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Changes in Traffic Density and Vehicle Usage Habits During and After the Pandemic in Balıkesir Province

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Abstract

The COVID-19 pandemic profoundly impacted social dynamics and individuals' lifestyles worldwide, leading to significant changes in traffic density and vehicle usage habits. This study analyzes the changes in urban traffic density and individual vehicle usage habits in Balıkesir province during the pandemic period (2021-2022) and the post-pandemic normalization period (2023-2024). Within the scope of the research, vehicle passage densities at 19 signalized intersections in the city center of Balıkesir were examined, and predictive models were created using machine learning methods such as linear regression and the Random Forest algorithm. The findings reveal that traffic flows in economically active areas, such as industrial zones, were less affected by the pandemic, whereas traffic density significantly decreased in commercial and social centers. Additionally, an increase in individual vehicle usage and a decline in public transportation preferences during the pandemic period were observed. The study also explores recovery trends in post-pandemic traffic flow and intersection-based differences in detail. This study underscores the importance of traffic data obtained during the pandemic for sustainable traffic management and transportation planning. At the end of the study, solutions such as the integration of intelligent traffic systems, the promotion of environmentally friendly transportation modes, and increasing the appeal of public transportation systems were proposed. These findings are expected to guide decision-makers in improving urban traffic dynamics and preparing for similar crises in the future.

Keywords: "Intelligent transportation systems, intersection analysis, signalization systems, traffic density, COVID-19."

1. Introduction

COVID-19 was first identified in China on December 1, 2019, and rapidly spread to Europe, North America, and Asia-Pacific countries. [1]. The spread of COVID-19 altered individuals' perceptions and lifestyles, leading to the implementation of measures such as school closures, travel restrictions, and lockdowns to control the outbreak. Transportation restrictions played a critical role among these measures, as a positive correlation between travel and infectious diseases has been demonstrated. Shahin and Yetişkul [2] emphasized that individual protective measures are as important as administrative interventions and should continue during the normalization process.

In April 2021, a bulletin on motor vehicles released by the Turkish Statistical Institute (TÜİK) revealed a 155% increase in the number of vehicles registered compared to the same period in the previous year [3]. However, the preference of citizens to stay at home and restrictions reducing urban mobility played a significant role in maintaining balanced traffic density during the pandemic period. Measures such as lockdowns and remote work created constant fluctuations in traffic flow on urban roads. It is evident that these fluctuating traffic patterns observed during the pandemic are not directly applicable for road planning. Therefore, it is crucial to examine in detail the changes in traffic flow on main arteries caused by factors such as reduced demand for public transportation and increased use of private vehicles during restrictions. This detailed analysis is essential for transportation planning [4].

The pandemic and subsequent normalization period have had significant impacts on traffic density and vehicle usage habits in Balıkesir. This study aims to analyze how the increase in private vehicle usage, the decline in public transportation preferences, and changes in working patterns during the pandemic have reshaped urban transportation dynamics. By analyzing vehicle passage data, the research highlights trends in traffic density changes at different intersections in Balıkesir. The study evaluates traffic data using a linear regression model and conducts intersection-based comparisons between the pandemic period

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and the normalization process. Dynamics such as increased traffic density in industrial zones are explored, and the environmental impacts of individual vehicle usage are emphasized. Based on field observations and data from traffic monitoring systems, this research aims to provide recommendations for sustainable traffic management solutions. Reducing increased vehicle density in the post-pandemic period and minimizing environmental impacts are central focuses of the study. Furthermore, it examines the reflections of findings from the literature in a local context, aiming to offer suggestions for future transportation policies.

2. Literature Review

The pandemic period caused profound changes in traffic density and flow on a global scale. Observations conducted on Antalya's main arteries revealed a significant decrease in traffic density during restriction days [4]. Similarly, in China's Zhejiang province, traffic volume decreased by 95.5% during the pandemic, and gradually began to recover as restrictions were eased [5]. In Portugal, highway traffic dropped by 80% during the pandemic, with this decrease being more pronounced for light vehicles, while heavy commercial vehicle traffic was less affected due to logistical requirements [6]. Across Turkey, daily travel behavior and traffic density underwent significant changes; individuals postponed non-essential trips and preferred private vehicle use over public transportation [7]. The relatively limited impact of the pandemic on commercial transportation played a critical role in ensuring the continuity of logistics operations. While the presence of commercial vehicles in traffic remained consistent throughout the pandemic, fluctuations in individual vehicle traffic highlighted the vulnerability of urban transportation systems. Studies emphasize that in the post-pandemic period, greater priority should be given to smart traffic management solutions and policies that promote environmental sustainability.[6, 29]

The increase in private vehicle usage during the pandemic led to a substantial decline in public transportation usage. For instance, in Japan's Hokkaido region, traffic volume decreased by 65% [8], while on India's Nagpur-Jabalpur highway, traffic density reached its lowest levels in April 2020 and began to gradually increase by June 2020 [9]. In major Turkish cities like Istanbul and Ankara, the decrease in public transportation usage led to an increase in private vehicle traffic, highlighting the need for urban traffic reorganization [1, 10]. This trend was not limited to Turkey; similar patterns were observed in other regions such as California and China [11, 12]. During the pandemic, traffic congestion, particularly on major transportation arteries such as the İpekyolu, increased significantly, leading to bottlenecks in urban centers. High-density areas, including industrial zones, university campuses, and shopping centers, emerged as primary contributors to traffic congestion. It is emphasized that new intersection management systems should be implemented to optimize traffic flow in these regions[30].

In the post-pandemic period, it has become evident that cities require new approaches to traffic management. The integration of shared transportation and micromobility options emerges as an effective strategy to encourage public transportation use and reduce dependency on private vehicles [13]. Additionally, green wave systems and adaptive traffic control applications play a crucial role in reducing carbon emissions and supporting environmental sustainability [14]. The dynamic management of signalized intersections has also become more critical due to the increase in private vehicle use. For example, in Istanbul and Ankara, the decrease in public transportation usage during the pandemic reduced congestion at signalized intersections, but the rise in private vehicle traffic made this trend less sustainable [1, 10].

Smart traffic management technologies hold critical importance in improving traffic flow and supporting environmental sustainability in the post-pandemic period. Analyses conducted in cities like Van, Konya, and Samsun have shown that properly adjusted signal timings can reduce accident rates and minimize waiting times [15, 16]. Moreover, while some intersections required less signalization during the pandemic due to low traffic volumes, the normalization process has led to a resurgence in these requirements [17, 18]. The importance of dynamic signaling systems in smart traffic management has become particularly evident during crisis periods such as the pandemic. For instance, it has been noted that vehicle speeds increased during restrictions when traffic congestion decreased, leading to a rise in the severity of accidents. Smart signaling systems are highlighted as playing a critical role in adapting to such changes in traffic speeds and preventing accidents [11].

In conclusion, the pandemic deeply influenced traffic dynamics and transportation preferences. The decline in public transportation usage increased private vehicle ownership, necessitating the reorganization of urban traffic systems. Solutions such as green wave applications and adaptive traffic control systems offer effective strategies to improve traffic flow and support environmental sustainability in the post-pandemic period [14]. In the future, prioritizing smart traffic management technologies and sustainable transportation policies will enable cities to address traffic issues more efficiently and environmentally friendly.

3. Balıkesir Province

Balıkesir is one of Turkey's prominent agricultural, commercial, and industrial cities, experiencing a growing population due to migration. According to the 2023 results of the Address-Based Population Registration System (ABPRS), the population of Balıkesir province has reached 1,273,519, constituting 1.49% of the country's total population. Among its districts, Karesi has the highest population with 188,846 residents, while Marmara is the least populated district with 11,454 residents. Turkey's total population stands at 85,372,377, with a population density of 111 people per square kilometer. Covering an area of 14,272 square kilometers, Balıkesir has a population density of 89 people per square kilometer, which is below the national average [19].

