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Research Paper

Analyzing and Predicting Fatal Road Traffic Crash Severity Using Tree-Based Classification Algorithms

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Abstract

School transportation services operate in connection with the urban transportation network. The compatibility of the network's carrying and congestion capacity depends on the functional system of its activities across temporal and spatial dimensions to enable adaptive performance. This study aims to examine the rhythmic structure of private school transportation services in Zanjan city and their role in generating and reproducing traffic within urban networks. The research employs a qualitative-exploratory methodology with an applied focus. Data were collected from a sample of over 200 school transportation services using interviews and observations. The collected data were analyzed and categorized using a rhythmic interpretation approach, considering variables such as movement patterns, routing, traffic nodes, origins and destinations, temporal characteristics, routes, spatial occupation, and functional amalgamation, and implemented in a Geographic Information System (GIS). The findings indicate that the functional structure of private school transportation services in Zanjan operates at the urban scale and is dependent on the origin-destination system of residences and schools. The results show that the functional rhythm of these services in central city schools peaks in the afternoon, whereas in peripheral areas it peaks in the morning. The main arterial and primary road networks serve as the framework for the movement and traffic system of these services, operating proportionally to residential weights and traffic nodes. Consequently, the study concludes that the functioning of private school transportation services in Zanjan is based on regional and urban traffic patterns. Given the size and spatial scale of the city, the flows of these services exhibit relatively long temporal and spatial intervals.

Keywords: Traffic, Private Schools, Network Flow, Zanjan

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1. Introduction

If the urban structure is conceived as an organic system in which all components interact and operate collectively to achieve desirable urban development, it becomes evident that the very existence of this system depends on its functional integration and operational coherence. Among the core functions of the city, intra-urban transportation plays a pivotal role, with urban networks functioning in a mutually dependent and interconnected manner [Nassiri et al., 2022]. Public transportation systems constitute a fundamental driver of economic growth, social sustainability, and quality of life, forming an inseparable part of citizens' daily activities [Chow et al., 2016].

Urban public transport networks are indispensable for achieving sustainable development, safeguarding public health, and ensuring societal security (Chow et al., 2016). These systems encompass collective modes of movement designed to facilitate the spatial redistribution of people within pre-planned networks. Buses, taxis, trains, airplanes, motorcycle taxis, freight carriers, and school transport services are key components of this system. The operational efficiency of public transport depends not only on supporting factors—such as fleet quality, maintenance services, and network safety but also on the temporal scheduling and functional rhythm of movements within the urban traffic structure [Ramazanzadeh et al., 2015].

Urban trips account for a substantial share of public transport movements and are strongly influenced by the organization of the urban network and the time-sensitive pattern of residents' activities [Ramazanzadeh et al., 2015]. However, persistent challenges such as air pollution and traffic congestion have prompted urban decision-makers to encourage greater reliance on public transport [Kazemi & Hosseinali, 2022]. Yet, inefficient temporal and spatial management has not only failed to mitigate congestion but has, in some cases, generated new operational challenges, thereby diminishing the effective performance of urban transport networks [Kazemi & Hosseinali, 2022].

The temporal overlap of public and private transport, the weak performance of certain network segments, and the dispersed spatial distribution of travel-attracting land uses collectively produce heavy traffic masses during peak hours. These conditions increase travel times and generate psychological and social stress among urban residents. Such tensions arise less from human behavior or vehicle numbers than from the mismanagement of time, space, and the distribution of transport functions across the urban network [Kazemi & Hosseinali, 2022]. Within this context, urban school transport services represent a particularly critical component of public transportation. Operating at least twice daily, these services are responsible for the safe movement of children a highly sensitive population group. Therefore, designing school transport systems with maximum safety and community well-being in mind is essential [Sakellariou & Kotoula, 2017]. The departure times of school vehicles often coincide with the start of other urban functions (e.g., government offices and private companies), thereby intensifying congestion within the urban network (Nassiri et al., 2022).

The issue becomes even more complex in the case of non-governmental (private) schools. Unlike public schools, which generally admit students based on residential proximity, private schools enroll students according to parental preference, irrespective of distance. Consequently, their catchment areas and the associated transport service areas are considerably wider [Nassiri et al., 2022]. The city of Zanjan, a mid-sized urban center in northwestern Iran, contains approximately 80 private schools with dispersed spatial distribution, of which 24 are elementary schools. These institutions admit students from across the city and even surrounding rural areas,

relying heavily on public school transport services. Their dispersed locations and non-residential admission patterns integrate their school transport services into local, district, and citywide networks, significantly influencing overall traffic dynamics.

Analyzing the spatio-temporal rhythm of private school transport services and understanding their functional patterns within the urban transportation system can provide valuable insights for controlling and optimizing portions of the city's traffic network. This study therefore aims to identify the rhythmic model of elementary private school transport services in Zanjan to reveal how their operational structure is formed and how it interacts with the broader urban transport network.

In contrast to previous studies that have primarily focused on route optimization, service allocation, cost analysis, or quality and user satisfaction indicators [Amiri & Montazeri, 2016; Ahmadi & Mousavi, 2020; Nasiri, 2023; Trihantoyo et al., 2019], the present study employs a rhythmic exploration model to simulate, for the first time, the spatio-temporal effects of school-bus scheduling and movement overlap on urban transportation network performance. Unlike descriptive analyses or time-dependent routing studies [Entekhabii, 2022; Rokni, 2023; Shokri et al., 2024] the primary innovation of this research lies in the integration of rhythmic analysis, GIS-based spatial data, and network simulation, the introduction of novel rhythm-oriented indicators (such as overlap intensity and traffic impulse index), and the development of policy scenarios for service scheduling to manage traffic peaks and mitigate environmental impacts. Accordingly, the central research question is: What is the functional model of urban school transport services for private elementary schools, and which rhythmic pattern governs their impact on urban traffic?

