285,000.00
	Total (Σ)			**6,886,400.00**

When analysed, Table 9 shows that the initial cost of converting public transport to EVs is approximately 7 million TL. Table 10 shows the economic benefits of replacing three diesel-fuelled buses and three minibuses with electric versions. The analyses show that, for an average daily travel distance of 400 km for the bus and 210 km for the minibus, a benefit of approximately 66 million TL per year will be provided. This benefit is approximately 10 times the purchase cost. These results clearly demonstrate the significant economic benefits that municipalities could realise by switching to EVs in public transport.

Table 10. Comparison of fuel costs of fossil fuelled and electric cars

Vehicle Type	Fuel Type	Number of Vehicles	Average Daily Utilisation (km)	Fuel Consumption (for 100 km)	Unit Fuel Cost	Fuel Cost (TL)	
						Daily	Annual (~ 264 working days)
Bus	Fossil (Diesel)	3	400	45 lt	6.22 TL/lt	335,880.00	88,672,320.00
	Electricity	3	400	100 kwh	1.03 TL/kwh	123,600.00	32,630,400.00
		Difference (TL)				212,280.00	56,041,900.00
Minibus	Fossil (Diesel)	3	210	17 lt	6.22 TL/lt	66,616.20	17,586,676.80
	Electricity	3	210	44 kwh	1.03 TL/kwh	28,551.60	7,537,622.40
		Difference (TL)				38,064.60	10,049,054.40

Table 11 shows the contribution that e-buses and e-minibuses, which are proposed for conversion to EVs for use in public transport, would make in reducing air pollution.

Table 11. Environmental benefits of e-bus and e-minibus utilization

Vehicle Type	Fuel Type	Number of Vehicles	Average Daily Utilisation (km)	CO_2 Emissions per km (gr)	CO_2 Emission (tonnes)	
					Daily	Annual (~ 264 work days)
Bus	Fossil (Diesel)	3	400	1300	1.56	411.84
	Electricity	3	400	840	1.01	266.11
		Difference (Tonnes)			0.55	145.73
Minibus	Fossil (Diesel)	3	210	280	0.18	47.52
	Electricity	3	210	180	0.11	29.04
		Difference (Tonnes)			0.07	18.48

As can be seen in Table 11, replacing just three buses and three minibuses with electric models would result in an annual reduction of 145.73 tonnes for buses and 18.48 tonnes for minibuses. This achievement with such a small number of vehicles clearly demonstrates the potential for larger gains if the conversion to EVs were to be implemented across the entire public transport fleet.

5.3 Economic Costs and Benefits of Installing an Electric Bike/Scooter Fleet and Charging Station

One of the most important and easily applicable recommendations of the study is undoubtedly the use of e-bikes and e-scooters. In recent years, they have been used effectively around the world because they are ideal for short journeys, allow people to travel without expending too much energy, and provide access to public transport systems from locations such as homes, schools and workplaces (micromobility). Even in Türkiye, many citizens use these vehicles for their own transportation. However, since these vehicles are very weak in terms of security, their use and routes should definitely be regulated and controlled by municipalities. In this context, this study has developed suggestions for using these vehicles on two different routes. To this end, it is suggested that e-bikes and e-scooters be purchased for use in the initial phase (promotion and raising awareness) and that charging stations be installed along the designated routes. The results of the economic analyses are given in Table 12.

Table 12. Total procurement cost of e-bike/e-scooter and e-charging stations (TL)

		Unit Cost (TL)	Unit (Adet)	Total Cost (TL)
Bike	e-Bike	9,000.00	35	315,000.00
	e-Bike Charging Station	10,000.00	15	150,000.00
Scooter	e-Scooter	8,000.00	65	520,000.00
	e-Scooter Charging Station	9,000.00	19	171,000.00
Total (Σ)				**1,156,000.00**

A detailed analysis of Table 12 reveals that the total cost of both types of EVs and the required charging stations is approximately 1.15 million TL. Table 13 shows the net income obtained from operating e-bikes and e-scooters by the municipality for one year.

Table 13. Annual economic benefit to be obtained as a result of the operation of e-bike/e-scooters by the municipality

Vehicle Type	Number of Vehicles	Average Daily Usage (minutes)	Usage Fee (TL/min)	Rental Return (TL)		Fuel Cost*	
				Daily	Annual (~ 264 working days)	Daily	Annual (~264 working days)
e-Bike	35	500	0.30	5.250.00	1,386,000.00	700.00	184,800.00
e-Scooter	65	500	0.15	4,875.00	1,287,000.00	650.00	171,600.00
Total (Σ)				10,125.00	2,673,000.00	1350.00	356,400.00
Net Annual Income				2,673,000.00-356,400.00=2,317,000.00			

*The values calculated in the second table below are taken into consideration in fuel costs.

