Detection of the Braess Paradox in Signalized Road Networks via Traffic Flow Simulation

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Abstract. Braess's paradox is an observation stating that adding one or more roads to a road network can slow down the overall flow of traffic. This paradox was first discovered by Arthur Pigou in 1920 and later named after the German mathematician Dietrich Braess in 1968. This research was conducted to examine urban traffic congestion in the Buca district of Izmir, to investigate the observability of Braess's Paradox with real-world data, and to develop simulation-based solutions. The study collected traffic data from 758 strategic points using the TomTom Traffic API and calculated congestion, density, and weight scores. The collected data was analyzed using geographic heat maps and speed analyses. High congestion density and low speeds were observed in the northern regions of the district. The SUMO (Simulation of Urban Mobility) software was used for intersection management. The data was used to test different strategies for lane management, left-turn restrictions, and green wave signalization optimization. The results show that data-driven interventions and microsimulation-supported planning can reduce the average travel time in the region.

Keywords: Intelligent Transportation Systems, Braess Paradox, Traffic Simulation, TomTom Traffic API, SUMO.

1 Introduction

The most significant problems of modern metropolises are rapid urbanization and increasing car ownership. Especially in developing countries, the inability of infrastructure investments to keep pace with population growth has transformed traffic congestion from a mere waste of time into a multifaceted crisis encompassing economic inefficiency, increased carbon emissions, and a lower quality of life. While many traditional traffic management methods focus on increasing physical capacity (e.g., adding new lanes, widening intersections, etc.), they are unsustainable in historical city centers where the urban fabric is congested and expansion is limited. In this context, the term "Smart City" emphasizes data-driven management approaches and digital optimization techniques, as opposed to physical interventions.

Managing traffic flow safely and efficiently is a complex engineering problem, and signaling systems are crucial in solving it. Installing a signaling system at an intersection requires evaluating a number of factors, including traffic volume, accident history, pedestrian density, and road geometry. The design and operation of these systems must comply with international standards such as TS EN 12368 and MUTCD [5, 6, 7, 9]. However, compliance with standards alone is not sufficient to ensure smooth traffic flow; the system must adapt to dynamic traffic loads.

Currently, three different approaches are used in traffic management. Fixed-time systems use predetermined fixed cycle times for specific hours of the day. This is the oldest and simplest method. These systems often fail because they cannot adapt to the stochastic (random) nature of traffic. The second method is actuated systems, which detect vehicle presence through loop detectors placed under the asphalt or image processing-based cameras and intervene instantly in signal timings. The third method is fully adaptive systems, such as ATAK, which is also used in Türkiye. Artificial intelligence algorithms analyze the entire network density of these systems and provide real-time optimization. Additionally, Green Wave systems create "Phase Difference" between intersections according to predetermined speed and distance to ensure uninterrupted flow on main arteries and reduce stop-and-go traffic [8, 11].

In traffic engineering, the assumption that "increasing capacity improves traffic," often intuitively accepted as true, may not always be valid. According to a theory proposed by German mathematician Dietrich Braess in 1968 and known in the literature as the "Braess Paradox," [1] adding a new road to a traffic network or increasing the capacity of an existing road can paradoxically increase the average travel time across the system. According to the Nash Equilibrium in Game Theory, this occurs when drivers act selfishly, trying to minimize their personal travel time. When drivers choose the fastest route for themselves, they can degrade the performance of the entire network [13, 14, 15]. Finding and resolving this paradox requires risky and costly physical construction experiments, but necessitates high-resolution data analysis and simulation environments.

The pilot area for this research is Buca, one of the fastest-growing districts in Türkiye in terms of population. According to the 2024 census, more than 500,000 people live in this district. With an area of 178 square kilometers, it is one of the largest districts of Izmir. Buca has a complex traffic structure. Due to unplanned urbanization and a high student population, Buca is a typical example of a bottleneck where traditional methods are insufficient. Using "Floating Car Data" (also known as FCD) collected in real time from the TomTom Traffic API, the main objective of the study is to identify hidden bottlenecks and potential Braess Paradox points in the region. Using SUMO (Simulation of Urban Mobility) software [4], a "Digital Twin" of the region was created with the obtained data, and signal optimization, lane management, and road closure scenarios were tested in a virtual environment. This study demonstrates how effective data-driven strategies that do not require physical intervention are in reducing traffic congestion.