2. Literature Review

Over the past decade, Empirical Studies on public transportation and, more specifically, school bus services although still limited has gradually illuminated various aspects of this field. A considerable body of work has focused on the optimization of service allocation and routing. Amiri and Montazeri (2016), employing a cuckoo search algorithm, demonstrated that intelligent algorithmic design can optimize the allocation of school buses and reduce the traffic burden generated by student transport. In a similar vein, Ahmadi and Mousavi (2020) developed a time-dependent routing model solved with a metaheuristic approach, confirming its effectiveness in managing traffic flows along school bus routes. Another stream of research has examined the traffic and environmental impacts of school bus systems. Entekhabi and Ekhtelafi (2022) reported a significant positive correlation between the use of school bus services and urban traffic management in the city of Mashhad. Rokni (2023), using a descriptive–analytical method with GIS tools, found that extensive reliance on school buses not only increases urban traffic volume but also contributes notably to air pollution. Likewise, Shokri et al. (2024) evaluated the operational performance of student drop-off and pick-up systems in Saudi Arabia and revealed that the level of service (LOS) in many cities ranged between C and D, indicating weak operational efficiency during peak pick-up/drop-off periods.

Service quality and user satisfaction have also attracted scholarly attention. Nasiri (2023), through a field-based questionnaire study, identified key quality indicators for school transport and showed that defining satisfaction metrics enables the prioritization of interventions and enhances their effectiveness. In addition, some international studies have investigated the economic and policy dimensions of school transport. Trihantoyo et

al. (2019), in a Malaysian context, reported that school transport costs are determined by personal expenses, operational costs, travel distance, the number of potential users, and the type of vehicle used. Gu et al. (2024) highlighted that government authorities and schools act as the main stakeholders in resource allocation, often engaging in a competitive yet collaborative relationship when providing school bus services.

Although less frequently explored, the educational consequences of school bus services have begun to emerge as a critical area of inquiry. Sanderson Edwards (2022), examining urban schools in Michigan (USA), found that traffic congestion and fatigue associated with school bus transport can negatively affect student attendance and academic achievement.

Taken together, these studies reveal that while domestic research has predominantly emphasized algorithmic optimization and traffic impacts, the economic, policy, and educational dimensions of school transport remain underexamined within an integrated framework. Furthermore, the interplay between service quality indicators and optimization models has rarely been addressed in a combined manner. The present study seeks to bridge these gaps by integrating analytical modeling with qualitative assessment to provide a more comprehensive understanding of the role of school bus services in urban transportation management.

Urban transportation constitutes a fundamental pillar of intra- and intercity communication systems, connecting urban functions through a network of routes. This system comprises three interrelated sectors: public transport, private transport, and freight transport, which continuously compete within the spatial and temporal dimensions of the city for access to limited corridors and communication networks [Rodrigue, Comtois, & Slack, 2006]. Continuous transformation of urban structure and the evolution of transportation networks reshape the physical form of the city, intensifying this competition [Dargahi, Shafiei, & Pourmohammadi, 2016]. In this context, public transportation is recognized by traffic engineers as one of the primary strategies for improving urban mobility and promoting sustainable urban development [Saghaei, Tabrizi, & Alizadeh, 2021].

In an efficient urban system, easy, safe, comfortable, and cost-effective mobility is indispensable, and, alongside economic growth, the demand for the movement of people and goods increases [Ahmadzadeh, Hosseini, & Rahimi, 2023]. Therefore, urban managers aim to strengthen the role of public transport, as reliance on private vehicles entails multiple negative consequences, including excessive fuel consumption, traffic congestion, air and noise pollution, and time loss. However, public transport vehicles generally operate along fixed routes, and many urban trips cannot be completed using a single mode of transport. Consequently, passengers often need to transfer across multiple lines or transport modes, sometimes walking portions of their journeys.

Functionally, urban transportation ensures point-to-point accessibility, addressing essential needs such as employment, income generation, education, health, leisure, and physical and mental well-being. Providing this access is a fundamental right of citizens and a core responsibility of urban management. Therefore, improving service quality and enhancing the efficiency of public transport networks remains a major focus of urban research [Kazemi & Hosseinali, 2022]. Dittmar and Poticha (2004) highlight factors such as spatial efficiency, network design, density, social values, accessibility, diversity of routes and transport modes, and minimizing conflicts between network nodes and destinations as crucial for achieving effective urban transportation.

Public transport networks are shaped in interaction with urban functions, and changes in these functions directly affect the operational

structure of the network. In other words, urban activities generate traffic flows that define the identity and spatial distribution of public and private transport networks. Any changes in activity scheduling, location of centers, feeder network structures, and user characteristics influence urban traffic patterns and distribution. Among urban functions, schools are significant generators of traffic flows, producing distinct temporal and spatial travel patterns that influence the intensity and diversity of daily mobility. The organizational scale of school catchment areas from neighborhood-level to city-wide—directly affects the volume and direction of these flows. Neighborhood schools primarily generate short, localized trips, whereas schools with district-wide or city-wide enrollment contribute to broader and more intensive intra-urban travel. Despite regulations favoring local enrollment, the expansion of specialized schools, such as exemplary or private institutions, has generated regional and city-wide traffic flows [Ahmadzadeh et al., 2023].

School bus services are closely linked to student enrollment patterns: the wider the catchment area, the longer the travel distances and the higher the traffic density. To analyze such spatiotemporal patterns, the rhythm analysis approach is particularly useful. Rhythm analysis examines recurring patterns in space and time [Azami, Moradi, & Ebrahimi, 2022], and rhythm, as a product of movement, describes sequential spatial experiences [Judson, 2011]. In urban studies, the extraction and analysis of rhythmic effects is often referred to as rhythm mining [Daviran, 2023]. The concept of rhythm was first introduced by Henri Lefebvre, who argued that wherever interactions occur among space, time, and energy, rhythms emerge, encompassing quantitative and qualitative, mechanical and organic, rational and irrational, linear and cyclical dimensions [Lefebvre, 2002].