When Table 13 is analysed in detail, it shows that, as a result of the municipality operating e-bikes and e-scooters, twice the investment cost can be obtained within one year. This demonstrates that investing in these electric vehicle applications is feasible for the municipality. Furthermore, when the fuel costs of e-bikes/e-scooters and fossil-fuelled motorbikes/cars used for the same purpose are compared (Table 14), the difference is evident.

Table 14. Comparison of e-bike/e-scooter fuel costs with fossil fuelled motorbikes and cars

Vehicle Type	Number of Vehicles	Average Daily Usage (Km)	Fuel Consumption (for 100 km)	Unit Fuel Cost	Fuel Cost (TL)	
					Daily	Annual (~ 264 working days)
Automobile (diesel)	35	100	6 lt	6.22 TL/lt	130,620.00	34,483,680.00
Motorcycle (petrol)	35	100	3 lt	6.84 TL/lt	71,820.00	18,960,480.00
e-Bike	35	100	4 kwh	0.05 TL/kwh	700.00	184,800.00
e-Scooter	65	100	2 kwh	0.05 TL/kwh	650.00	171,600.00

According to the economic comparison of fuel costs in Table 14, it is clear that using these EVs instead of fossil-fuelled motorcycles or cars would be highly beneficial economically. Similarly, Table 15 shows that these EVs have significant environmental benefits compared to fossil-fuelled cars and motorcycles. In summary, the use of e-bikes and e-scooters will provide significant economic and environmental benefits.

Table 15. Environmental benefits of e-bike/e-scooter use

Vehicle Type	Number of Vehicles)	Average Daily Usage (Km)	CO_2 Emissions per km (gr)	CO_2 Emission (tonne)	
				Daily	Annual ($\sim$ 264 working days)
Automobile (diesel)	35	100	130	0.46	120.1
Motorcycle (petrol)	35	100	95	0.33	87.8
e-Bike	35	100	30	0.11	27.7
e-Scooter	65	100	15	0.1	26.4

6 General Evaluation

In recent years, fossil energy sources have caused serious increases in air pollution. With global warming increasing rapidly day by day, there has been a shift towards EVs as a means of reducing air pollution caused by transport. Significant improvements in battery technology, particularly in developing countries, have increased interest in EVs, and their use has become widespread since the beginning of the 2000s. As interest and demand for EVs has increased, many countries around the world have started producing and effectively using electric versions of transport vehicles. Türkiye has seen significant developments in this area in recent years, with a positive outlook emerging for the use of EVs. In this context, many municipalities have started using different types of electric vehicle and encouraging city residents to do the same. It is crucial for Trabzon, one of Türkiye's leading cities with many distinctive features, to spearhead the effective and efficient use of EVs and develop new projects to promote its status as an environmentally friendly and energy-efficient municipality. In this context, the Trabzon Metropolitan Municipality plays a key role in introducing EVs to the people of Trabzon and raising awareness of their benefits. To this end, the municipality has created a road map to guide its initial phase of electric vehicle use and set an ambitious target. Furthermore, the economic and environmental impact analyses carried out as part of the study concluded that the benefits of implementing the proposed electric vehicle types are feasible. In summary, introducing the proposed electric vehicle types under the leadership of the Metropolitan Municipality will be an important step in the transition from fossil fuel vehicles to EVs and in developing urban micromobility. The realisation of this study will be an important step towards becoming a smart city, with the scope being expanded further by carrying out projects supported by foreign funding, such as EU funds, for the wider use of EVs.

Within the scope of the study, signalised intersections in Trabzon province that experienced significant traffic congestion and confusion were examined, and six priority intersections that should be converted to smart, traffic-activated intersections were identified. The approximate improvements in waiting times resulting from the conversion of the identified intersections to smart intersections were calculated. According to the results of these calculations, the economic benefits in terms of fuel consumption and the environmental benefits in terms of reduced carbon emissions were determined. The results show that operating the proposed intersections as 'smart intersections' will provide economic and environmental benefits, as well as reduce traffic congestion. The transformation of the intersections will be a significant step towards Trabzon becoming a 'Smart City' and an 'Eco-Friendly City'. By developing new projects with domestic and international support, it will achieve significant gains that will meet current expectations on the way to becoming a 'smart city'.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

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