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Urban Environmental Determinants and Spatiotemporal Patterns of Emergency Medical Service Response to Traumatic Injuries: A Five-Year Population-Based Study

Akerke Chayakova and Oxana Tsigengagel *

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Urban Environmental Determinants and Spatiotemporal Patterns of Emergency Medical Service Response to Traumatic Injuries: A Five-Year Population-Based Study

Akerke Chayakova and Oxana Tsigengagel *

Department of Epidemiology and Biostatistics, Astana Medical University, Astana, Kazakhstan; chayakova19@gmail.com

* Correspondence: tsigengagel.o@gmail.com

What are the main findings?

Trauma-related EMS demand is highest among males (60.1%) and the 10–30-year age group, with significant diurnal peaks (17:00–21:00) coinciding with urban traffic congestion.

A significant gender disparity in clinical outcomes was identified, with males exhibiting higher hospitalization rates than females (45.5% vs 40.3%, $p< 0.001$), suggesting higher injury severity.

Spatiotemporal analysis revealed that 74.9% of trauma calls exceeded the 10-minute travel benchmark, with critical "accessibility gaps" found in the peripheral northern Baikonur district.

What are the implications of the main findings?

EMS resource allocation in rapidly growing capitals should shift from citywide population averages to proximity-based models targeting high-burden urban corridors and underserved outskirts.

The high rate of hospitalization refusal (56.5%) suggests a need for integrated urgent care centers to alleviate the burden on the emergency dispatch system.

Implementing flexible staffing during evening peak hours and establishing satellite EMS posts in identified hotspots can reduce preventable delays and enhance health equity.

Abstract

Background: Timely prehospital management is critical for survival after traumatic injury. In rapidly growing metropolises, emergency medical service (EMS) systems often struggle to provide equitable care amid urban sprawl and traffic congestion. This study investigated spatiotemporal inequalities in trauma-related EMS response in a rapidly expanding capital city (Astana, Kazakhstan) to inform healthcare optimization and urban health equity. **Methods:** We analyzed a five-year population-based dataset of 26,073 trauma-related EMS calls recorded between 2020 and 2024. Spatial patterns were examined using Kernel Density Estimation (KDE) and Getis–Ord Gi* hotspot analysis. Road-network modeling assessed accessibility at 3, 5, and 10-minute thresholds using a GIS-based network analyst framework. **Results:** Males accounted for 60.1% of utilization and had higher clinical severity (hospitalization rate: 45.5% vs 40.3%, $p < .001$). Demand peaked at 20:00, coinciding with peak traffic. The mean total response time was 21.63 minutes, and only 16.9% of calls met the 10-minute benchmark. Significant accessibility gaps were found in the Baikonur district (61.4% delay rate). **Conclusions:** The findings demonstrate that while the EMS system provides broad geographic coverage, it suffers from systemic spatiotemporal bottlenecks. Targeted infrastructure expansion in underserved peripheral districts and the implementation of dynamic deployment models are necessary to enhance urban health equity and reduce preventable mortality in expanding metropolitan areas.

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1. Introduction

Traumatic injuries, defined as abnormal bodily conditions resulting from external physical force, wounds, or shock [1,2], represent one of the most pressing global public health challenges of the 21st century. Beyond the immediate clinical impact, injuries impose a staggering socioeconomic burden, serving as a leading cause of premature mortality and long-term disability worldwide [3]. In economically developed nations, trauma is the second most prevalent cause of death, disproportionately claiming lives during an individual's most productive working years [4,5]. Globally, approximately 4.4 million deaths, roughly 8% of total annual mortality, are attributed to injuries, with over 90% occurring in low- and middle-income countries where rapid access to specialized healthcare is often restricted [6,13].

The economic consequences of this crisis are equally profound. Road traffic crashes alone impose an annual global burden of approximately US$ 518 billion, consuming between 1% and 3% of the gross domestic product (GDP) in most nations [15]. This urgency is compounded by accelerating urbanization, economic instability, and increasing motorization. According to World Health Organization (WHO) projections, traumatic injuries will become the third leading contributor to the global burden of disease by 2030. Given the scale of casualties and associated costs, trauma has been aptly described as the "longest war of the modern world" [7,8]. Consequently, this research directly aligns with the United Nations Sustainable Development Goals (SDGs), specifically Goal 3.6, which aims to halve global traffic-related fatalities, and Goal 11.2, which emphasizes providing safe, resilient, and accessible transport systems for all.