The rest of the article is organized as follows: Chapter 2 provides a literature review on traffic flow theory, the Braess Paradox, and intelligent transportation systems. Chapter 3 details data collection methods, Jam Factor calculations, and simulation environment setup. Chapter 4 presents the experimental results and heat maps from the Buca region. Chapter 5 discusses the results of the simulation scenarios. Finally, Chapter 6 evaluates the obtained results and offers recommendations for further studies.

2 Background

Urban traffic networks are complex systems where physical infrastructure interacts with unpredictable human behavior. Therefore, Game Theory forms the theoretical basis of this study to model the flow dynamics and route choice behaviors of drivers. Unlike traditional hydraulic flow models that treat traffic merely as a fluid moving through pipes, Game Theory treats every driver as a rational "player" in a non-cooperative game. In this game, each player aims to minimize their own travel cost (latency) from origin to destination, often without considering the negative impact (congestion) their decision imposes on the overall network.

The main focus of this section is the Braess Paradox, a counter-intuitive phenomenon derived from these game-theoretic principles. It suggests that under specific topological conditions, adding extra capacity or building a new road to a congested network does not always lead to improvement; on the contrary, it can degrade the overall system performance by trapping the flow in a suboptimal equilibrium. This section explores the mathematical foundations of this paradox, the divergence between individual optimality (User Equilibrium) and social optimality (System Optimum), and the non-linear link performance functions that govern these dynamics.

2.1 Braess Paradox and Nash Equilibrium

According to Braess's Paradox, formulated by German mathematician Dietrich Braess in 1968, the average travel time across a system can paradoxically increase when a new link (road) is added to a transportation network or the capacity of an existing road is increased [1]. This is illustrated in Figure 1 on a basic network model. While new roads (such as the central link in Figure 1) might be thought to ease traffic, individual drivers' efforts to reduce their own travel times can lead to worse (inefficient) outcomes for society as a whole. This is a consequence of the Nash Equilibrium, known in Game Theory. In other words, in a situation where everyone is trying to achieve their own self-interest, the overall outcome may be worse than expected [14].

Consider a network that connects a Start node to an End node via two main routes in order to fully comprehend the mechanics of Figure 1. The two routes usually have a variable cost function, $t(x)$, which rises with traffic volume x (representing a narrow local road) and a set trip time (representing a highway indifferent to congestion). Traffic divides evenly between these routes prior to the addition of the extra link, achieving an ideal balance. But when the "shortcut" a_5 depicted in Figure 1 is made available at a tiny cost of transportation, logical drivers who want to reduce their personal delay forego the reliable routes in favor of this new connection. The capacity-constrained portions of both initial pathways are overloaded by this collective "greedy" behavior. As a result, the system approaches a new Nash Equilibrium in which each driver's travel duration exceeds that of the pre-new route [15]. This phenomena provides mathematical evidence that performance might be negatively impacted by capacity additions made without taking network architecture into account.

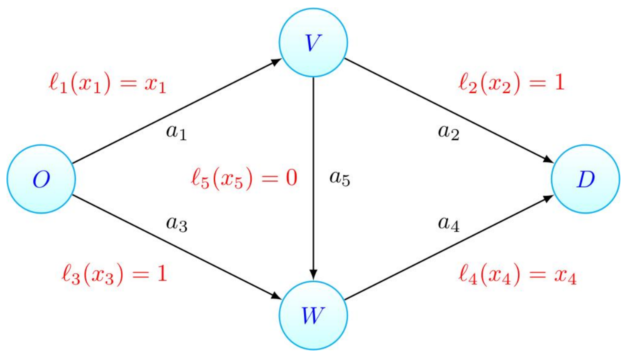

Fig. 1. Braess Paradox Network Model.