While Balıkesir's population has shown a steady increase over the years, the population growth rate was below the national average in 2015, 2016, and 2017. However, in 2014, 2018, 2019, and 2020, the growth rate exceeded the national average. Although the population growth rate was below the national average in 2021 and 2022, it surpassed the national average in 2023. As depicted in Figure 1, the details of Balıkesir Province are clearly illustrated.

Fig. 1. Balıkesir Province [20].

This rapid population growth has significantly increased the demand for urban transportation. Urban mobility in Balıkesir is primarily supported by private vehicles and public transportation. The city’s main roads witness heavy traffic from private and public transportation vehicles, and in industrial zones, the prevalence of heavy vehicle traffic is notable. This situation significantly impacts traffic flow, especially around organized industrial zones [19]. According to Table 1, the population growth rates by year are thoroughly detailed.

Table 1. Population Growth Rates by Year [19].

Year	Population	Population Growth Rate (‰)	
		Balıkesir	Turkey
2014	1 189 057	22.6	13.2
2015	1 186 688	-2.0	13.4
2016	1 196 176	8.0	13.5
2017	1 204 824	7.2	12.4
2018	1 226 575	18.1	14.7
2019	1 228 620	17.0	13.9
2020	1 240 285	9.5	5.5
2021	1 250 610	8.3	12.7
2022	1 257 590	5.6	7.1
2023	1 273 519	12.7	1.1

The urban transportation network in Balıkesir predominantly consists of at-grade intersections. However, grade-separated intersections have been constructed along the city's bypass to alleviate transit traffic and reduce delays. As of 2020, Balıkesir had a car ownership rate of 152 vehicles per 1,000 people, placing it among the top 10 cities in Turkey in this category [21]. As outlined in Table 2, the summary of key statistics for Balıkesir in 2023 is comprehensive.

Table 2. Summary of Key Statistics for Balıkesir in 2023 [19].

Indicator Name	Turkey	Balıkesir
Total Length of Road Network (km):	68.654	1.338,7
Total Number of Automobiles	29.987.701	613.784
Number of Traffic Accidents	1.314.136	18.307
Number of Fatalities in Accidents	6.504	136
Provincial and State Roads	64.297,5	1.235,5

In Balıkesir, 47% of the population travels on foot for short distances (0-3 km). For distances exceeding 3 km, private vehicles and public transportation dominate as the primary modes of travel. Medium-distance trips (5-10 km) are predominantly made by public transportation, accounting for 63% of such journeys [22]. The intersections serving the city are mostly signalized, though modern roundabouts have been introduced in newly developed areas [23].

4. Intersections and Their Functions

Intersections are the points where two or more roads meet, making them one of the most critical areas for traffic flow. These zones play a strategic role in traffic management due to their high traffic density and vehicle-pedestrian interactions [18]. Considering the movement of traffic in different directions on highways, it can be said that the likelihood of traffic accidents occurring at intersections is relatively high. Therefore, designing intersections correctly and in accordance with relevant standards is of great importance for minimizing material and emotional damages. During the intersection design process, factors such as safety, user comfort, and capacity must be taken into account. In summary, intersections should be planned to adapt optimally to environmental conditions, minimize accident risks, vehicle delays, and maintenance costs, while providing maximum capacity. As shown in Figure 2, the images of selected intersections in Balıkesir Province provide clear visual insights.

4.1. Types of Intersections

Intersections can be classified into various types based on their characteristics. When considering the features of the intersecting road approaches, intersections can be grouped into two main categories. These categories are designed in various shapes and structures to regulate traffic flow and ensure safety. Generally, intersections are divided into the following types:

4.1.1. At-Grade Intersections

At-grade intersections are where roads intersect at the same level, and traffic flows interact directly. In such intersections, vehicles, pedestrians, and cyclists move on the same level, requiring the application of various traffic control methods. At-grade intersections can be further divided into the following subtypes:

- Simple Intersections: Basic intersections where two roads meet, typically involving four-way traffic controlled by traffic lights or stop signs.

- T-Intersections: Three-way intersections where one road merges with another. These are controlled by traffic lights, priority signs, or stop signs.

- Roundabouts: Intersections where traffic flows in a circular pattern, with vehicles entering the roundabout in a prescribed order. These facilitate smoother traffic flow and reduce accident risks.

- Box Junctions: Marked areas within an intersection that only allow movement according to the signals. These are used where vehicles must stop before proceeding through the intersection.

- Zebra Crossings: Designated areas at intersections for safe pedestrian crossings. These are often supported by traffic lights and are also referred to as pedestrian crossings.

At-grade intersections are commonly used in areas with low traffic density, while areas with higher traffic volumes may require more complex management systems.

(a) Hastane Roundabout

(b) Zeytinli Roundabout

(c) Çayırhisar Multi-Level Intersection Design

(d) Rüzgar Av. Roundabout

Fig. 2. Images of Selected Intersections in Balıkesir Province

4.1.2. Grade-Separated Intersections

Grade-separated intersections are designed where roads intersect at different levels, allowing traffic to flow without interruption. These intersections facilitate continuous and safe traffic flow by using overpasses or underpasses. They can be categorized into the following subtypes:

- Overpasses: Structures that allow one road to pass over another without intersection.
- Underpasses: Tunnel-like structures enabling one road to pass beneath another, similar in function to overpasses.
- Multi-Level Intersections: Complex intersections combining overpasses and underpasses, often used in urban areas with heavy traffic.
- Roundabout Combinations: Some grade-separated intersections incorporate roundabouts to manage more complex traffic patterns, particularly in large, high-traffic areas.

Grade-separated intersections are preferred in high-density traffic areas to reduce congestion and minimize accident risks. However, their application may be limited due to high construction costs and space requirements.

The selection and design of intersection types depend on factors such as traffic density, road structure, environmental conditions, and safety requirements. While at-grade intersections are commonly used in low-traffic areas, grade-separated intersections are suitable for regions with high traffic volumes. Well-designed intersections optimize traffic flow while enhancing the safety of both vehicles and pedestrians.

4.1.3. Intersection Signalization

Signalized intersections manage traffic flows using traffic lights. Vehicles approaching the intersection stop or proceed depending on the signal colors. These intersections are typically preferred in high-traffic areas as they regulate flow, increase capacity, and ensure safety. Signalized intersections can be implemented as fixed-time or traffic-adaptive systems. Traffic signals create intermittent traffic flow by periodically interrupting the movement of vehicles. Signal timing, which allows specific movements at designated intervals, directly affects the capacity of the intersection. Consequently, traffic flow is shaped by the type of signalization used [24]. Optimizing traffic flow is critical not only for vehicles but also for pedestrian safety.

Signalized intersections enhance traffic safety and ensure the orderly flow of traffic by minimizing conflicts between vehicles and pedestrians [25]. Modern intersection signalization systems go beyond basic traffic regulation to reduce delays and optimize traffic flow in high-traffic scenarios. Today, these systems utilize advanced algorithms and sensor-based technologies, setting a new standard in traffic management [26].

Compared to traditional signalization systems, smart traffic systems are far more complex and adaptive. These systems analyze vehicle speed, density, and traffic flow in real time, automatically adjusting signal timings. Effective traffic signal control should provide real-time control with an adaptive characteristic, responding to traffic demands with optimal timing plans. However, the non-linear nature of traffic control systems has rendered traditional methods less effective. On the other hand, with the rapid development of computer technologies, artificial intelligence techniques have successfully solved non-linear problems. Techniques such as fuzzy logic, artificial neural networks (ANNs), evolutionary algorithms, and reinforcement learning can produce effective solutions for traffic signal control problems [27].

In recent years, the concept of smart traffic intersections has garnered significant attention among governments, transportation agencies, technology providers, and the general public. This growing interest stems from recognizing the inadequacy of traditional traffic management approaches to address complex issues arising from rapid urban transformation, increased vehicle ownership, and changing mobility patterns. By integrating advanced technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and Vehicle-to-Everything (V2X) communication, smart traffic intersections provide an effective way to enhance the efficiency and sustainability of urban transportation networks. Additionally, they contribute significantly to managing and integrating various transportation options, including shared mobility services, autonomous vehicles, and public transportation [28].