Rhythm analysis allows the investigation of movement patterns, periodicity, continuity, causality, and recurrence, revealing the lived experiences of humans in urban spaces [Daviran, 2024]. Rhythm is the product of the flow of time through space (Henriques et al., 2014), and with human presence, urban activities acquire a rhythmic character [Daviran, 2023]. Temporal cycles reflect periods of space consumption, which may be continuous, intermittent, or sinusoidal, and can be analyzed on daily, monthly, seasonal, or multi-year scales [Lefebvre, 1992]. The results of rhythmanalysis provide insight into the production, reproduction, and consumption of space within the geography of time and place, demonstrating that, despite spatial integration, different rhythms create diverse lived experiences [Daviran, 2023].

The empirical and theoretical literature indicates that, in the field of urban transportation and school services, despite significant advances in service allocation optimization, routing, and traffic flow analysis, the policy and educational dimensions have not yet been fully explored, and optimization models have rarely been analyzed within an integrated framework. Since schools serve as primary generators of urban mobility flows, they play a key role in the structure of transportation networks, influencing both the intensity and distribution of travel. Analytical approaches such as "rhythm exploration" enable the examination of recurring patterns in space and time, as well as the understanding of interactions among human activities, temporal cycles, and urban transportation network structures. Therefore, integrating quantitative and qualitative analyses, optimization algorithms, and service quality assessments can provide a more comprehensive understanding of the role of school transportation services in urban mobility management. This study emphasizes the investigation of the "public transport rhythm based on urban school services" to identify spatial and temporal movement patterns, routes, congestion nodes, origins and destinations, space occupancy,

functional overlaps, and the spatial distribution of school transport systems in urban (non-profit) schools. The findings are intended to support educational and urban management authorities in traffic control and optimization planning.

3. Methodology

3.1. Research Method

The present study is qualitative and exploratory in nature and employs a phenomenological approach to achieve an in-depth understanding and interpretation of experiences related to the analysis of the rhythm of transportation services in non-governmental schools in Zanjan city. In terms of purpose, this study is applied and aims to utilize its findings to enhance the management and organization of school transportation services.

3.2. Population and Statistical Sample

The geographical unit of the study encompasses all private primary schools in Zanjan, including 24 girls' and boys' schools, which collectively operate approximately 1,200 student transportation services, covering more than 6,000 students.

3.3. Data Collection Method

Data were collected in the field using observation and interviews. The study population consisted of school transportation services, with a sample size of 200 services selected through convenience sampling. In studies based on urban rhythm analysis, the primary principle is to achieve a deep understanding of the phenomenon and interpret it from multiple dimensions. Accordingly, in the present study, data collection was mainly carried out through field observation and interviews with rhythm creators (school transportation services). Given the complexity and diversity of factors influencing the formation of urban rhythm such as social issues (population density, family composition, parental attitudes), economic factors (service costs, family income levels), and environmental or incidental events (traffic congestion, weather conditions, accidents) a simultaneous examination of all these variables is practically and structurally challenging. Therefore, the researcher focused on the most significant and influential components of the rhythm, extracting and analyzing them through empirical and tangible data to provide a comprehensive and interpretable understanding of the patterns and relationships within the school transportation system. Interviews were conducted directly and in person during the waiting period of school transportation services before the transfer of students, ensuring real-time and context-specific data collection. The main axes of the interview questions included the reasons and process for choosing schools in different areas of the city, the residential locations of school service drivers and the criteria for school selection, the relationship and level of influence between the driver's residence, the school's location, and the student's residence, temporal and spatial routing methods of school services and the key factors affecting route selection, important and influential factors in the movement between origin and destination (such as traffic volume, time constraints, and environmental conditions), reasons for school selection by families or drivers, and the pattern of selecting primary and secondary urban road networks for transporting students. This interview approach and the structured questions made it possible to collect accurate, empirical, and interpretable data on the functioning of school transportation services, movement patterns, and the interactions between residential locations and travel routes.

3.4. Data Analysis Method

In studies based on the analysis of urban rhythms, the fundamental principle is to understand and interpret phenomena from multiple perspectives and dimensions. This means that researchers do not limit themselves to superficial observations but strive to comprehensively analyze the structures, relationships, and patterns inherent in urban

behaviors. Accordingly, observation and interview methods targeting rhythm creators—individuals who directly shape and sustain the phenomenon—form the core of data collection in this study. However, in analyzing any phenomenon, rhythm producers comprise a diverse set of factors and elements. Simultaneous examination of all these components is practically and structurally challenging, often constrained by limitations of time and resources. Therefore, researchers in rhythm analysis generally focus on the portion of the rhythm generated by its primary creators, allowing the phenomenon to be identified and analyzed in its empirical and tangible dimensions. In the present study, the rhythm creators include students, schools, and school transportation services within urban networks. Collectively, these actors constitute the temporal rhythm of public transportation based on non-profit school services in the city. Analyzing these elements provides comprehensive insights into traffic flows, movement patterns, and the structural organization of the school transportation network. The data collected through observations and interviews were first categorized and then implemented in the Geographic Information System (GIS) based on the rhythmic analysis framework, which included movement patterns, routing, traffic nodes, origin and destination, temporal characteristics, routes, spatial occupation, and functional amalgamation. The data were visually represented, and the final analysis was conducted using an interpretive approach, enabling a comprehensive and intelligible presentation of the patterns, relationships, and phenomena inherent in the rhythm of private school transportation services.