Behind these staggering global statistics are thousands of individual lives interrupted during their most productive years [3]. In Kazakhstan, traumatic injuries occupy the fifth position in the structure of overall morbidity and mortality, yet they rank third in primary disability, highlighting a profound threat to the nation’s human capital [9]. In the management of acute trauma, the temporal element is the most critical determinant of survival and functional recovery [10–12]. The "Golden Hour" that thin line between life and death represents more than a medical benchmark; it is a universal promise of timely care that every citizen expects. The principle that definitive intervention within the first 60 minutes can avert up to 50% of trauma-related deaths underscores the necessity of efficient emergency medical services (EMS) [17]. Consequently, ensuring the equitable geographic distribution and operational resilience of EMS is a fundamental requirement for modern urban sustainability [14,16].

In 2024, the Ministry of Health of the Republic of Kazakhstan reported that EMS providers attended to over 740,000 patients with traumatic injuries, a significant portion of which were casualties of road traffic accidents [18]. While national efforts have successfully reduced average urban response times to 15–20 minutes [19], citywide averages often mask deep-seated spatiotemporal inequalities. In rapidly expanding metropolises like Astana, unprecedented metropolitan expansion has created a "geography of risk." Urban sprawl and traffic congestion create localized "pockets" of delayed care, where a person's chance of survival may depend more on their neighborhood's infrastructure than on the severity of their injury.

To address these complexities, injury epidemiology and EMS research have increasingly adopted geospatial methods to quantify Urban Health Equity. Prior studies have utilized spatial scan statistics (SaTScan) to detect statistically significant clusters of traumatic events [20], while others have employed Kernel Density Estimation (KDE) to produce continuous intensity surfaces that reveal how demand fluctuates by time of day [21]. Furthermore, hot spot statistics (e.g., Getis–Ord Gi*) allow researchers to distinguish persistent high-risk zones from random fluctuations, providing actionable data for infrastructure optimization [22].

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Despite the global maturity of GIS-based injury surveillance, evidence from Central Asia and Kazakhstan in particular remains sparse. Most existing studies lack an integrated framework that combines multi-year spatiotemporal patterns with network-based accessibility modeling aligned with national performance benchmarks [23,24]. There is a critical need to understand how Astana's unique urban morphology affects the "equity of access" to life-saving trauma care during its phase of rapid expansion. Astana serves as a unique laboratory for studying the 'accessibility-urbanization mismatch' common in rapidly expanding administrative centers across the Global South and Central Asia.

To address these gaps, this study aims to quantify spatiotemporal inequalities in trauma-related EMS demand and prehospital accessibility in Astana (2020–2024). By integrating road-network service-area modeling and statistically validated hotspot detection, we seek to identify high-burden underserved zones, providing a data-driven foundation for the strategic optimization of EMS infrastructure and the advancement of health equity in the capital.

2.1. Study Design and Data Sources

We conducted a retrospective, population-based study of emergency medical service (EMS) utilization for traumatic injuries in Astana, Kazakhstan. The study period spanned 54 months, from January 1, 2020, to June 30, 2024. The primary dataset was obtained from the centralized digital archive of the Astana City Ambulance Station. The initial database consisted of anonymized records for N = 26,073 trauma-related calls. Each record included: patient demographics (age and gender); temporal markers (exact date and time of the call, dispatch, arrival at the scene, and hospital admission); clinical outcomes (managed on-scene vs. hospitalized); and location addresses for geocoding.

2.2. Demographic and Temporal Analysis

To construct a comprehensive demographic profile, we analyzed the distribution of calls and subsequent hospitalizations across age cohorts and gender. Temporal patterns were evaluated at two scales: (i) Seasonal trends, analyzing fluctuations by month and season; and (ii) Diurnal cycles, examining hourly demand. EMS performance metrics (service intervals) were calculated as: Call-to-Dispatch (processing time), Dispatch-to-Scene (travel time), Call-to-Arrival (total response), and Call-to-Hospitalization (total prehospital time).

