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Spatial Patterns of Road Traffic Crashes in Baghdad with an Emphasis on Road Network Topology Metrics

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ABSTRACT

Aims Urban traffic safety was understood to be shaped by the spatial organization of street networks. For Baghdad, this study examined the relationships between network-topological metrics and crash risk, addressing the limited evidence base in the Middle East.

Methodology Data from Baghdad City, Iraq, between 2024 and 2025 were assembled and quality-controlled. Crash rates were normalized by vehicle-kilometers traveled. A global ordinary least squares model with robust errors was estimated; When residual autocorrelation was detected, spatial lag/spatial error/spatial Durbin models were fitted. Geographically weighted regression with adaptive bandwidth was applied to capture spatial non-stationarity.

Findings Significant clustering of crash rates was observed (Moran's I=0.22; p<0.001). In ordinary least squares, positive effects were observed for annual average daily traffic, building area, openness, and meshedness, and a negative effect for betweenness. The selected spatial Durbin model confirmed spatial spillovers (ρ≈0.19) and large total effects of annual average daily traffic (~0.36) and building area (~0.26), while betweenness remained negative (~−0.12). Geographically weighted regression revealed broad spatial consistency: Betweenness was significantly negative across ~48% of cells, whereas annual average daily traffic and building area were significantly positive across ~68% and ~61% of cells, respectively. Crash rates peaked within 1-3km of hospitals (~310 per 100m vehicle-kilometers traveled) and declined beyond 5km (~170).

Conclusion These patterns indicate that corridor-scale, network-oriented safety strategies are needed, with priority given to speed management, protected intersection design, and access control in high-exposure, highly meshed and more open sections, especially around hospitals.

Keywords Traffic Crashes; Betweenness Centrality; Meshedness; Intersection Density; Openness

CITATION LINKS

[Ali, 2022] Spatial analysis of traffic accidents in Baghdad ...; [Azizi & Najafi, 2011] Fuzzy classification in forest area for road design ...; [Boeing, 2017] OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street ...; [Bonera *et al.*, 2024] Network-wide road crash risk screening ...; [Chaudhuri *et al.*, 2022] Spatio-temporal modeling of traffic accidents incidence on urban road networks based on an explicit ...; [Clemente *et al.*, 2024] Hierarchical spatial network models for road accident risk ...; [Climate-Data.org, n.d.] Baghdad climate (Iraq): Data and graphs for weather ...; [Cui *et al.*, 2025] Quantifying spatial inequities in traffic injury rates through the integration of urban road network ...; [Encyclopaedia Britannica, n.d.] Baghdad ...; [Gilardi *et al.*, 2022] Multivariate hierarchical analysis of car crashes data considering a spatial ...; [Hazaymeh *et al.*, 2022] Spatiotemporal analysis of traffic accidents hotspots based on geospatial techniques ...; [Kadam, 2025] Spatial analysis of traffic accidents on the Baghdad–Diyala road ...; [Khudhair *et al.*, 2025] Identification of hazardous intersections based on crash severity level ...; [LeSage & Pace, 2009] Introduction to spatial ...; [Liu *et al.*, 2024] Using geographically weighted logistic regression to investigate factors affecting serious ...; [Marshall & Garrick, 2011] Does street network design affect traffic ...; [Sánchez-Vaquerizo & Helbing, 2025] Spatial econometrics to estimate traffic reduction by transforming office space into ...; [Wang *et al.*, 2024] Geographically weighted machine learning for modeling spatial heterogeneity in traffic crash frequency ...; [Wang *et al.*, 2013] Investigation of road network features and safety ...;

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Introduction

Urban traffic safety is fundamentally influenced by the spatial organization of the road network. Beyond point-level street attributes (e.g., carriageway width, gradient, junction control), the overall pattern of connectivity and linkage—who travels from where to where, and how—determines exposure conditions, prevailing speeds, the number of conflict points, and the availability of alternative routes, thereby shaping the occurrence and severity of road traffic crashes. In recent years, a growing body of research has shown that network topology/typology metrics—such as betweenness centrality, meshedness, intersection density, openness, and kindred indicators of urban form/geometry—can explain a meaningful portion of the spatial variability in crashes. This agenda aligns with the methodological shift in the field from purely link- or segment-based models towards network-centric approaches and spatial modeling of dependence and spatial heterogeneity [Clemente *et al.*, 2024; Gilardi *et al.*, 2022; Marshall & Garrick, 2011].