The accuracy and validity of this study were ensured through the collection of data in real-world settings using direct field observation and face-to-face interviews with the primary contributors to the rhythm of school transportation services. The interview questions were designed to cover social, economic, and environmental factors affecting the rhythm. Data were systematically categorized and analyzed using a rhythm analysis framework and GIS tools to comprehensively identify patterns, structures, and relationships. These procedures enhanced the study's accuracy and validity, ensuring an accurate representation of the actual functioning of non-governmental school transportation services.

4. Results and Discussion

Zanjan, a city located in northwestern Iran with a population exceeding 430,000 and serving as the capital of Zanjan Province, hosts 80 non-profit schools with an overall enrollment of approximately 20,000 students. Among these, 24 institutions are non-profit elementary schools accommodating around 7,000 pupils. The citywide enrollment system allows students from all districts to attend these schools. Approximately 95% of students utilize transportation services, with more than 80% depending on public modes such as taxis, minibuses, and vans. The spatial distribution of non-profit elementary schools reveals a concentration in the central and midtown zones, predominantly aligned along secondary arterial networks. Analysis within the standard functional radius of 1,200 meters indicates that, due to the citywide enrollment pattern, the spatial functionality of schools does not fully conform to this benchmark. To investigate the dynamics of school transportation services, the study first examined the spatial distribution of schools across the city and subsequently, through interviews and field observations, analyzed aspects such as travel patterns, routing, scheduling, trip distances, the spatial relationship between schools and residences, collection and transfer mechanisms, and the organizational structure of transportation services within the urban network (Figure1).

Figure 1. Distribution System and Standard Functional Radius of Non-Profit Elementary Schools

4.1. Rhythm of Students' Residential Origins and School Transportation Services

Findings from interviews with 200 school transportation services indicate that the average distance between students' residences and schools exceeds 3 km, ranging from 1.5 to 10 km. Given the scale of Zanjan city, this shows that school transportation services move students over relatively long distances. Analysis of movement rhythms based on students' residential patterns reveals that non- profit school students are not confined to local areas but are distributed across urban and regional scales. Consequently, the school transportation network operates at both citywide and regional levels. The dispersion of student residences combined with long distances to schools contributes to urban traffic congestion, as vehicles must traverse primary and secondary road networks to transfer students.

Considering the spatial distribution of non-profit schools, residential distances, and the corresponding transportation system, the residential-educational gap emerges as a significant source of traffic congestion. This rhythm indicates that the urban enrollment system of these schools is a contributing factor to congestion in the city's road networks. Preliminary estimates suggest that over 1,000 school transportation vehicles commute in a pendulum movement during school start and

end times, and their overlap with other urban activities has a notable impact on traffic volume (Table 1).

Table 1. Characteristics of Residential Origins, Distances, and Average Travel Distances from Origin to School (and vice versa)

School Codes	Average Residential Distance of Students (Mt)		Service Residential Distance from Movement Origin (Mt)	Average Distance Traveled from Movement Origin (Mt)	School Codes	Average Residential Distance of Students (Mt)		Service Residential Distance from Movement Origin (Mt)	Average Distance Traveled from Movement Origin (Mt)
	Min	Max				Min	Max		
1	1500	9500	1200	10000	13	1250	7000	2300	6000
2	1250	7000	2000	7800	14	1250	7000	2700	6000
3	700	2500	500	2000	15	1200	7000	800	2300
4	1100	7000	1400	6500	16	1500	9500	1500	11000
5	950	4500	3400	5600	17	1400	7000	700	8500
6	1200	5000	4800	6000	18	1500	9500	2500	9000
7	950	4500	5000	4000	19	1200	5000	950	7000
8	1400	7000	2500	7600	20	900	8000	1300	6000
9	1500	8000	5000	7000	21	950	4500	1500	6000
10	1500	9500	3200	9000	22	1200	5000	1000	5000
11	1200	4500	2400	5600	23	1500	9500	3000	4500
12	700	2500	1200	2200	24	1400	7000	3000	4000

The analysis of residential patterns indicates that the concentration of students and the origins of school transportation services are primarily located in the eastern and northern parts of Zanjan city. The main student commuting origins include neighborhoods such as Golshahr, Vahidiyeh, Honarestan, Etemadiyeh, Zibashahr, Karmandan Town, Andisheh, and Koye Shahriar, with students traveling toward non-profit schools situated in the central and western parts of the city. This geographical disparity between students' residences and school locations results in a pendulum movement within the school transportation system, which directly affects traffic flow during peak hours. Studies reveal that school transport services operate from eastern origins to destinations in central and western areas of the city, and these routes are frequently congested during the morning peak period between 7:00 and 8:00 a.m. Considering the transportation system and the fact that over 60% of students reside in relatively socioeconomically advantaged areas, it can be argued that in non-profit school transportation systems, school choice is prioritized over travel distance; families prefer to enroll their children in higher-quality non-profit schools and utilize transportation services regardless of the distance to ensure better educational options for their children.

The rhythm analysis of average origin distances weighted by student residential density shows that the mean distance from home to school is approximately 5 kilometers, primarily using primary and secondary main road networks. This regular and predictable commuting pattern provides a suitable basis for route planning, scheduling services, and mitigating traffic pressure (Table 2 and Figure 2). Furthermore, this pattern of school choice and the spatial concentration of students have implications for the operational management of school transport and urban traffic. The pendulum movement from east to west and central areas, combined with peak-hour congestion, exerts considerable

pressure on the main road network, highlighting the need for precise route planning and service scheduling.

Overall, the findings indicate that the quality and reputation of schools are of greater importance to families than physical proximity, influencing the patterns of school transportation. The school transport system plays a critical role in facilitating access to non-profit schools and enabling school choice. The concentration of students and schools contributes to traffic pressure during peak hours, making route management essential. Moreover, the socio-economic characteristics of student residential areas are directly linked to school selection patterns and access to transportation services, reflecting relative inequalities in educational access.