5. Material and Method

This study analyzes the changes in traffic density and vehicle usage habits in Balıkesir province during the pandemic period (2021-2022) and the post-pandemic normalization period (2023-2024). The research is supported by traffic density measurements conducted at 19 different intersections and linear regression analyses based on these data. Additionally, machine learning methods such as the Random Forest algorithm were employed to evaluate past traffic data and predict traffic trends. The methods used in this study aim to provide a detailed understanding of the fluctuations caused by the pandemic and the transition to regular traffic flow in the post-pandemic period. The study seeks to identify intersection-based differences and provide valuable insights for future traffic management and sustainable transportation policies.

Table 3 contains the geographical location data of the 19 different intersections included in the study within the boundaries of Balıkesir province. The table presents the names, latitudes, and longitudes of each intersection, illustrating the regions analyzed. These data serve as a fundamental source of information for intersection-based traffic density analyses and modeling studies.

5.1. Methods

As part of this study, Balıkesir province was selected as the pilot region due to its population of 1,273,519 by the end of 2023, making it the 17th most populous city in Turkey, and its 572,446 registered vehicles as of August 2023 (TÜİK, 2023). The methods used to analyze traffic density and vehicle usage habits in Balıkesir are based on two primary approaches. The first approach involves fixed-time analyses that compare traffic density and passage data with historical data. The second approach utilizes adaptive analyses to understand fluctuations in traffic flow. These analyses provide a detailed examination of traffic data during and after the pandemic.

In the study, linear regression models were employed to determine intersection-based vehicle passage densities. The regression analyses revealed changes in traffic density by identifying vehicle passage trends at each intersection. These analyses were critical in understanding the decrease in vehicle traffic during the pandemic restrictions and the increase in individual vehicle usage in the post-pandemic period. Additionally, machine learning methods, such as the Random Forest algorithm, were utilized to analyze abrupt changes in traffic flow during the pandemic and the subsequent increases in traffic more effectively. This algorithm provided a robust tool for predicting traffic trends based on historical data and identifying varying traffic dynamics between intersections. The modeling process analyzed intersection-based traffic data to assess the pandemic's impact on traffic density from a broader perspective. This method was used to gain deeper insights into changing transportation habits during the post-pandemic normalization process. The detailed analyses of intersections were developed by drawing on similar studies and a review of the literature. Traffic flow and vehicle density data were categorized into central, industrial, and mixed regions, allowing for more in-depth analyses.

In this study, vehicle passage data derived from traffic density measurements were analyzed using linear regression and machine learning models. These methods not only clarified vehicle passage trends but also facilitated the development of alternative scenarios based on changes in traffic density. Consequently, these methods provided a clear evaluation of the decreases during the pandemic and the increases in the post-pandemic period, offering valuable insights for future traffic management policies.

Table 3. Intersection Coordinates.

#	Intersections	Latitude	Longitude
1	Sanayi 2. Kapı	39.666944	27.918056
2	Sanayi 1. Kapı	39.661389	27.911111
3	Çengel Dereboyu Av.	39.666944	27.904722
4	Karizma	39.662500	27.897778
5	Okul Av.	39.666389	27.889167
6	Eski Vali konağı	39.654167	27.899722
7	TTM Gazi Bulvarı ext.	39.648333	27.890000
8	İstasyon	39.647222	27.887778
9	Hükümet	39.644167	27.883889
10	Çardaklı	39.640833	27.880556
11	Eski SSK altı Yeni İzmir y.k	39.629444	27.881389
12	Eski Çayırhisar	39.612778	27.895556
13	TTM Gazi Bulvarı ext.	39.648056	27.886944
14	Kurtdereli T.M. Lisesi	39.649444	27.885278
15	Eski Cami	39.651111	27.883056
16	Yonca	39.651111	27.880556
17	Başçeşme	39.652500	27.874167
18	Azerbaycan Av.	39.644444	27.905833
19	Ağır Bakım	39.651111	27.907222

6. Experimental Results

This section presents the results of traffic density analyses conducted at 19 selected intersections in Balıkesir between 2021 and 2024. The study evaluated changes in traffic flow during the pandemic and post-pandemic periods using regression analysis, detailing fluctuations and upward trends in vehicle passage volumes. Additionally, the performance of the Random Forest algorithm in predicting intersection-based traffic trends was analyzed, supported by R^2 values to demonstrate the model's accuracy. The primary objective of the study is to reveal traffic density dynamics and intersection-based differences, enabling these findings to contribute to future traffic management strategies.

6.1. Linear Regression Analysis

6.1.1. Pandemic Period

Figure 3 illustrates vehicle passage trends and regression analyses for 19 different intersections in Balıkesir during the pandemic period, covering the years 2021-2022. Blue dots represent actual vehicle passage data, while red lines indicate regression curves fitted to these data points.

To provide a detailed interpretation of the graph, the following observations can be made:

- At most intersections, vehicle passage volumes showed fluctuating patterns, particularly from mid-2021 onward. However, there was an overall trend toward recovery to pre-pandemic levels. By mid-2022, some intersections exhibited increasing traffic volumes, while others displayed stable or declining trends.

- The red regression curves generally align well with the blue data points, indicating a good fit. However, some intersections, such as the TTM Gazi Boulevard Exit, reflect seasonal or periodic fluctuations that are not fully captured by the regression curves. For intersections with more consistent increases or decreases in traffic trends, the regression lines more accurately reflect the data.

- At the Sanayi 1 Gate and Sanayi 2 Gate intersections, there was a general increase in vehicle passages from 2021 to 2022, highlighting the resilience of industrial zones to pandemic-related disruptions.

- Intersections like Çengel Dereboyu Street and Eski Çayırhisar showed minor fluctuations but generally maintained stable traffic volumes until mid-2022.

- In intersections near educational institutions, such as Okul Street and Kurtdereli T.M. High School, a recovery in traffic volumes was notable, particularly from late 2021 onward, reflecting the impact of school reopenings on traffic patterns.

- In contrast, a significant decline in traffic was observed at İstasyon Intersection as 2022 approached, potentially due to a shift in station-related traffic to alternative routes or a decrease in demand in the area.

- At intersections like Pancar, Yonca, and Azerbaijan Street, traffic volumes remained relatively stable, with minor fluctuations. These areas, influenced by rural activities, retained consistent traffic levels even during the pandemic, suggesting that rural traffic demand was less affected.