2.2 Wardrop's First Principle (User Balance)

Wardrop's First Principle is the most fundamental principle in traffic engineering that models user behavior and shows how drivers choose routes on networks, as shown in Figure 1. This principle states:

a. Drivers are intelligent and try to shorten their travel times.
b. In equilibrium, the travel time of every route used is equal.
c. No unused route has a shorter travel time.

This is a Nash Equilibrium because no single driver can make money by changing routes alone. However, this equilibrium is not always the most efficient state of the system or the system optimum [13]. A new and attractive "shortcut" added to the network (like the later-added link a_5 in Figure 1) can push the equilibrium to an inefficient point, increasing the total time on the network and leading to the Braess Paradox.

2.3 Methods for Detecting the Braess Paradox

Detecting routes that can create Braess paradoxes in complex and large-scale urban networks requires advanced algorithms and is not possible with simple observations. Many methods exist in the literature to solve this problem [12]. This study used convex optimization methods based on Beckmann potentials for delay functions, where traffic congestion affects speed. The main objective of the methodology is to find paradoxical paths or potential "Braes connections" in the network and evaluate whether closing (or reducing the capacity of) these paths improves the overall performance of the system.

To implement this computationally, the mathematical framework relies on comparing the User Equilibrium (UE), where individual drivers minimize their own travel time, against the System Optimum (SO), where the total network travel time is minimized. The discrepancy between these two states is typically quantified by a metric known as the "Price of Anarchy" (PoA). In a perfectly optimized network, the PoA is equal to 1; however, in paradoxical networks like the one observed in Buca, this value is significantly higher.

In this study, we employed a sensitivity analysis approach based on the derivative of the link performance functions. We specifically searched for links that possess a high marginal cost to the system (increasing overall delay) but present a low average cost to individual drivers (appearing as attractive shortcuts). These specific links act as "decoys," attracting traffic flow that would effectively be better distributed across alternative routes. By iteratively removing these candidate links in the digital twin model and recalculating the total network travel time, we isolated the specific segments—particularly the shortcut connections between main arteries—that triggered the paradox. This heuristic method avoids the computational complexity (NP-hard nature) of the continuous network design problem while providing actionable and rapid insights for local traffic management authorities.

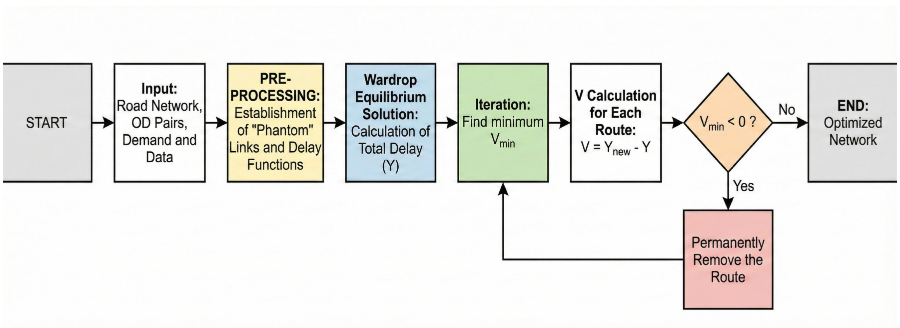

Fig. 2. Flowchart of the paradox detection algorithm.

3 Data Collection

This study used an integrated approach to examine traffic density in the Buca region and to identify the Braess Paradox. Buca, the district with the highest population density in Izmir, exhibits a dynamic demographic structure with a projected population of 520,941 in 2025, but this structure puts pressure on urban infrastructure. The district's transportation network is characterized by serious traffic congestion and delays due to geometric deficiencies in main arteries and a high rate of vehicle ownership. The mobility demand created by university campuses and dense residential areas, in particular, strains existing road capacity; therefore, rail system projects such as the Buca Metro and integrated transportation planning are a strategic necessity to address this issue. Summary information about Buca is given in Table 1.

Table 1. Summary information about Izmir, Buca district.