2.3. Geospatial Data Processing and Geocoding

Call addresses were converted into geographic coordinates using a multi-stage geocoding procedure. Records with ambiguous addresses were excluded. After processing, 26,073 geocoded points were integrated into a GIS environment (Figure 1). A topological road network model of Astana was constructed using OpenStreetMap (OSM) datasets, incorporating road hierarchies, surface types, and connectivity rules to ensure realistic routing.

2.4. Spatial Analysis and Modeling

Analysis was performed in ArcGIS Pro 3.1.0 using three methodologies, Kernel Density Estimation (KDE), to visualize the spatial intensity of trauma demand per square kilometer. To identify statistically significant spatial clusters. Confidence intervals (90%, 95%, and 99%) were used to validate the stability of high-demand (hot spot) and low-demand (cold spot) zones. Accessibility zones were modeled using the Network Analyst module for EMS stations and emergency hospitals. Modeling assumed a baseline speed of 50 km/h, with downward coefficients applied to secondary and residential roads. Service areas were defined at 3, 5, and 10-minute intervals. Calls falling outside the 10-minute zone were identified as "underserved pockets" at high risk for delayed care. To account for temporal variability, impedance factors for the road network were adjusted based on historical traffic flow patterns during morning and evening rush hours, ensuring the model reflects the 'Accessibility Paradox' identified in the results.

3. Results

3.1. Demographic Profile and Clinical Outcomes.

An epidemiological analysis of N = 26,073 trauma-related EMS calls was conducted. The demographic assessment revealed a significant male predominance (60.1%, n = 15,661). Clinical outcomes were stratified by gender and treatment result, as shown in Table 1.

Table 1. Demographic Profile and Clinical Outcomes (N = 26,073)

Clinical Outcome	Males, n (%)	Females, n (%)	Total, N (%)
Refusal of Hospitalization	8,529 (54.5%)	6,214 (59.7%)	14,743 (56.5%)
Inpatient Admission	7,132 (45.5%)	4,198 (40.3%)	11,330 (43.5%)
Total Call Volume	15,661 (60.1%)	10,412 (39.9%)	26,073 (100%)
Statistical Significance			χ 2 =70.97, p<.001

Note: Data are presented as absolute frequency (n) and row percentage (%). Percentages may not sum to 100% due to rounding.

The population pyramids (Figure 1A) indicate that trauma demand is concentrated in the pediatric (under 18 years) and young adult (18–44 years) cohorts. A critical observation is the high rate of hospitalization refusal; 56.5% (n = 14,743) of trauma encounters were managed on-site without subsequent transport. Pearson's chi-square test confirmed a statistically significant gender disparity in outcomes (p<.001): males were significantly more likely to be hospitalized than females (45.5% vs. 40.3%). As shown in Figure 1B, the peak demand for inpatient care is concentrated in the 10–30-year age group, likely reflecting exposure to high-energy unintentional injuries [25].