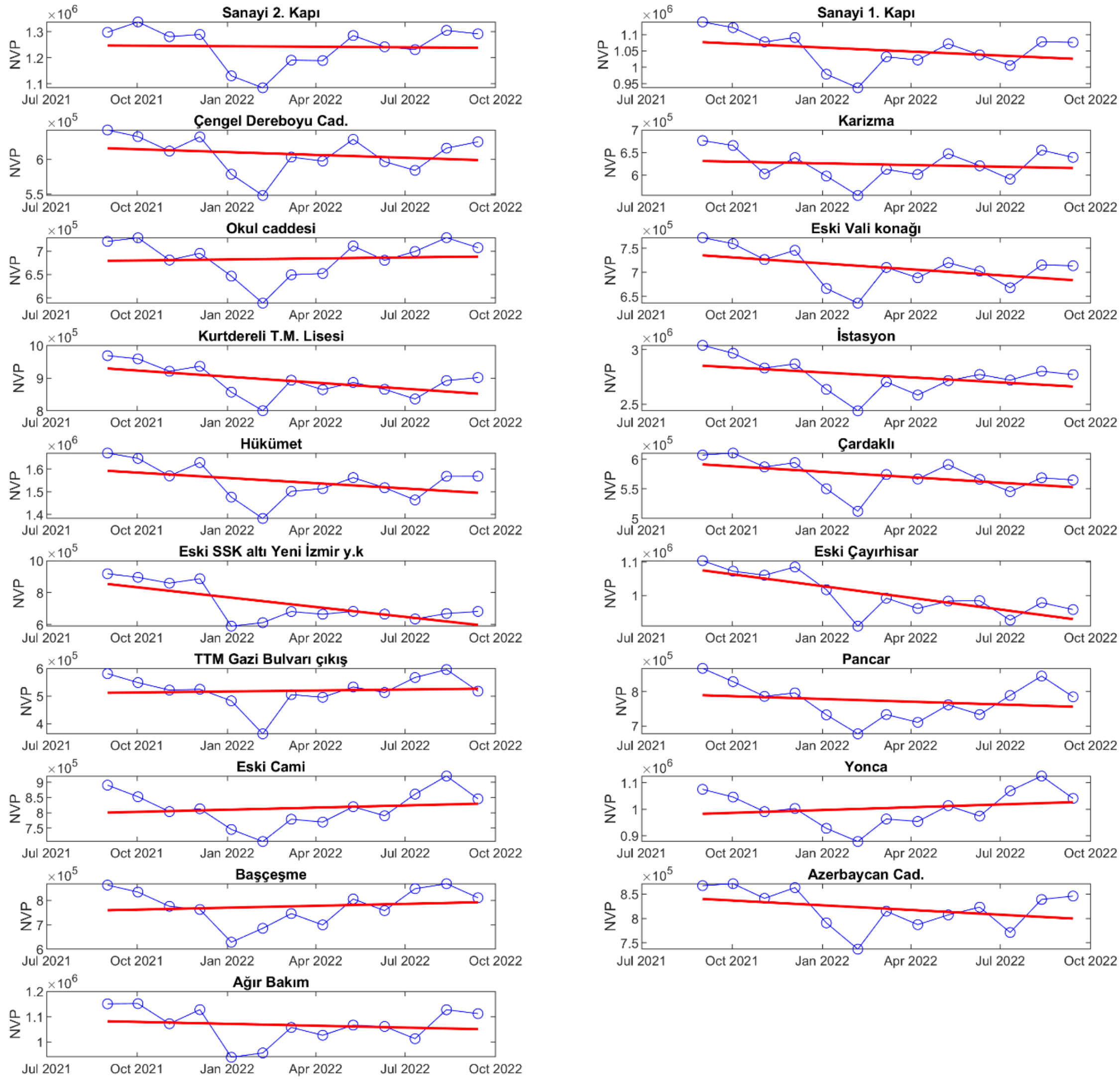

Fig. 3. Vehicle Passage Trends and Regression Analysis for the 2021-2022 Period.

Overall, vehicle passages decreased during periods of lockdowns in 2021 but began to recover in 2022 as social and economic activities increased.

In industrial and commercial zones, particularly at industrial gates and logistical connection points, there was a general trend of increasing traffic volumes, indicating economic recovery and the continuity of logistical movements. Similarly, in educational zones, traffic recovery was driven by the reopening of schools and the return to in-person education. In city centers and residential areas, intersections like Eski Vali Konağı and Çardaklı showed fluctuating traffic volumes, reflecting the lingering effects of mobility restrictions. Fluctuations in traffic at some intersections highlight the need for traffic management and signalization systems to adapt to pandemic conditions.

Recommendations:

- Signal timing at intersections with increasing traffic should be reevaluated to reduce waiting times and improve traffic flow, particularly in industrial areas.

- Data-driven planning, utilizing insights from regression analyses, could serve as a crucial decision-making tool for future traffic management.

- In urban areas, enhancing the appeal of public transportation and promoting sustainable mobility are vital steps to reduce vehicle density. These measures would contribute significantly to intersection-based traffic management policies and preparations for potential future crises**.**

The data presented in the graph provide a valuable resource for understanding intersection-based traffic changes in Balıkesir during the post-pandemic period. Different strategies should be developed depending on the type of intersections and the dynamics of the regions where they are located.

6.1.2. Post-Pandemic Period

As illustrated in Figure 4, vehicle passage trends and regression analyses for 19 intersections in Balıkesir during 2023-2024. Red lines represent regression curves, while blue dots indicate actual vehicle passage data. This analysis is crucial for evaluating changes in traffic flow and the impacts of normalization during the post-pandemic period.

Most intersections exhibited an upward trend in traffic volumes, indicating that social and economic activities had started to return to pre-pandemic levels. Notably, intersections focused on trade and logistics, such as the Sanayi 1 Gate and Sanayi 2 Gate, experienced a significant increase in traffic.

Regression curves (red lines) generally showed good alignment with the blue data points, although seasonal effects and short-term fluctuations affected the fit at some intersections. For instance, intersections like Karizma and Pancar displayed such irregularities. In other cases, regression curves represented clear upward or downward trends, while actual data showed more variability.

Intersection-Based Observations:

- Industrial and Logistical Zones: Continuous increases in vehicle passages were observed at intersections like Sanayi 1 Gate and Sanayi 2 Gate, reflecting intensified industrial and logistical activities. Regression curves aligned closely with actual data at these intersections. Similar trends were noted at Ağır Bakım Intersection, supporting the mobility of industrial zones.

- Urban Areas: Significant fluctuations in traffic volumes were observed at intersections such as Çengel Dereboyu Street and Karizma from early 2023 onward, reflecting variability in traffic demand in densely populated areas. At Eski Vali Konağı Intersection, traffic exhibited a fluctuating pattern but maintained an overall horizontal trend.

- Educational Zones: Intersections near educational institutions, such as Okul Street and Kurtdereli T.M. High School, showed increasing traffic volumes, particularly from the fall of 2023, correlating with the start of the academic year.

- Other Areas: Partial recovery was observed in traffic volumes at intersections like İstasyon and Çardaklı. Fluctuations in these areas indicate short-term changes in traffic flow. Traffic volumes at rural intersections, such as Yonca and Pancar, remained relatively low and stable even in the post-pandemic period, suggesting that rural traffic demand was less impacted.