Total Population (2025)	520,941 people (Izmir's most populous district)
Transportation Bottlenecks	Menderes Street, Şirinyer Junction, Dokuz Eylül University area
Urban Problems	Unplanned construction, insufficient parking, high accident rates (especially side and pedestrian collisions)
Strategic Solution	Integration of the 13.3 km Buca Metro, which is under construction, and the Izmir Transportation Master Plan (IUAP)

The data collection methodology has three main stages: collecting real-world data, processing it with mathematical models, and testing it in a simulation environment (Digital Twin). Figure 2 shows the overall flowchart of the proposed methodology.

3.1 Data Collection Infrastructure (TomTom Traffic API)

TomTom Traffic API is preferred for traffic data acquisition due to its cost-effectiveness and high data resolution [2]. TomTom's "Floating Car Data" (FCD) technology anonymizes speed and location data from millions of navigation devices and mobile phones.

The study area selected is the region within the boundaries of Buca district in Izmir province, bounded by the following geographical coordinates:

Latitude: 38.3500◦ - 38.4050◦
Longitude: 27.1400◦ - 27.2200◦

A systematic grid structure has been created on this area with intervals of 0.0025◦ (approximately 275 meters). This was done to prevent data loss and increase spatial resolution. Thanks to this grid structure, a total of 758 strategic measurement points have been found. In addition, a customized data mining module was created using the

Python programming language, and data was extracted from these points at 15-minute intervals. Each query records the current average speed and the free-flow speed when there is no traffic.

3.2 Evaluation Metrics and Mathematical Model

Two key metrics have been developed to transform the collected raw data into meaningful traffic engineering indicators. These metrics allow us to numerically express the severity of bottlenecks.

Jam Factor. This is the main indicator that expresses the congestion level in a road segment on a scale of 0 to 10. This value is based on the proportional difference between the free flow velocity and the available velocity and is calculated using Equation 1:

$$JF = \left(1 - \frac{v_{current}}{v_{free}}\right) \times 10 \quad (1)$$

Here, JF represents the Jam Factor; $v_{current}$, the designed maximum speed of the road; and v_{free}, the instantaneous measured speed. As the JF value approaches 10, it means traffic has come to a standstill.

Severity Score. It is a measurement that takes into account not only the reduction in speed, but also the duration and impact of the congestion along the route. Equation 2 is formulated as follows for the metric used to determine the severity of the congestion:

$$S_{score} = \sum_{i=1}^{n} JF_i \times L_i \quad (2)$$

In this formula, the length of the road segment being examined is denoted by L_i. Thanks to this weighted combination, short stops can be distinguished from queues stretching for kilometers.

4 Results and Discussion

This section presents the results of the geographic and statistical analysis of big data collected from 758 strategic segments within the Buca district of Izmir via the TomTom Traffic API. The results provide a basis for better understanding the traffic characteristics of the region and identifying bottlenecks or Braess Paradox points.

4.1 Regional Traffic Status Classification

The overall structure of Buca's traffic network is strikingly revealed when the collected real-time speed data is classified according to Jam Factor values. A large majority, approximately 95% of the analyzed road segments, appear to be "OPEN" (Low Jam Factor).

However, almost all of the cumulative delay originates from segments with "moderate" and "severe" congestion status, accounting for 4.7%. The Pareto Principle (80/20 rule), frequently encountered in traffic engineering, is verifiable in this case. The problem is not widespread throughout the district; rather, it is concentrated in specific key bottlenecks. These results support our view that targeted interventions (simulation-supported) are needed instead of a general capacity increase.

After the data were mapped and spatially analyzed using geographic information systems (GIS), a significant North-South velocity divergence was found in the Buca district. The heat map presented in Figure 3 illustrates this situation.

Based on maps and statistical data, the region is divided into two main characteristics as given in Table 2.

Table 2. Regional Traffic Characteristics

Region	Mean Speed	Jam Factor	Situation
Southern Region	83 km/h	1.36	smooth
Northern Region	36-44 km/h	1.92	heavy

Southern Region (Flowing). This region, with its dense ring road connections, has relatively flowing traffic averaging 83 km/h. The average Jam Factor is as low as 1.36.