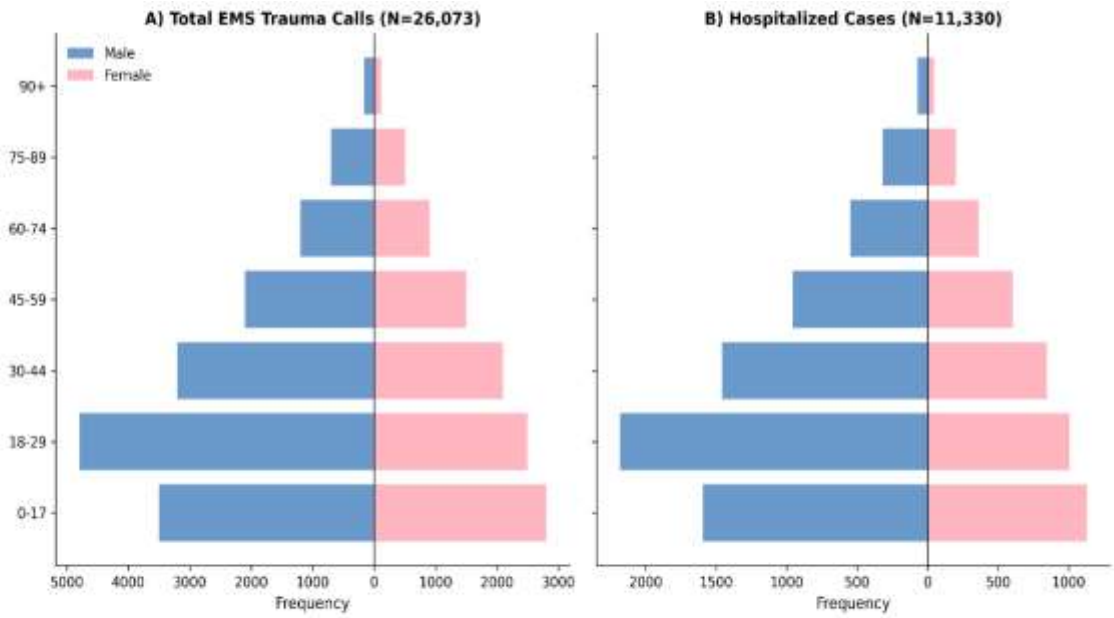

Figure 1. Population pyramids of trauma-related EMS utilization: (A) total calls; (B) hospitalized patients.

3.2. Temporal Trends and Performance Audit

Trauma demand exhibited pronounced seasonality, peaking during Spring (31.1%) and reaching its minimum in Winter (19.8%). Analysis of the diurnal rhythm (Figure 2) revealed a cyclical demand curve with activity reaching its absolute peak at 20:00 (approx. 4,500 cumulative calls).

The EMS Performance Audit (Table 2) identified systemic bottlenecks in travel efficiency. While dispatch processing (Call-to-Dispatch) was relatively efficient (78.1% compliance with the < 5 min benchmark), the mean travel time (Dispatch-to-Scene) was 15.02 minutes. Crucially, travel delays reached their maximum during the 17:00–21:00 interval, coinciding with peak urban traffic congestion. Overall, only 16.9% of trauma calls met the national 10-minute total response benchmark.

Table 2. EMS Performance Audit: Prehospital time intervals and benchmark compliance.

Service Interval	Mean (SD), min	Median (IQR), min	Benchmark Compliance (%)
Call-to-Dispatch	6.29 (2.1)	5.1 (4.0–7.2)	78.1% within < 5 min
Dispatch-to-Scene	15.02 (4.8)	13.8 (10.5–18.2)	25.0% within < 10 min
Call-to-Arrival (Total)	21.63 (5.3)	19.5 (15.2–24.1)	16.9% within < 10 min
Call-to-Admission	55.78 (12.4)	51.88 (41.7–64.2)	Target: "Golden Hour"

Note: SD: standard deviation; IQR: interquartile range (25th–75th percentiles). The critical bottleneck is identified in the Dispatch-to-Scene interval, primarily driven by urban traffic congestion during peak demand hours.