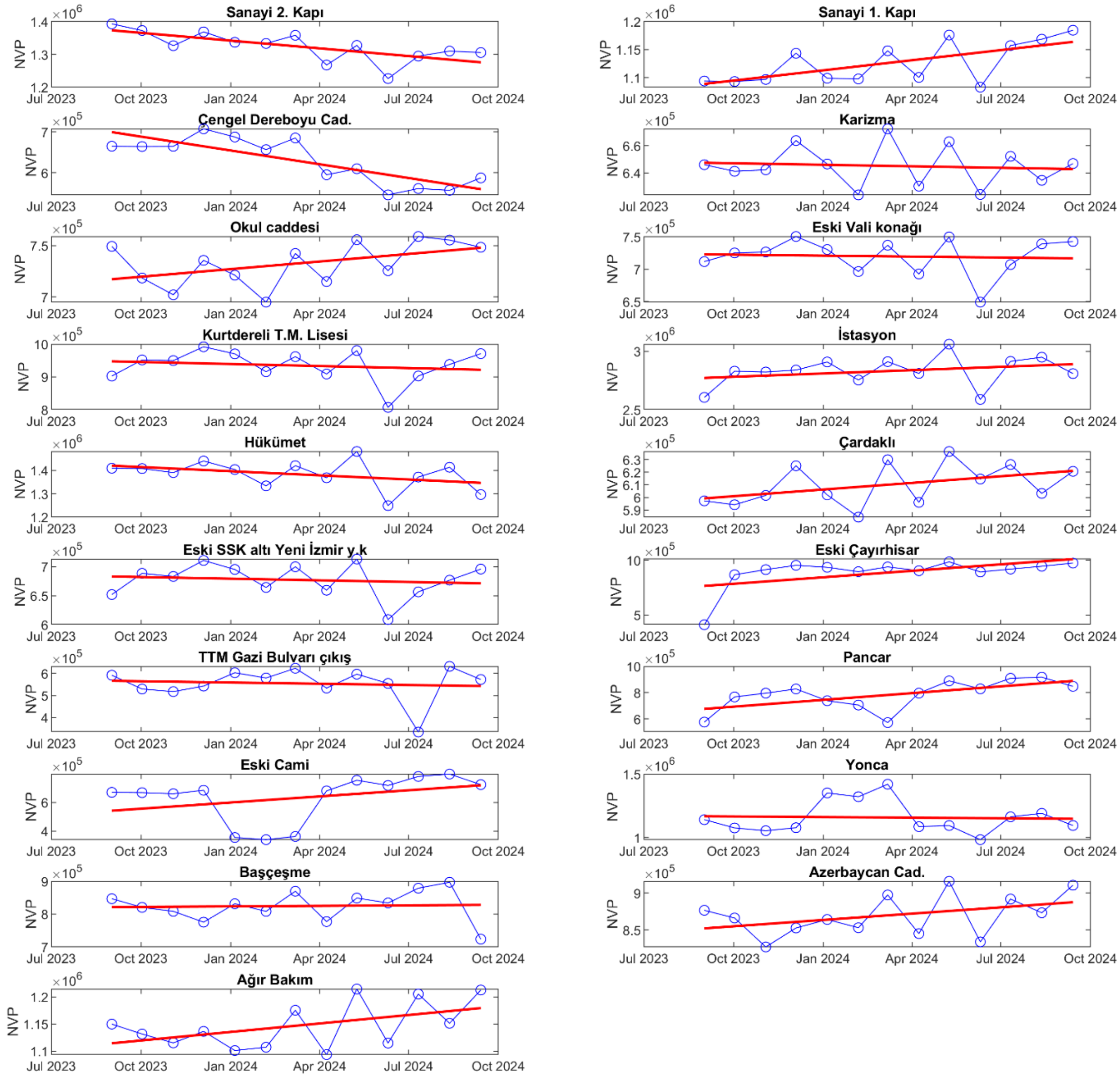

Fig. 4. Vehicle Passage Trends and Regression Analysis for the 2023-2024 Period.

6.1.3. Comparison of the Pandemic and Post-Pandemic Periods

During the pandemic (2021-2022), traffic volumes were generally lower, with fluctuations driven by lockdowns and seasonal effects. Although there was an increase in individual vehicle usage, overall traffic demand remained limited due to restrictions. In contrast, the post-pandemic period (2023-2024) saw a significant increase in vehicle passages as restrictions were lifted, and economic and social activities recovered.

- Industrial and Commercial Zones: Traffic volumes in these areas showed a gradual recovery during the pandemic but accelerated significantly during the post-pandemic period, particularly at industrial gates and logistical hubs.

- Educational Zones: Increased traffic volumes were observed near educational institutions during the post-pandemic period due to the full resumption of in-person education.

- City Centers and Residential Areas: Fluctuations persisted in central intersections like Eski Vali Konağı during both periods, reflecting ongoing adjustments in mobility.

Intersection-Based Variations:

In industrial-focused intersections, such as Sanayi 1 Gate, Sanayi 2 Gate, and Ağır Bakım, traffic volumes during 2021-2022 were relatively low and fluctuating. While logistical activities were less affected by pandemic restrictions, an overall decline was observed. However, during 2023-2024, a significant increase in vehicle passages was noted at these intersections, primarily driven by the acceleration of industrial activities in the post-pandemic period. Regression curves also reflected a consistent upward trend.

In educational and public zones, such as Okul Street and Kurtdereli T.M. High School intersections, traffic volumes were low during 2021-2022, especially when schools were closed or operating under restricted capacity. By 2023-2024, traffic volumes increased as educational institutions returned to full capacity. This indicates the positive impact of resuming in-person education on traffic density.

In city center intersections, such as Çengel Dereboyu Street, Karizma, and Eski Vali Konağı, traffic volumes exhibited fluctuations during 2021-2022, reflecting the effects of reduced human mobility during the pandemic. In 2023-2024, traffic volumes at these intersections recovered, although occasional fluctuations persisted. This suggests that traffic density in city centers has not fully returned to pre-pandemic levels.

In transit and rural areas, such as Pancar, Yonca, and Azerbaijan Street intersections, traffic volumes remained stable or showed minor fluctuations during 2021-2022. Mobility in these areas is largely influenced by rural activities. During 2023-2024, a general increase in traffic volume was observed in these intersections; however, the rate of increase was more limited compared to city centers and industrial zones.

Differences in Traffic Dynamics:

During 2021-2022, the pandemic period, traffic flows at many intersections experienced significant fluctuations due to restrictions and seasonal effects. This period was marked by sudden changes and unpredictable variations in traffic volumes, adversely affecting intersection stability. However, during 2023-2024, traffic flow exhibited a more stable pattern overall. Regular increases in traffic were particularly noticeable at industrial gates and intersections near city centers, reflecting economic recovery and increased demand for traffic in urban areas.

When analyzing the alignment of regression curves, it was evident that the high fluctuations in 2021-2022 made it difficult for regression lines to fully match the actual data points. These fluctuations negatively impacted the accuracy of predictive models, making it challenging to capture real traffic data at some intersections. However, during 2023-2024, the recovery process brought greater regularity to traffic flow, improving the alignment between regression curves and actual data. This improvement allowed traffic management strategies and models to better adapt to the post-pandemic period, enhancing prediction accuracy. Overall, the reduction in traffic fluctuations and improved alignment of regression curves highlight the positive impact of the post-pandemic normalization process on traffic management.

Effects of Economic and Social Activities:

During 2021-2022, economic restrictions limited traffic volumes while accelerating the shift from public transportation to individual vehicle use. This led to reduced traffic density in city centers while increasing individual vehicle use. In 2023-2024, increased economic activity and a return to public transportation contributed to a renewed rise in city center traffic density. However, the rise in individual vehicle use added an additional burden to traffic volumes, particularly in industrial zones.

To effectively manage the increased traffic observed at industrial gates during 2023-2024, signalization systems and solutions to optimize logistical traffic should be implemented. Policies to encourage greater use of public transportation are recommended to manage traffic density in city centers. Traffic flow in educational zones could be regulated with traffic planning tailored to school hours. In rural intersections, traffic volume increases have remained relatively limited; however, future changes in rural activities and their impact on traffic should be monitored.

Considering the upward trend brought by the recovery process during 2023-2024, adaptive traffic management and environmentally sustainable solutions should be swiftly implemented. In conclusion, traffic volumes and consistency have increased in the post-pandemic period. However, this increase underscores the need for more effective traffic management strategies, particularly in city centers and industrial zones.

6.2. Monthly Vehicle Passage Prediction Using the Random Forest Algorithm

This section examines the performance and results of the Random Forest algorithm used to predict monthly vehicle passage volumes at 19 selected intersections. The model was applied to capture fluctuations during the pandemic period and the regularity of traffic flow during the post-pandemic normalization process. By analyzing the impact of multiple variables in the dataset, the Random Forest algorithm was employed as a robust tool for predicting seasonal and periodic traffic trends. Within the study, the model's R^2 values and prediction errors were assessed, and accuracy rates across different intersections were compared. This analysis was conducted to measure the model’s performance under fluctuating traffic conditions and to support data-driven decision-making processes in traffic management.

Various performance metrics were analyzed to evaluate the prediction accuracy of the Random Forest algorithm used in this study. These metrics provide a detailed framework to assess the differences between the predicted and actual values by measuring the model's success from multiple perspectives.

Mean squared error (MSE) evaluates the overall accuracy of the predictions by measuring the magnitude of errors, while root mean squared error (RMSE) reduces the dependency on scale and enhances interpretability. Mean absolute error (MAE) measures the level of error by calculating the absolute difference between predicted and actual values. The R^2 metric indicates the proportion of variance explained by the model, evaluating the alignment between the predicted and actual data. Together, these metrics offer a comprehensive framework to understand the model's overall performance and accuracy under varying conditions.

6.2.1. Pandemic Period

Figure 5 depict vehicle passage trends and Random Forest model predictions at 19 intersections in Balıkesir during the pandemic period. The model's performance was evaluated by comparing its predictions with actual vehicle passage data. Hükümet Intersection (Intersection 9) emerged as the central hub of traffic density during the pandemic, and the model's predictions for this intersection were highly accurate. At other intersections, traffic density remained low, though minor fluctuations, including increases and decreases in some months, were observed. Overall, the model produced predictions that closely matched the actual data.