Table 2. Characteristics of Maximum Residential Weights (Above 60%) of Student Neighborhoods and Average Distance Traveled from Origin to School

Schools	Residential Areas with >60% Student Residential Weight	Average Distance from Service Origin to School (km)	Schools	Residential Areas with >60% Student Residential Weight	Average Distance from Service Origin to School (km)
1	Golshahr, Honarestan, Vahidiyeh, Zibashahr, Andisheh, Elahieh	7	13	Golshahr, Honarestan, Zibashahr, Etemadiyeh	5
2	Golshahr, Honarestan, Zibashahr, Etemadiyeh	5.5	14	Etemadiyeh, Golshahr, Honarestan, Zibashahr, Kooye Shohada	5.5
3	Elahieh, Shahrak Ara, Amjadiyeh, Nanvayan, Kooye Farhang	3	15	Karmandan, Zibashahr, Arazi, Golshahr, Vahidiyeh	4
4	Golshahr, Honarestan, Etemadiyeh, Zibashahr	5.5	16	Kooye Shohada, Zibashahr, Elahieh, Etemadiyeh, Honarestan	4.5
5	Karmandan, Zibashahr, Andisheh, Golshahr, Fateh	6	17	Etemadiyeh, Honarestan, Golshahr, Zibashahr, Andisheh	5
6	Ansariyeh, Vahidiyeh, Honarestan, Arazi, Zibashahr, Manzariyeh	4	18	Karmandan, Zibashahr, Golshahr, Andisheh, Honarestan, Arazi, Nik Sazan	5
7	Karmandan, Zibashahr, Arazi, Golshahr, Vahidiyeh	4.5	19	Ansariyeh, Vahidiyeh, Honarestan, Arazi, Zibashahr, Manzariyeh	4
8	Karmandan, Zibashahr, Arazi, Golshahr, Vahidiyeh	4	20	Karmandan, Zibashahr, Fateh, Nik Sazan, Vahidiyeh, Arazi	5
9	Honarestan, Golshahr, Etemadiyeh, Vahidiyeh, Zibashahr	5.5	21	Zibashahr, Honarestan, Golshahr, Andisheh, Vahidiyeh	4.5
10	Honarestan, Karmandan, Zibashahr, Vahidiyeh, Golshahr	5	22	Ansariyeh, Vahidiyeh, Honarestan, Arazi, Zibashahr, Manzariyeh	4

Schools	Residential Areas with >60% Student Residential Weight	Average Distance from Service Origin to School (km)	Schools	Residential Areas with >60% Student Residential Weight	Average Distance from Service Origin to School (km)
11	Honarestan, Karmandan, Zibashahr, Golshahr, Sarjangaldari, Etemadiyeh	4.5	23	Honarestan, Karmandan, Zibashahr, Vahidiyeh, Golshahr	5
12	Elahieh, Shahrak Ara, Amjadiyeh, Nanvayan	3	24	Honarestan, Karmandan, Zibashahr, Golshahr, Ansariyeh, Etemadiyeh	4.5

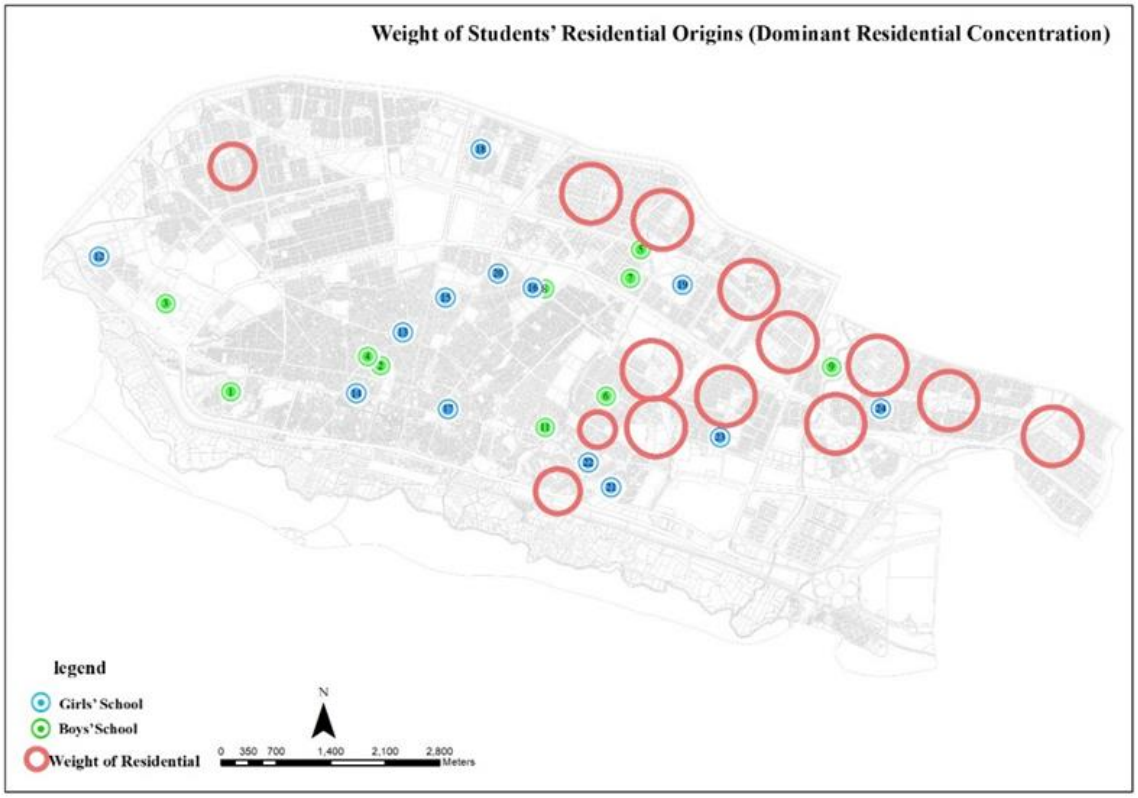

Figure 2. Points of Over 60% Concentration of Students' Residential Origins in Relation to Non-Profit Schools in Zanjan City