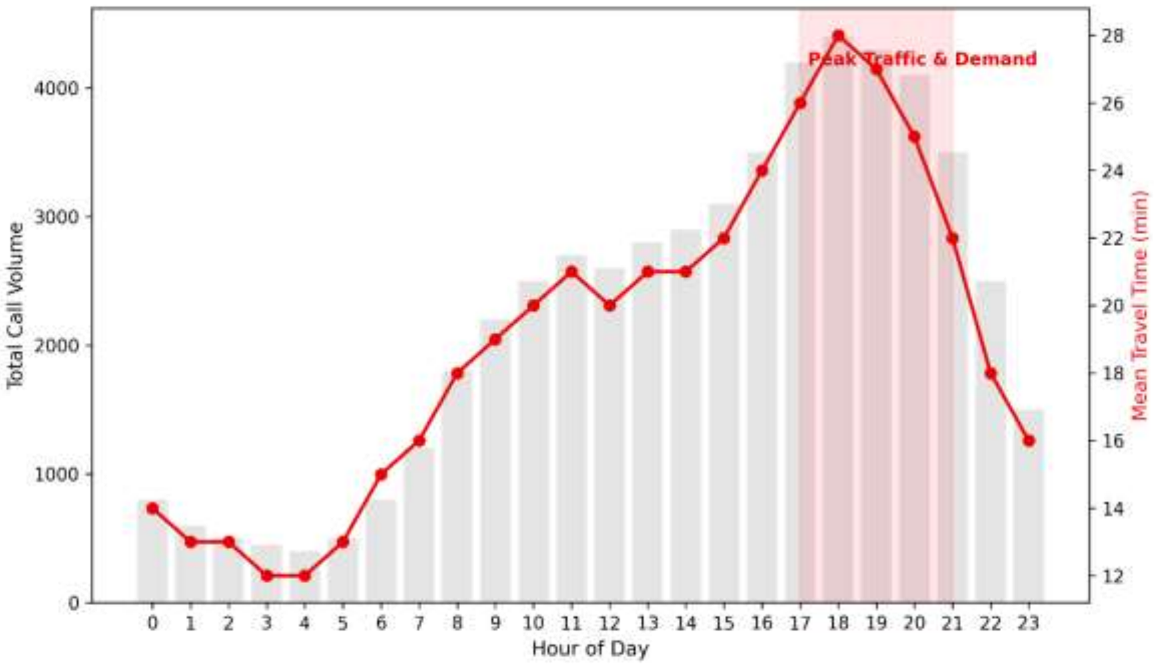

Figure 2. Diurnal rhythm of trauma demand vs. mean travel time.

3.3. Spatiotemporal Analysis and Accessibility Gap

Kernel Density Estimation (KDE) (Figure 3) confirmed that trauma-related demand is heavily concentrated in the central urban core and along major arterial corridors. Hotspot Analysis (Figure 4) identified statistically significant clusters (99% CI) in the southern and central districts (Baikonur, Esil, and Saryarka), while the Nura district formed a persistent "cold spot."

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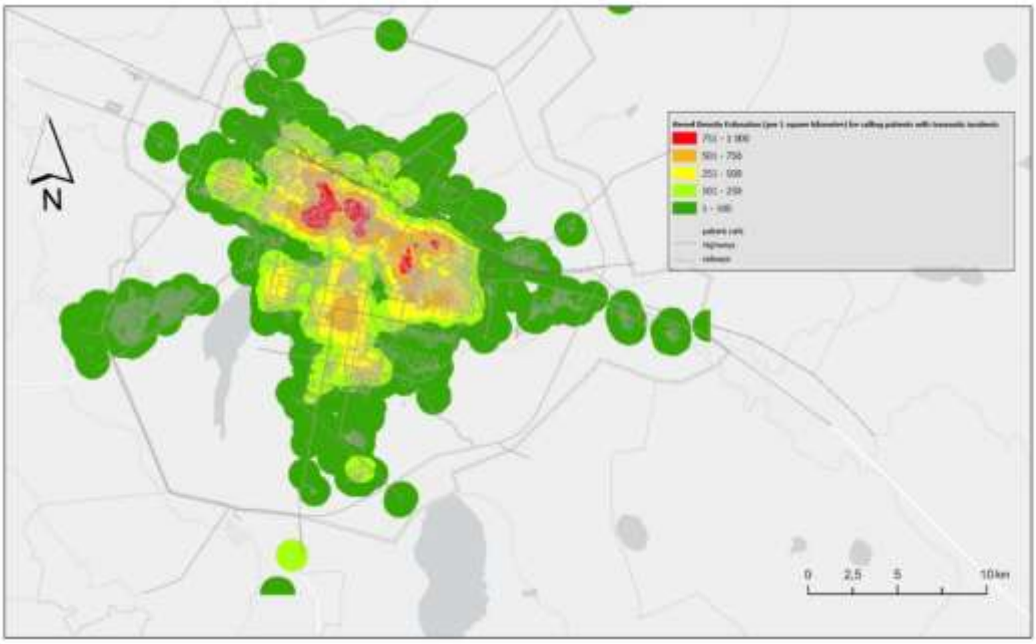

Figure 3. Spatial intensity of trauma incidents (KDE Analysis).