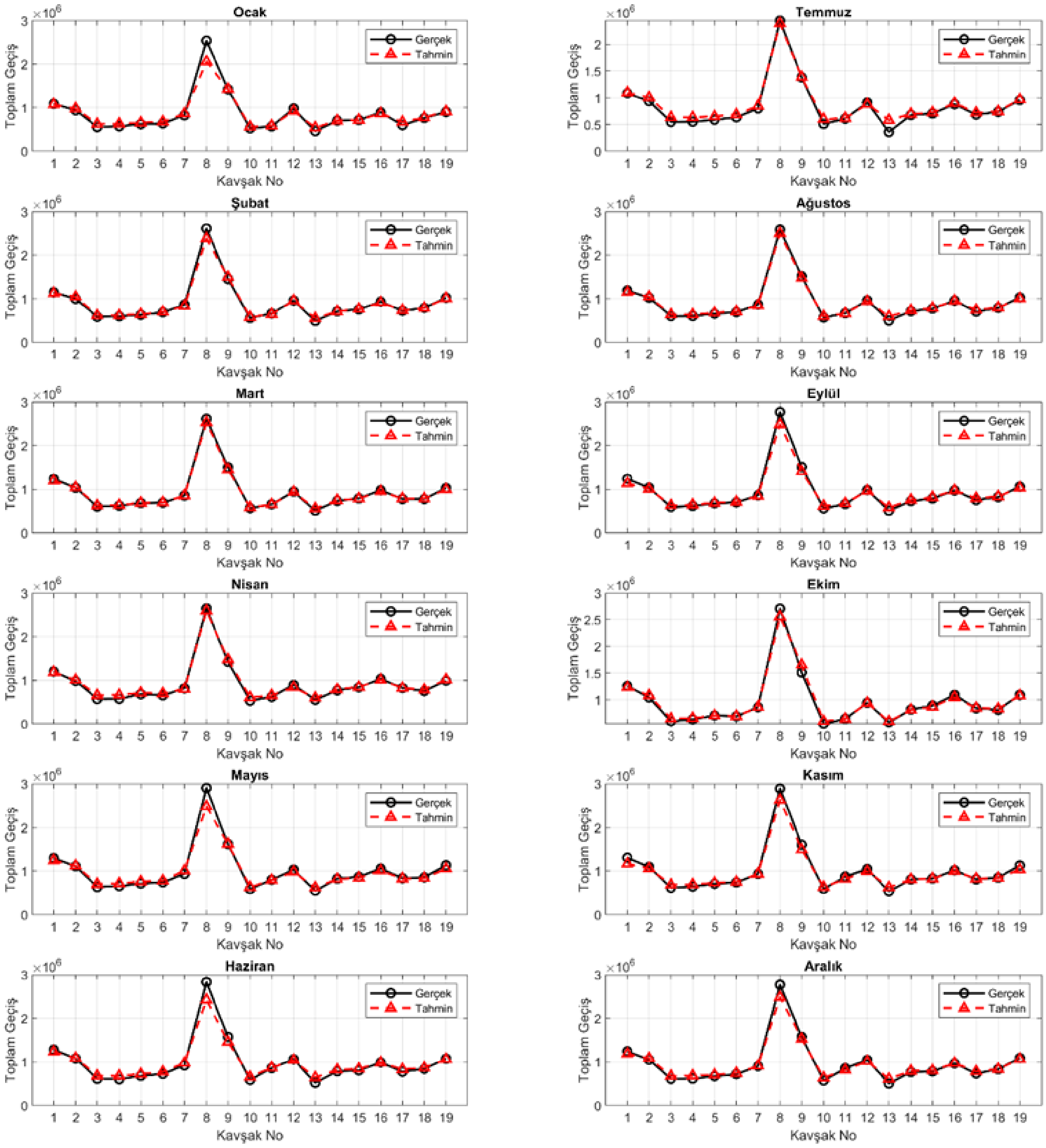

Fig. 5. Estimation of Monthly Vehicle Passage Numbers by Intersections During the Pandemic Period.

At most intersections, vehicle passage volumes exhibited fluctuations, particularly from mid-2021 onward. However, a general trend of recovery toward pre-pandemic levels was noted. While seasonal effects and social dynamics limited prediction accuracy at certain intersections, general trends were consistently captured. The Random Forest model demonstrated a high level of alignment with actual data. However, error rates increased during months with pronounced fluctuations, indicating the challenges posed by the unpredictable changes during the pandemic on the model's accuracy. Table 4 presents the performance metrics for the Random Forest model.

Table 4. Performance Metrics During the Pandemic Period.

#	MONTH	MSE	RMSE	MAE	R^2
1	January	13846884984	117672,7878	57009,97095	0,933721399
2	February	3420441889	58484,54402	31955,51195	0,984098257
3	March	877270981,3	29618,76063	21160,09485	0,995937737
4	April	2097908265	45802,92856	39084,04313	0,99043202
5	May	11390027752	106724,073	59825,85914	0,957094292
6	June	11783647130	108552,5086	66320,89172	0,953683755
7	July	4759431864	68988,63576	48428,56149	0,975415166
8	August	1426954835	37775,05572	30055,49685	0,993311972
9	September	6017905467	77575,16012	47881,01965	0,975507417
10	October	2724566737	52197,38248	32321,92544	0,988083369
11	November	6957178503	83409,70269	56311,06724	0,973624762
12	December	6323134919	79518,14208	51637,4936	0,974173599

In this experiment, the monthly prediction performance of the Random Forest model for vehicle passages was evaluated. Although the model generally exhibited high accuracy ($R^2 > 0.95$), its predictive accuracy peaked in March and August. Conversely, the model's performance declined in January, May, and June. Variations in error rates were attributed to seasonal effects and fluctuations in traffic density. Overall, the model successfully captured vehicle passage trends and provided a reliable data source for traffic management.

The Random Forest model demonstrated strong performance during the pandemic period. March and August were the most successful months for the model. In March, the model achieved the highest accuracy with an R^2 value of 0.9959, while MAE (21,160) and RMSE (29,618) values were notably low. These results indicate that the model was able to produce predictions very close to the actual data. Similarly, in August, the model achieved a high accuracy rate with an R^2 value of 0.9933 and exhibited low error rates compared to other months. However, January (R^2: 0.9337), June (R^2: 0.9537), and May (R^2: 0.9571) were months where the model's performance was relatively weaker. Particularly in January, high error values such as RMSE (117,672) and MAE (57,009) indicated larger deviations in the model's predictions. Overall, the Random Forest algorithm demonstrated successful predictive performance, with R^2 values exceeding 0.95 in most cases, proving to be an effective tool for understanding vehicle passage trends.

Hükümet Intersection became the focal point of traffic density during the pandemic. Vehicle passages at this intersection were accurately predicted by the Random Forest model. The 1st and 2nd Industrial Gate Intersections showed stable traffic flow, even during the pandemic, due to the continuation of economic activities. Predictions for these regions generally aligned closely with the actual data. Although İstasyon and Çardaklı Intersections exhibited lower vehicle passage volumes, the model successfully captured general trends in these areas. Traffic density showed significant fluctuations in January and February, leading to increased prediction errors. In February, predictions were more stable. The model's predictive performance peaked in March, as regular vehicle passage trends allowed it to produce more accurate results. In April, error rates slightly increased. In May and June, the model's performance declined, and prediction errors rose. Sudden fluctuations in traffic during this period challenged the model's adaptability. During the summer months, as traffic density increased, the model delivered successful predictions in August, although deviations were notable in July. In the autumn and winter months, the model generally achieved high accuracy, though prediction errors rose again toward the end of the year. The Random Forest model accurately predicted vehicle passage trends, even under pandemic conditions. Its accuracy exceeded 95% in many months, with particularly close predictions in March and August. However, prediction errors were relatively higher in January, May, and June, indicating the model's difficulty in adapting to periods of intense fluctuations.

6.2.2. Post-Pandemic Period

As illustrated in Figure 6, vehicle passage trends at 19 different intersections during the post-pandemic period (2023-2024). The black lines represent actual vehicle passage numbers, while the red lines represent the predictions made by the Random Forest model. Overall, Hükümet Intersection (Intersection 9) continued to experience the highest traffic density, whereas other intersections (particularly Intersections 1-8 and 10-19) maintained lower traffic volumes. The Random Forest algorithm accurately predicted general trends and traffic density with high precision.