4.2. Travel Scheduling (Temporal Rhythm)

The study of travel times from student collection points to schools and vice versa, as well as the planned departure times of school service vehicles from their own residences to students' homes and schools, illustrates the temporal rhythm of movement within the urban transport network. Research indicates that primary schools in Zanjan including public schools, Farhangian (teachers' schools), Shahed schools, and non-profit schools follow a uniform morning start time, beginning at 7:30 a.m., with student admission commencing at 7:15 a.m. However, school dismissal occurs within three-time intervals: 12:30 p.m. for two-shift schools, 1:15 p.m. for Shahed schools, and 1:30 p.m. for non-profit schools. The simultaneous start of schools, coupled with the near-simultaneous opening of government offices and private-sector workplaces, generates significant traffic volumes on urban

corridors, particularly along main routes leading to schools. This concurrency often creates social challenges and psychological stress resulting from delays.

Given that rhythm analysis examines the flow of time through space, the study explored the temporal and spatial patterns of school service activity at both the origins and destinations of student transport. Specifically, data were collected on the departure times of vehicles from the service residence, arrival times at the origin (the student's residence), and arrival times at the school during the morning trip, as well as the corresponding return trips in the afternoon. In this context, the concept of "speed" refers to the pace at which activities and events unfold in space ranging from fast to medium or slow depending on the nature of the activity. This can also be understood through the perception of time in spaces of varying scales: in smaller environments, time is perceived to pass more slowly, whereas in larger spaces it seems to pass more quickly. Temporal continuity of rhythm relates to the duration allocated to a specific activity, which may span moments, hours, or an entire day [Shakibamanesh & Ghorbanian, 2017]. Rhythmic sequence, on the other hand, empirically reflects the succession of minutes, hours, days, and seasons as bases of change and movement, which remain in constant flux [Carr, 2017].

Findings reveal that urban school transportation services schedule trips based on the spatial relationship between the student's residence and the school, as well as the distance separating them. The location of the school within the city's access network and the positioning of student residences within the residential structure significantly shape trip timing. The travel time for a service vehicle to reach a student's residence, combined with the time needed for pick-up and drop-off, results in school transport services operating with a high degree of regularity in their departure and stopping schedules. Interviews with school transport drivers confirm that operations follow precise time intervals: drivers typically leave their own residences at fixed times, collect students punctually, and deliver them to schools with consistent accuracy. Drivers also emphasized that any delay or disruption in this tightly scheduled system whether due to student lateness, traffic incidents, peak congestion, or personal issues creates significant temporal setbacks, complicating the timely delivery of students and causing stress for both students and their families. To mitigate such risks, drivers actively consider network conditions and congestion patterns when planning their routes and schedules.

The rhythm analysis of primary non-profit school services in Zanjan shows that the average departure time of school transport vehicles from their starting location is approximately 15 minutes before arriving at the first student's residence on the morning trip and about 20 minutes before reaching the school on the afternoon return trip. Interviews indicate that the distance between the service residence, the student's residence, and the school strongly influences these time intervals. The variation in timing across the studied schools ranges from 5 to 25 minutes on outbound trips and from 15 to 25 minutes on return trips. Moreover, because of the dispersed residential patterns of students and the need for multiple pick-ups stops particularly in taxi-based services carrying four students travel times may increase or decrease depending on route conditions. The combined effects of student–school distances and the characteristics of the road network shape not only the duration of morning and afternoon trips but also the departure times from service residences and arrival times at both student origins and schools. Temporal rhythms of the transport system measured as the intervals between student arrivals and departures demonstrate that schools located in the central areas of Zanjan experience longer average travel times compared to those situated in the middle or peripheral zones of the city (Table 3).

Table 3. Average travel times of school services from residence to student location and from student residence to school in Zanjan city

School Code	Avg. time from service residence to student location (min)	Avg. time from student residence to school (min)	School Code	Avg. time from service residence to student location (min)	Avg. time from student residence to school (min)
1	15	20	13	20	20
2	20	25	14	20	25
3	10	15	15	15	20
4	20	25	16	15	15
5	15	20	17	20	20
6	10	15	18	15	15
7	15	10	19	15	20
8	15	15	20	15	15
9	10	25	21	15	20
10	15	20	22	15	20
11	15	20	23	15	15
12	10	15	24	10	15

The time-rhythm radar analysis reveals that the spatial distribution of non-governmental schools in Zanjan has generated a diverse temporal system of commuting patterns. Radar findings indicate that, on the outbound route (from the service origin to the school), travel times tend to concentrate within minimal time intervals, whereas on the return route (from the school to the student's residence), the longest time intervals are observed. In other words, the closer the time curve lies to the radar periphery, the longer the travel duration, while proximity to the radar center represents shorter travel times. The time ratios derived from the radar data demonstrate a significant increase in travel duration on the return trip, primarily due to afternoon traffic congestion on the city's main thoroughfares. Moreover, a marked difference exists between the travel time from the service origin to the student's residence and the travel time from the service origin to the school, a difference that depends on the distance of the service origin from the school as well as the distance between the school and the student's residence. The analysis further shows that service origins are largely concentrated near schools and within the urban periphery; consequently, the time–distance curves of service vehicles relative to schools are closer to the radar center, while those relative to students' residences are farther away. These results indicate that, despite variations in school locations, the temporal rhythms of school transport services between schools and student residences tend toward the radar periphery, reflecting the impact of morning traffic congestion (Figure 3).