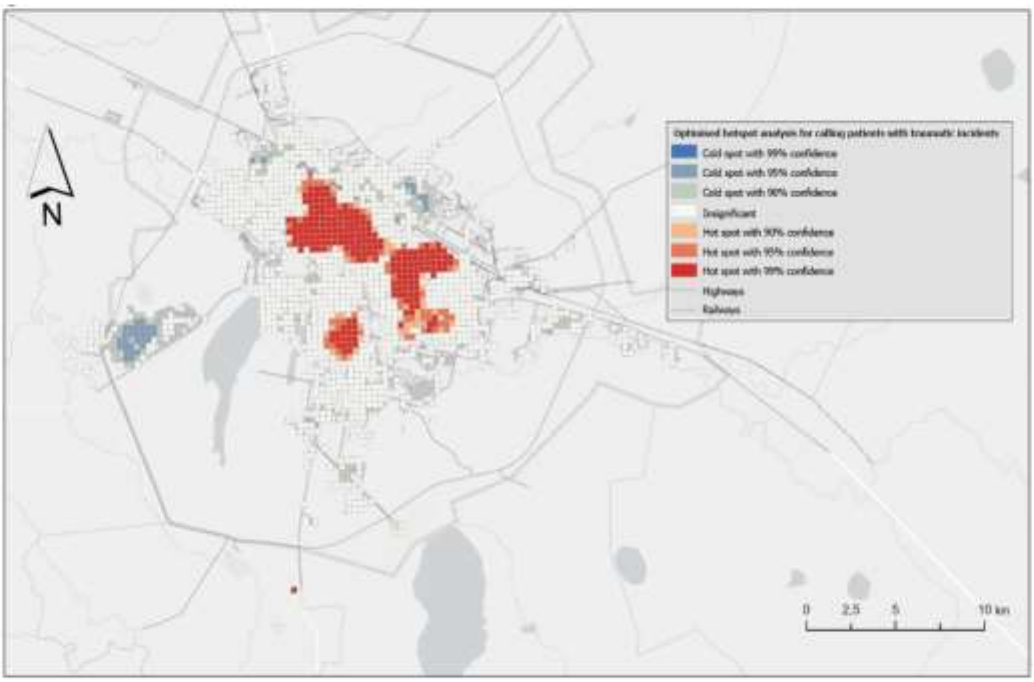

Figure 4. Optimized Hotspot Analysis (Getis-Ord Gi), identifying clusters of high demand (99% CI).).

The road-network modeling revealed a stark "equity gap" (Table 3). Although the majority of the city districts are within 10 minutes of an EMS post, 1.5% of calls (n = 394) originated from locations exceeding this critical threshold. These underserved pockets are primarily located in the northern peripheral zones of the Baikonur district, where the EMS arrival delay rate reached a critical high of 61.4% (Figure 5).

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Table 3. Spatial accessibility and regional inequity in EMS response by administrative district.

Administrative District	EMS Station Access (0–10 min)	Hospital Access (0–10 min)	Delay Rate (>10 min travel)
Baikonur	98.2%	98.8%	**61.4%**
Saryarka	98.5%	99.5%	58.2%
Almaty	99.1%	99.8%	45.1%
Esil	99.6%	99.9%	32.7%
Nura	99.8%	99.9%	28.4%
Statistical Test			Kruskal-Wallis p<.001

Note: Spatial accessibility was modeled using road-network service areas. The "Delay Rate" represents the proportion of actual calls where travel time exceeded the national 10-minute threshold. Regional differences are statistically significant, highlighting a critical accessibility gap in the northern "Old City" districts.