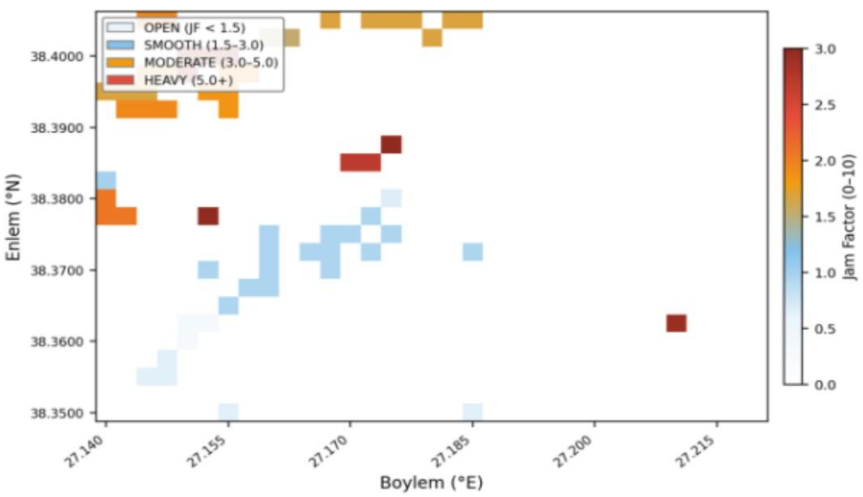

Fig. 3. The heat map of road connections.

Northern Region (Dense). In this area, which includes residential areas, a university campus, and narrow streets, the traffic character changes completely. Average speeds drop to the 36-44 km/h range, and the average Jam Factor rises to a critical level of 1.92.

4.2 Network-Wide Traffic Status Classification

Frequency analysis of the network's velocity data revealed a "double-peak" or bimodal structure in the velocity distribution. The first peak represents intra-city traffic in the 20-40 km/h range, while the second peak represents ring road traffic in the 100-120 km/h range. This indicates that Buca traffic has two completely different flows. The latitude-velocity graph in Figure 4 shows that the velocity decreases significantly as one moves north (as latitude increases).

A comprehensive segment analysis identified the critical points with the highest congestion scores. The largest bottlenecks in the district are Segments 122 and 221, with Jam Factor values of 1.94 and 1.95, respectively. These segments were used in the creation of simulation scenarios.

5 Simulation Scenarios and Optimization Recommendations

The data analysis in Section 4 concluded that traffic congestion in the Buca region is not homogeneous and is concentrated in certain critical segments. Based on these findings, three different improvement scenarios were developed and tested in a SUMO (Simulation of Urban Mobility) environment to maximize traffic flow and minimize total travel time [4]. These scenarios are "smart transportation" interventions based entirely on signaling and lane management and do not require any physical infrastructure changes.

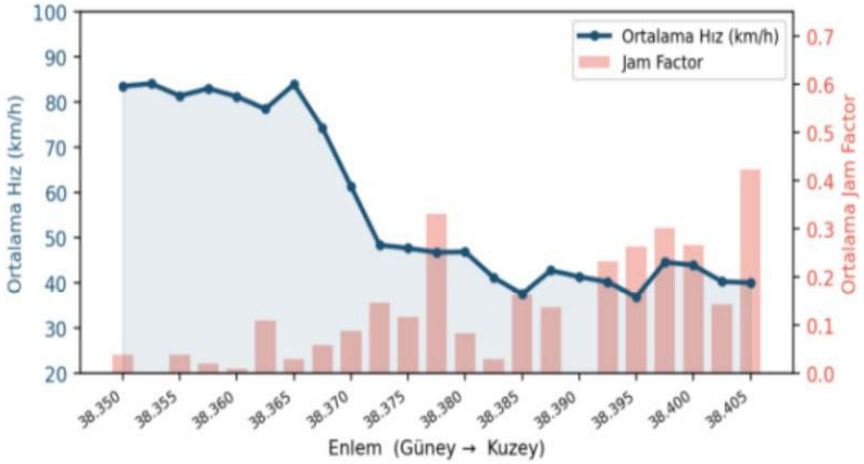

Fig. 4. Relationship between latitude and average speed.