In the post-pandemic period, an overall increase in traffic volume has been observed. This increase can be attributed to the revival of economic activities and the normalization of social life. However, fluctuations persist in certain months and intersections. These fluctuations highlight the impact of seasonal effects and social dynamics on traffic flow during specific periods. The Random Forest model demonstrated a high level of alignment with actual data. The model's R^2 values largely remained above 95%, underscoring its prediction accuracy. These high accuracy rates indicate that the model is an effective tool for forecasting traffic flow. Nevertheless, in some intersections, seasonal effects and social dynamics limited the accuracy of predictions; despite this, general trends were consistently captured. This showcases the strengths of the model while also indicating areas where improvements are needed under specific conditions.

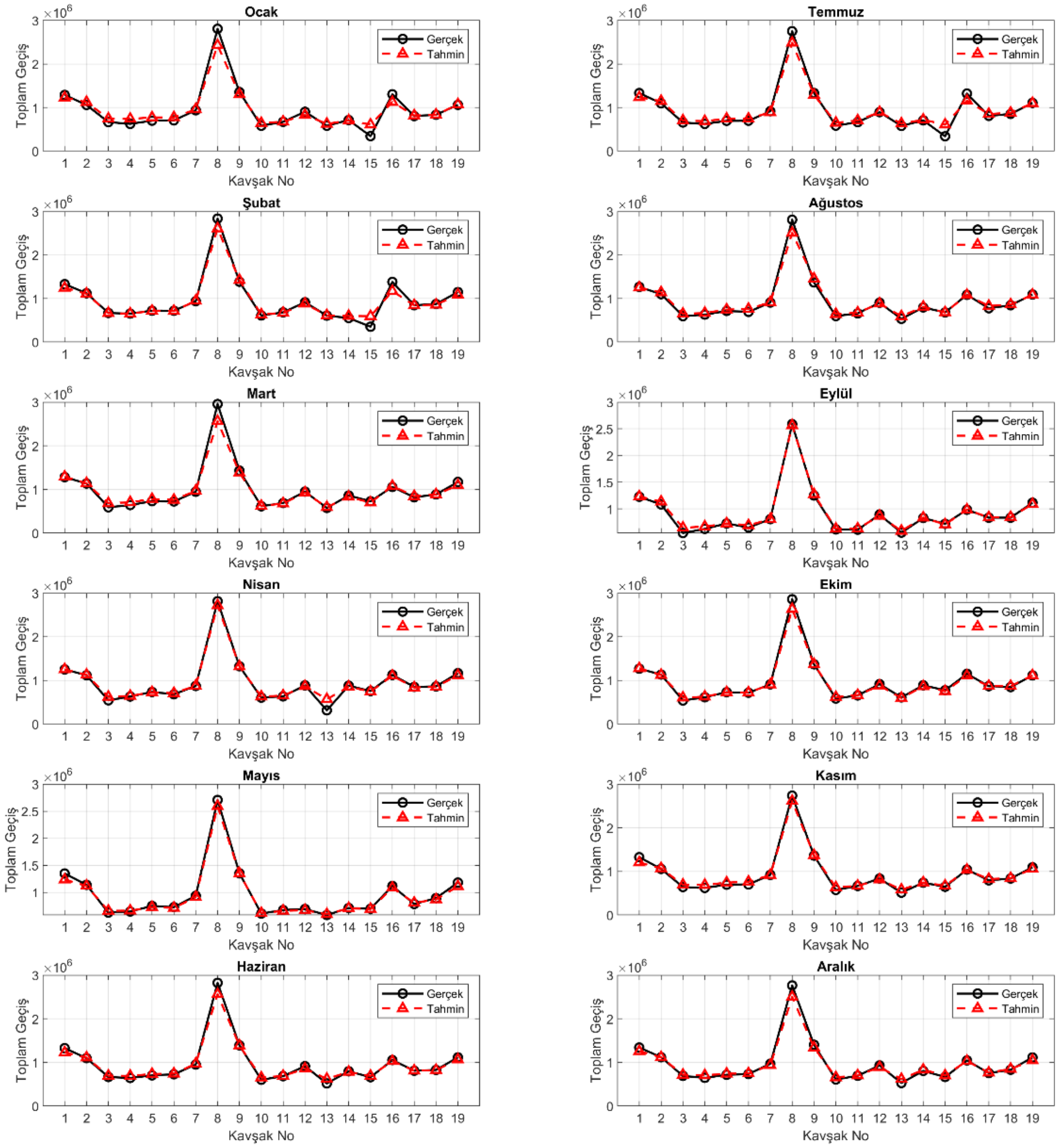

Fig. 6. Estimation of Monthly Vehicle Passage Numbers by Intersections After the Pandemic Period.

Overall, the increase in traffic volume during the post-pandemic period and the high predictive accuracy of the Random Forest model provide valuable insights for traffic management and planning. Conducting additional analyses and improving the model for intersections influenced by seasonal and social dynamics could further enhance the accuracy of future predictions. These findings form a foundation for more effective traffic management and the development of sustainable transportation solutions. As detailed in Table 5, the performance metrics during the post-pandemic period provide valuable insights.

Table 5, evaluates the monthly vehicle passage prediction performance of the Random Forest model during the post-pandemic period (2023-2024). The model achieved its highest accuracy rates in September (R^2: 0.9947) and May (R^2: 0.9916), with particularly low error rates in these months. However, prediction accuracy was lower in January (R^2: 0.9405) and July (R^2: 0.9578), suggesting that fluctuations in traffic flow adversely affected the model's performance. Overall, the model's prediction accuracy remained notably high ($R^2 > 0.95$), indicating that it reliably captured traffic trends.

The Random Forest model demonstrated high performance during the post-pandemic period. September was the most successful month for the model, achieving the highest accuracy with an R^2 value of 0.9947. Low error values, such as MAE (22,802) and RMSE (32,567), indicate that the model accurately predicted vehicle passage volumes for this month. Similarly, May also showed strong performance, with an R^2 value of 0.9916 and low error levels (MAE: 30,142, RMSE: 43,903). However, a slight decline in model performance was observed in January and July. In January, the R^2 value dropped to 0.9405, while RMSE (125,239) and MAE (83,051) values increased significantly, suggesting that the fluctuating nature of traffic challenged the model's predictive power. Likewise, in July, the model struggled to fully capture fluctuations, resulting in higher error rates. Overall, the Random Forest model delivered a successful prediction performance during the post-pandemic period, with R^2 values exceeding 0.95 in most cases, proving itself as a reliable tool for understanding traffic trends.

Table 5. Performance Metrices During Post-Pandemic Period.

#	MONTH	MSE	RMSE	MAE	R²
1	January	15684901485	125239,3767	83051,69603	0,940507971
2	February	9024935956	94999,66293	54427,58374	0,967391510
3	March	9644502909	98206,43008	50127,13268	0,964476300
4	April	4513402025	67181,85785	35745,09337	0,982476068
5	May	1927497010	43903,26878	30142,41602	0,991603098
6	June	5470652272	73963,85788	45435,29955	0,977944812
7	July	10827003396	104052,8875	71763,4365	0,957809187
8	August	6342764004	79641,47163	46186,84769	0,974226465
9	September	1060659451	32567,76706	22802,64585	0,994688139
10	October	3264816622	57138,57385	28289,22732	0,987055951
11	November	2896196847	53816,3251	39978,44552	0,987683048
12	December	5504246856	74190,61164	48260,69823	0,976705948

Hükümet Intersection (Intersection 9) was consistently the point with the highest traffic volume throughout all months. Traffic trends at this intersection were successfully predicted by the model. In industrial zones, particularly at Sanayi 1 Gate and Sanayi 2 Gate intersections, economic activity persisted even during the pandemic, resulting in stable traffic flow. The Random Forest model accurately predicted traffic trends in these areas. At İstasyon and Çardaklı Intersections (Intersections 8 and 10), which had moderate traffic volumes, the model effectively captured overall trends. In the January-March period, fluctuations in traffic density were observed in January, leading to increased model errors. However, in March, the model predicted a more balanced traffic flow. During the April-May period, model performance improved, reaching its peak in May with an R^2 value of 0.9916. Traffic density increased during the summer months (June-August), with a rise in prediction errors in July, followed by a recovery in August. For the September-December period, the model achieved its highest performance in September (R^2: 0.9947), while prediction errors increased in December.