The radar pattern analysis also highlights a structural asynchrony between the outbound and return service routes. The spatial clustering of service origins near schools allows for shorter and more regular morning travel times, as service vehicles encounter lower traffic density at the start of the day. By contrast, afternoon return trips coincide with the end of office hours and peak urban traffic, resulting in longer and more irregular travel durations. This situation not only intensifies pressure on the urban transportation network, but also demonstrates how the spatial configuration of non-governmental schools and parental preferences for school choice directly influence the timing and operational efficiency of school transport services. Furthermore, the placement of service origins in peripheral areas but in close proximity to schools reflects a spatial–

economic strategy: drivers often locate their residence or service base near schools to minimize operational costs and maintain control over departure times, even if this arrangement leads to extended travel times for students on the return trip. This temporal disparity affects urban traffic management and service scheduling and can serve as a key indicator for monitoring the performance and quality of school transportation services within the city.

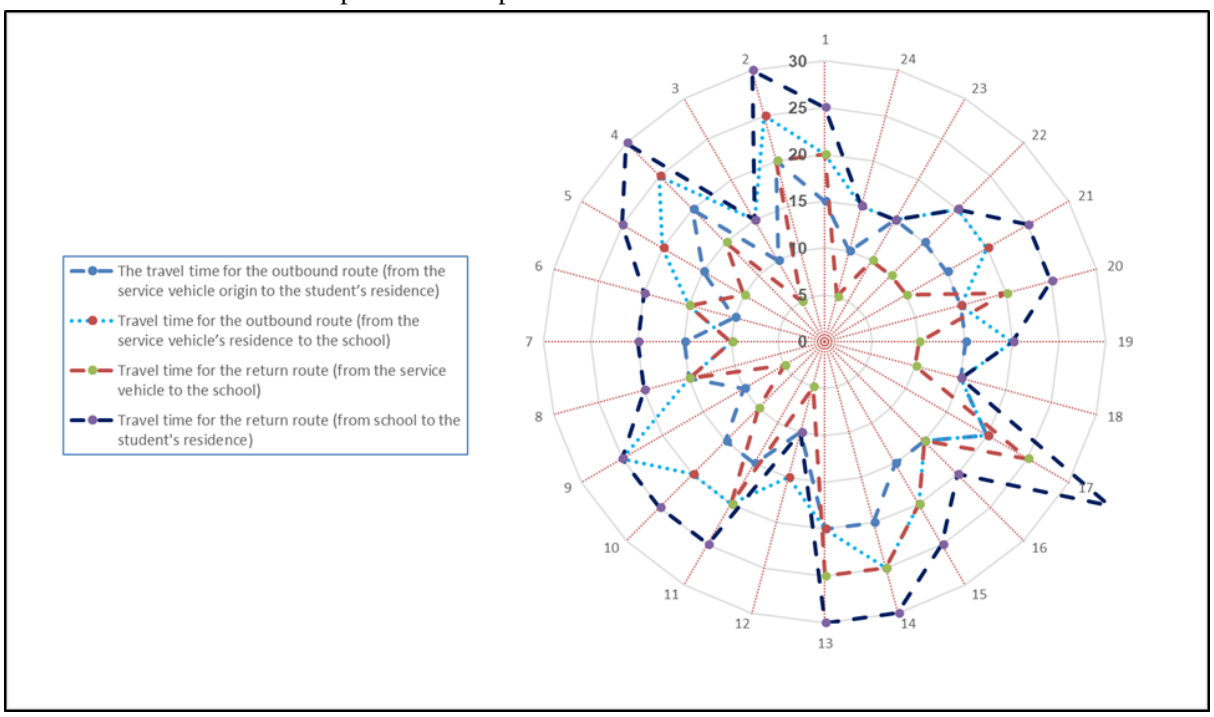

Figure 3. Temporal Rhythm Radar of Nonprofit School Transportation Services in Zanjan City

4.3. Route Planning of School Services (Spatial Rhythm of Movement)

To map the travel routes of school transportation services between students' residences and schools, drivers were asked to delineate or describe their typical routes on a detailed map of Zanjan city. The results indicate that route planning is strongly influenced by drivers' familiarity with both the origin and destination points as well as their knowledge of the urban road network. Drivers predominantly select routes that provide optimal and minimally congested access to schools and student residences. While the majority rely on experience-based, traditional knowledge of the city, a limited number utilize digital navigation systems to assist in route optimization.

The analysis shows that school transport services generally transition from primary arterial roads to secondary and tertiary networks, with the objective of avoiding traffic congestion nodes whenever possible. Despite unavoidable encounters with congested areas—particularly during morning peak hours—services operating in the central urban fabric predominantly utilize two main arterial highways, 22 Bahman Highway and Khayyam Highway, thereby minimizing direct penetration into the high-density central areas. These highways serve as collector and distributor corridors feeding into secondary networks but are consistently congested. Access to schools within the central urban fabric is primarily facilitated through secondary roads (e.g., Baset, Saadi, Emam, 17 Shahrivar, Sheikh Fazlollah, Safa), though the residential distribution of students reinforces the importance of primary arterial roads as key access routes.

In contrast, schools located in the northern and eastern sectors of the city rely predominantly on secondary and tertiary road networks, navigating through less congested secondary streets within the structured grid patterns of new urban developments to circumvent heavily trafficked main roads. Services in these areas typically maintain routing along these secondary and tertiary streets, reflecting both the spatial distribution of schools and the hierarchy of urban roads. Schools in northern Zanjan are often situated within tertiary networks that connect primary and secondary roads, resulting in diverse and adaptive routing patterns. Interviews with drivers indicate that routing decisions are systematically influenced by traffic conditions and congestion nodes, with services strategically allocating routes to minimize delays and to ensure efficient, timely, and cost-effective student transport (Figure 4).