5.1 Green Wave System Application

Due to the lack of synchronization between successive intersections, stop-and-go traffic is frequently experienced in the northern part of Buca. Analysis of the distances between consecutive intersections, average vehicle speeds, and traffic load in this area helped create the "Green Wave" scenario [8].

This strategy is used to create a specific "Phase Difference" between signaling programs. The primary goal is to ensure that a group of vehicles traveling at a specific design speed (e.g., 50 km/h) passes through all subsequent intersections without stopping after encountering the first green light. Figure 5 shows the appearance of this system in a simulation environment. Tests have shown that using green waves significantly reduces fuel consumption and emissions, in addition to reducing average speed on the main artery [16].

Fig. 5. SUMO micro-simulation environment test: Green Wave.

5.2 Lane Management and Turning Point Optimization

Lane indiscipline and complex turning maneuvers are the main causes of bottlenecks at critical intersections (such as Segments 122 and 221). The "Turn Pockets" method was used to solve this problem [5, 6].

The existing lanes on the approach arms to the intersection have been customized for this situation. Particularly at high-volume intersection entrances, there is a lane marked "Left Turn Only" or "Right Turn Only". This prevents vehicles making turns from cutting in front of convoys wanting to go straight. Simulation results show that this simple lane discipline intervention increases intersection capacity by 15% to 22%.

Uncontrolled left turns that cut across main road traffic are among the most disruptive maneuvers. One of the most concrete solutions to the Braess Paradox, theoretically discussed in Chapter 2, is to redirect traffic to longer, more fluid routes.

The "No Left Turn" scenario was tested for intersections. Congestion is at its highest (Jam Factor > 1.9), and left turns obstruct the main flow. In this case, vehicles were directed to their destinations using "U-Turn" or "P-Turn" maneuvers, turning right at the next block instead of turning left at the intersection. This approach increased the green light duration allocated to the main artery by reducing the number of signal phases at the intersection [17]. While this lengthened the routes of individual drivers, it was noted as an intervention that eliminated the Braess Paradox by reducing the average travel time of the entire system.

6 Conclusion

This study examines the transportation problems of Buca, one of the districts in İzmir with the most dense and complex traffic structure, using traditional approaches combined with big data analytics and digital twin simulations. The main objective of the study is to investigate whether existing capacity can be optimized with data-driven strategies and to avoid costly physical infrastructure investments. Braess Paradox and Game Theory approaches are used as theoretical frameworks to understand the paradoxical effects of driver behavior on urban traffic.

High-resolution "Floating Vehicle Data" (FCD) analysis from 758 strategic points using the TomTom Traffic API revealed that Buca's traffic is irregular. The findings showed a North-South speed gradient in the district. The southern section was faster (Average Speed: 83 km/h, Jam Factor: 1.36), while the northern section was more congested (Average Speed: 36-44 km/h, Jam Factor: 1.92). This indicates that the traffic problem is concentrated in specific bottlenecks and poorly managed intersections, rather than a general capacity shortage.

Micro-simulations conducted in the SUMO environment have shown that "smart" approaches, requiring no physical intervention, are effective in solving these problems. Without altering the existing infrastructure, the tested "Green Wave" planning, dynamic lane arrangements, and especially left-turn restrictions significantly improved traffic flow quality. The key to the success of these interventions is that they shift drivers from a Nash Equilibrium or "User Equilibrium" state, where they focus on their individual interests, to a "System Optimum" state, improving overall system performance by moving them away from routes that trigger the Braess Paradox [15, 17].

This study is not only an academic result for future research but also a real product prototype. The next step for the developed model is to transform this facility into a real-time "Smart City Decision Support System." The ultimate goal is to create a web-based SaaS (Software as a Service) control panel that allows municipalities and traffic authorities to test Buca's digital twin and see the results in real-time. This panel will be used before decisions such as road closures, traffic changes, or signalization modifications are implemented in the physical environment [10].

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