The Random Forest model performed well overall in predicting traffic trends during the post-pandemic period. It achieved peak accuracy in May and September, with particularly low prediction errors. April also stood out as a successful month, whereas January and July showed relatively weaker performance. The increase in error rates during these months highlights the adverse impact of sudden traffic fluctuations on the model's predictive accuracy. This indicates a need for further model improvements to better adapt to periods with volatile traffic flows. With the normalization of traffic flow in the post-pandemic period, the Random Forest model successfully captured overall trends and provided reliable results for traffic forecasting. This analysis serves as a valuable guide for understanding traffic density in Balıkesir during the post-pandemic period and for evaluating modeling outcomes. The insights provided by the model offer a valuable data source for developing traffic management strategies and informing future traffic planning efforts.

6.2.3. Evaluation of the Pandemic Period and the Subsequent Period

Traffic Trends and Intersection Densities:

During the pandemic period, traffic density generally remained at low levels due to factors such as lockdowns and business closures, with significant fluctuations observed in certain months. During this time, Hükümet Intersection (Intersection 9) stood out as the intersection with the highest traffic flow. In contrast, Sanayi 1 and 2 Gates, along with nearby intersections (Intersections 8 and 10), exhibited relatively lower traffic levels. These differences reflect the impact of the pandemic on economic and social activities in different regions.

In the post-pandemic period, specifically during 2023-2024, traffic density began to normalize, and vehicle passage volumes generally increased. Hükümet Intersection maintained its position as the intersection with the highest traffic flow during this period. Meanwhile, vehicle passage volumes at industrial and peripheral intersections showed a moderate increase compared to the pandemic period. This increase can be attributed to the revival of economic activities and the return to normalcy in social life. These changes in post-pandemic traffic dynamics emphasize the importance of reviewing regional traffic management strategies and adapting to evolving conditions.

Traffic Density and Fluctuations:

During the pandemic period, significant decreases and sudden increases in vehicle passage volumes were observed due to lockdowns and other measures. These fluctuations became particularly evident during the periods when restrictions were implemented or lifted, making it more challenging for the model to generate accurate predictions. The transitions between imposing and lifting restrictions caused unpredictable changes in traffic flow, which adversely affected the accuracy of the prediction models.

In the post-pandemic period, traffic flow became more regular. During 2023-2024, with the normalization process, vehicle passage volumes generally increased, and traffic dynamics followed a more stable pattern. Particularly in September, the model achieved highly successful predictions with low error rates. This success can be considered an indicator of the effectiveness of post-pandemic traffic regulations and the revival of economic activities.

Model Performance:

During the pandemic period, the Random Forest model demonstrated generally successful predictive performance. The model's R^2 values remained mostly above 0.95, indicating that it accurately captured fluctuations in traffic. Particularly in March, April, and August, the model's prediction errors were at notably low levels. However, the model's performance weakened in January and November due to fluctuating traffic conditions, resulting in higher error rates. This highlights the impact of unpredictable changes during the pandemic on the model's accuracy.

In the post-pandemic period, the Random Forest model made successful predictions with R^2 values ranging from 0.94 to 0.99. May and September emerged as the months with the highest accuracy levels for the model. The more stable traffic density during this period contributed to the model's consistent performance. However, relatively higher prediction errors were observed in January and July, attributed to increased traffic fluctuations during these months. While the normalization process following the pandemic made traffic flow more predictable, improving the model's overall performance, fluctuations during certain periods still challenged its predictive accuracy.

These findings demonstrate that the Random Forest model generally provided reliable results in traffic predictions during both the pandemic and post-pandemic periods, but its performance could fluctuate under specific conditions. The high accuracy rates suggest that the model can provide valuable insights for traffic management and planning, while also emphasizing the need for additional measures and model improvements during periods of fluctuation. In the future, the development of methods better suited to sudden changes in traffic dynamics could enhance the model's predictive success and support the effectiveness of traffic management strategies.

7. Conclusions and Recommendations

The COVID-19 pandemic has caused profound changes not only in health and social domains but also in transportation dynamics and traffic management. This study analyzed traffic density in Balıkesir province during the pandemic and post-pandemic periods, evaluating the potential contributions of machine learning and AI-based approaches to traffic management. The increase in individual vehicle usage and the decline in public transportation preferences clearly demonstrated the pandemic's impact. During the pandemic, traffic density in city centers decreased by over 50%, indicating a shift toward private vehicle use driven by health concerns. This decrease, particularly observed in commercial and social centers, highlights how transportation preferences were reshaped by health-related considerations.

The regression analyses and Random Forest model used in this study successfully analyzed traffic fluctuations during the pandemic and the increase in traffic volumes during the post-pandemic period. The findings revealed fluctuations in vehicle traffic during the pandemic and showed that traffic density in areas such as industrial zones, where logistical activities continued, was less affected. The relatively stable traffic flow at intersections near industrial zones demonstrates the continuity of economic activities in these areas. However, the increase in individual vehicle usage poses a risk of exceeding pre-pandemic traffic density levels at city center intersections. The decline in public transportation usage and the preference for private vehicles significantly impacted urban traffic, necessitating new arrangements at intersections.

Machine learning approaches such as the Random Forest model accurately predicted traffic normalization trends in the post-pandemic period. The model achieved high accuracy rates ($R^2 > 0.99$) in May and September, successfully forecasting post-pandemic traffic flow. However, during January and July, increased traffic fluctuations led to higher prediction errors. This indicates the need for model enhancements to better adapt to complex and variable traffic flows. Overall, the contributions of machine learning approaches to evaluating and predicting traffic trends underscore their value, particularly in analyzing post-pandemic traffic dynamics.

Comprehensive measures are needed in the post-pandemic period to encourage individuals to return to public transportation. Hygiene standards in public transportation systems should be improved, and regular health-related information campaigns should be conducted. Furthermore, enhancing accessibility and comfort standards is essential to make public transportation more appealing. To counter the increase in private vehicle usage, promoting environmentally friendly transportation modes can be an effective strategy to reduce urban traffic density. Investments in infrastructure supporting micromobility options such as bicycles and scooters should be prioritized, and pedestrian pathways should be improved for short-distance travel.

Given the critical role of intersections in traffic flow, upgrading existing signalization systems to adaptive systems is crucial. The implementation of smart traffic management systems can improve traffic flow by optimizing signal timings based on real-time traffic density. Solutions such as green wave applications can effectively reduce congestion in city centers. Additionally, physical adjustments to intersections, particularly in high-traffic areas, can alleviate congestion. In intersections with heavy vehicle traffic, the construction of grade-separated intersections (multi-level intersections) can provide long-term relief from traffic congestion. Heavy vehicle traffic concentrated in industrial zones increases pressure on infrastructure in these areas. Therefore, the optimization of logistics centers serving industrial zones and the regulation of heavy vehicle traffic during specific time intervals are necessary. The observed increases in traffic density in specific areas and times highlight the need for flexible traffic management systems. Moreover, the data obtained during the pandemic serve as a valuable guide for managing urban traffic more efficiently during crises. Based on these findings, more flexible and sustainable transportation policies should be developed to prepare for similar crises in the future.

The fluctuations in traffic density and changes in transportation preferences experienced during the pandemic necessitate the development of new approaches to traffic management and planning in cities like Balıkesir. In this context, transportation policies must be structured to support long-term and environmentally sustainable goals. The adoption of smart traffic systems, widespread implementation of green wave applications, and support for micromobility solutions will enable more efficient and sustainable urban transportation management.

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