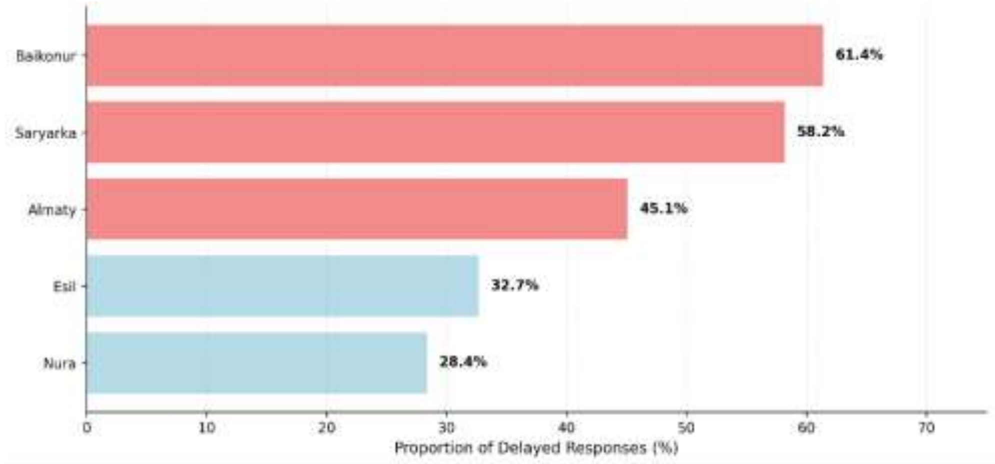

Figure 5. Delay Rate by District (>10 min travel time). The chart highlights the critical accessibility gap in the Baikonur and Saryarka districts.

4. Discussion

This study advances the evidence base on urban trauma-related EMS demand in Central Asia by providing a comprehensive spatiotemporal audit of Astana's emergency infrastructure. By integrating demographic, temporal, and geospatial analyses, we demonstrate that trauma burden is not randomly distributed; rather, it is deeply embedded in the city's urban morphology, mobility flows, and service accessibility [26,27]. Our findings reveal that behind the data points are thousands of individual lives interrupted during their most productive years, where the chance of survival is increasingly dictated by the "geography of risk" inherent in a rapidly expanding metropolis [28,29,34].

4.1. The Demographic Gap and Clinical Acuity

A primary finding of the demographic analysis is the concentration of trauma demand among the socially and economically active population, particularly men aged 10–44 years. This "severity gap" is underscored by the significantly higher hospitalization rate for males (45.5%) compared to females (40.3%, p<.001), suggesting that traumatic incidents involving men in Astana tend to be of higher clinical acuity. This pattern reflects higher occupational hazards in industrial and construction sectors and a greater prevalence of high-energy transport-related injuries among young adult males [28,29].

Notably, the high overall rate of hospitalization refusal (56.5%) warrants specific scrutiny. While some refusals are clinically appropriate, this volume reveals a substantial "low-acuity burden" on the

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EMS system. In this context, the ambulance service is effectively being utilized as a substitute for primary care, saturating dispatch capacity and delaying response to life-threatening cases [30,31]. To humanize this finding: every low-acuity call managed by an emergency crew represents a potential "invisible barrier" to a patient in critical need, highlighting the urgent necessity for integrated urgent care centers to protect the system's life-saving mission.

4.2. The Diurnal Paradox and Safety Culture

The temporal analysis identified a painful "Accessibility Paradox": EMS travel times reached their absolute peak (mean 28.0 minutes) during the evening hours (17:00–21:00), precisely when service demand was at its maximum. This mismatch is driven by urban traffic congestion, which nearly triples the travel time compared to pre-dawn hours. A 28-minute delay in an emergency is not just a statistical outlier; it is a systemic vulnerability that compromises the "universal promise" of timely care.

Addressing these organizational bottlenecks is a fundamental component of healthcare quality management. As previously emphasized in the Kazakhstani context, fostering a transparent safety culture, including the institutional willingness to identify and disclose medical errors, is essential for advancing healthcare standards [2]. In this light, GIS-based auditing serves as a vital diagnostic tool for "systemic errors" in resource distribution [32,33]. Acknowledging that 74.9% of calls fail to meet the 10-minute travel benchmark is an act of institutional transparency. It provides the empirical evidence necessary for accountability and a transition toward a more resilient, data-driven emergency care system that values every minute as a critical opportunity for survival.