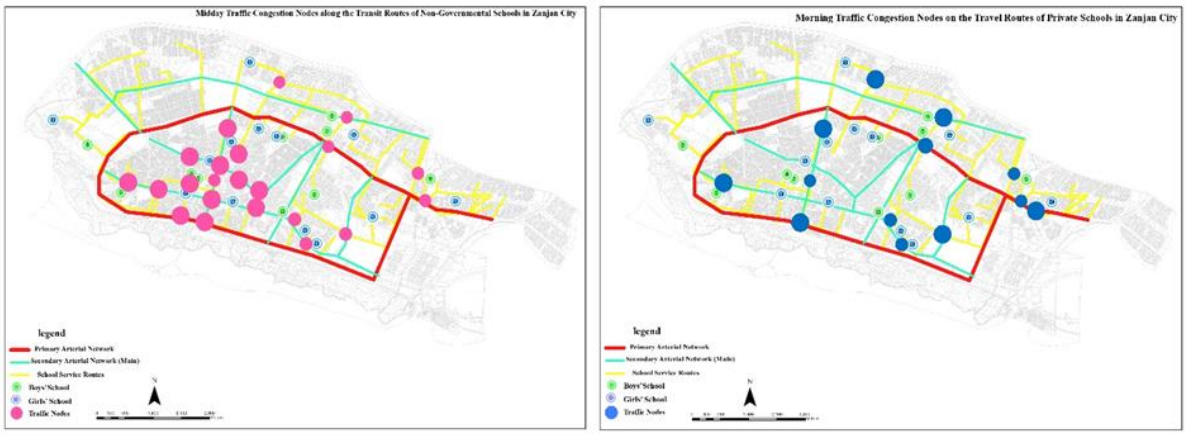

Figure 4. Morning and Midday Traffic Congestion Nodes in the Traffic Rhythm of School Service Routes

5. Conclusion

Although urban school services, as public transportation systems for student mobility within the urban transport network, play a crucial role in reducing private vehicle trips, the scheduling of school opening and closing times—when combined with other urban functions and activities—can contribute to increased traffic congestion in Zanjan city. The structural diversity of schools, including public, private (non-profit), exemplary, Shahed, and teachers' schools, has led to a wide variety of travel patterns in school services. The coexistence of neighborhood-based, zone-based, and citywide admission systems further amplifies urban travel demand. Schools with citywide admission functions generate diverse student movement patterns from different residential areas, acting as "magnets" that attract students from across the city. Consequently, the transportation network linked to these schools acquires an urban character, engaging multiple road structures. Outputs from urban transport flows indicate that schools with urban functions contribute to traffic congestion and increase network load, even if temporarily. The spatial dispersion of non-governmental schools, due to citywide admission systems, affects network performance and traffic congestion levels. Understanding the structure and function of these services is essential for improving urban traffic planning and management.

Rhythm mining of non-governmental school service flows in Zanjan revealed that the movement patterns of school services are influenced by the location of schools, students' residences, residential distances, urban transport network structure, peak congestion periods, and availability of alternative routes. Spatial analysis showed that non-governmental elementary schools are primarily concentrated in the central, middle, and northern urban fabrics, with schools in the central urban area significantly contributing to afternoon traffic

congestion. Schools in central and middle fabrics also experience traffic interaction with other urban activities during the afternoon peak, whereas schools in northern areas exhibit the opposite pattern. The temporal rhythm of school services is largely determined by the spatial location of student residences relative to schools. Time-radar analysis indicated a tendency toward longer travel durations for commutes between schools and students' residences. Average travel times were approximately 15 minutes in the morning and 20 minutes during the afternoon return trip.

These findings align with prior research, including Amiri (2016), who highlighted optimal allocation of school services; Entekabi (2022), who analyzed the role of school services in urban traffic congestion; Treihantovio (2019), who examined optimal school location; and Sanderson (2022) and Gu (2024), who emphasized the impact of urban structure, government policies, and student distribution on transport networks. Consistent with these studies, our results confirm that school services act as public transit flows, significantly influencing urban traffic systems. The operational structure of school transportation depends on both school distribution and student admission methods, which determine whether service coverage is local, regional, or citywide.

This study encountered several limitations that should be considered when interpreting the results. First, data and information constraints included incomplete access to comprehensive traffic and demographic data and partial coverage of school service routes via GPS tracking systems, as well as limited access to service drivers at certain times. Second, temporal limitations arose from data collection within a restricted period, focusing primarily on morning and noon peak hours, which may not capture seasonal variations, holidays, or unusual traffic conditions. Third, spatial limitations involved a focus on non-governmental schools located in the central, middle, and northern urban fabrics of Zanjan city, with less coverage of southern and peripheral areas. Fourth, methodological limitations included reliance on field observations and interviews with drivers, which may be subject to personal bias, and a lack of comprehensive assessment of the interaction between school services and other urban traffic flows. Finally, practical limitations involved the restricted generalizability of the findings to other cities and the potential impact of sudden changes in urban policies, school programs, or student admission practices.

With this in mind, and based on the findings, the practical recommendations are as follows: school start and end times should be coordinated with Zanjan's traffic management, and, where possible, flexible and staggered schedules should be implemented to reduce overlap with peak traffic hours. School service routes should be optimized through redesigning alternative and less congested paths based on rhythm mining analyses, and the use of smart navigation technologies along with standardized routes is recommended, particularly for schools located in the central and middle urban fabrics of Zanjan. Establishing service depots near schools and in low-traffic areas, taking into account the spatial distribution of students, is essential for reducing delays on morning and afternoon trips and for effective dispatch management. To integrate urban and educational policies, collaboration between municipal and educational authorities is advised to create dedicated or prioritized lanes for school services and to inform parents to reduce unnecessary private vehicle trips. Furthermore, continuous monitoring and feedback through GPS tracking systems to identify congestion points and adjust routes and schedules in real time, combined with data-driven analysis for ongoing operational improvements, is recommended. Implementing these measures can enhance the efficiency of school services in Zanjan, reduce traffic congestion, improve urban transport network

performance, and ensure the safety and timely mobility of students.

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