4.3. Spatial Inequity and the "Old City" Barrier

Geospatial analysis yields the most actionable evidence for urban health policy, revealing that trauma hotspots (99% CI) are inextricably linked to high-density, transport-intensive environments [35,36]. However, the modeling of accessibility zones uncovered a stark "equity gap." While citywide coverage appears effective on paper, 1.5% of incidents (n = 394) occurred outside the critical 10-minute threshold.

These underserved "pockets" are primarily localized in the northern peripheral zones of the Baikonur district. This "Old City" area, characterized by narrower streets and aging infrastructure, suffers from the highest delay rates (61.4%). From the perspective of Urban Health Equity, this spatial imbalance suggests that a resident's postal code may determine their clinical outcome, a clear issue of social justice in urban planning. Achieving United Nations Sustainable Development Goal 11 (Sustainable Cities and Communities) requires that essential infrastructure remains resilient and accessible to all citizens, regardless of their neighborhood's age or socioeconomic profile. Therefore, the transition from a population-based to a proximity-based EMS deployment model is not only a logistical necessity but a moral imperative for ensuring equitable health outcomes in a modern capital.

5. Limitations

This study has several limitations. First, the road-network modeling utilized a baseline speed of 50 km/h. While adjusted with coefficients for road hierarchy, it does not fully account for real-time traffic variability, extreme weather conditions (e.g., Astana's severe winter blizzards), or the hospital "handover" time. Second, the dataset lacks clinical severity scores (e.g., ISS), making it difficult to definitively link response delays to mortality outcomes. Finally, as a single-city study, the findings may not be directly generalizable to rural Kazakhstan. However, the GIS-based methodology provides a replicable framework for national healthcare equity monitoring.

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6. Conclusions

This study demonstrates that the path toward a Sustainable City must be paved with healthcare equity. While Astana's trauma EMS system exhibits broad geographic coverage on a macro level, city-wide performance averages mask localized crises that disproportionately affect those in underserved peripheral districts. Our findings reveal that system efficiency is severely constrained by urban traffic congestion during evening peak hours, resulting in only 16.9% of calls meeting the critical 10-minute response benchmark.

The integration of GIS technology is key to unmasking these spatiotemporal disparities. By identifying specific "accessibility gaps," particularly in the northern Baikonur district, we provide more than just maps; we provide a blueprint for a more compassionate and resilient urban health system. Ensuring that the "Golden Hour" is achievable for every citizen—regardless of their neighborhood or the time of day is the ultimate benchmark of a sustainable and equitable capital. Our research serves as a diagnostic call to action for urban planners and health authorities to transition toward proximity-based, dynamic resource allocation to protect the lives of a rapidly growing metropolitan population.

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Institutional Review Board Statement: The study was approved by the Local Ethics Committee, NpJSC Astana Medical University, approved this study on 29.04.2022. (Extract from Protocol No. 4 dated 04/29/2022). The requirement for informed consent was waived due to the retrospective nature of the study and the use of anonymized EMS call records. The research was conducted in accordance with the principles set out in the Declaration of Helsinki.

Informed Consent Statement: Informed consent was obtained electronically from all participants before participation in the study.

Data Availability Statement: The data assessed and reported here can be obtained from the authors upon reasonable request and following ethical and privacy principles.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Term
AMU	Astana Medical University
CI	Confidence Interval
df	Degrees of Freedom
EMS	Emergency Medical Services
GBD	Global Burden of Disease
GDP	Gross Domestic Product
GIS	Geographic Information System
HCF	Healthcare Facility
ICD-10	International Classification of Diseases, 10th Revision

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IQR Interquartile Range
ISS Injury Severity Score
KDE Kernel Density Estimation
MSHE RK Ministry of Science and Higher Education of the Republic of Kazakhstan
NpJSC Non-profit Joint-Stock Company
OSM OpenStreetMap
SD Standard Deviation
SDG Sustainable Development Goals
SRN Street and Road Network
WHO World Health Organization

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