Within this perspective, betweenness centrality, as a path-based measure, identifies nodes that are likely to lie along multiple shortest paths. Such nodes typically possess a greater capacity to channel flows efficiently and, by reducing local turbulence and movement conflicts, may be associated with a lower crash risk. By contrast, meshedness and intersection density reflect structural complexity and the proliferation of alternative routes and conflict points; While highly gridded and dense networks improve accessibility, the multiplication of junctions increases the scope for collisions and flow mismatches. Openness—the proportion of unobstructed surfaces—signals more open environments and straighter alignments, which can facilitate higher operating speeds and, in turn, elevate collision risk. In addition to these structural metrics, Annual Average Daily Traffic (AADT), as an exposure indicator, is classically positively correlated with crash frequency/rates and is usually included as an offset or control variable in count/rate models [Cui *et al.*, 2025; Chaudhuri *et al.*, 2022].

Methodologically, the transition from classical ordinary least squares (OLS) to spatial econometric and local models—such as SLM/SDM and GWR (Geographically weighted regression)—addresses two fundamental challenges; 1) spatial dependence (spillover/lag), whereby the behavior of a spatial unit depends on that of its neighbors, and 2) spatial non-stationarity, whereby the effect of a given network metric is not uniform across the city. Spatial lag/error/Durbin models' specifications capture global dependence, while GWR estimates local coefficients to uncover geographical variation in effects [Sánchez-Vaquerizo & Helbing, 2025; Liu *et al.*, 2024]. This combined strategy both mitigates bias arising from neglected spatial structure and enables policymakers to design place-targeted interventions. In one of the recent reference studies that coherently applied a network-centric and spatial-econometric framework, a clear pattern linking network metrics to injury/crash rates was reported: Betweenness centrality exhibited a reducing (negative) relationship with the rate across 80.32% of the study area, while meshedness (82.00%), building area (96.28%), and openness (100%) all showed positive and spatially stable associations; Intersection density displayed mixed effects. As expected, AADT had positive and significant coefficients in 88.25% of zones. These patterns are consistent with the theoretical mechanisms set out above—namely, more conflict points in meshed/dense networks and higher speeds in more open spaces—and, conversely, the role of efficient through-movement (higher betweenness) in reducing turbulence and risk [Cui *et al.*, 2025; Azizi & Najaf, 2011]. Alongside this evidence, systematic reviews and recent studies emphasize the need to integrate network theory with roadway attributes and advanced statistical/learning models to better explain crash patterns. This trajectory facilitates a shift from one-dimensional analyses (geometry-only or volume-only) to multi-dimensional, network-centric analyses, demonstrating that topological metrics can be incorporated into risk models alongside traditional engineering variables (e.g., lane width, junction control) [Wang *et al.*, 2024; Bonera *et al.*, 2024].

Nevertheless, a significant gap persists: Cities in the Middle East and North Africa—including Baghdad—have seldom been examined within a unified, network-centric framework using state-of-the-art spatial models, even though rapid urbanization, fast-changing land uses, imbalanced network loading, and cultural-behavioral differences likely yield distinctive patterns of exposure and risk. Existing studies in Iraq and Baghdad have tended to focus on trends, aggregate distributions, or particular street environments, with limited attention to network topology as a structural driver of risk [Ali, 2022; Khudhair *et al.*, 2025; Kadam, 2025; Hazaymeh *et al.*, 2022]. Accordingly, transferring and localizing a network-centric framework to Baghdad is valuable for both theory and policy.

The aim of this study was to address that need by extracting and implementing the subset of the reference framework that directly pertains to network-topology metrics and the exposure variable (AADT) and operationalizing it for the city of Baghdad under the title 'Spatial Patterns of Road Traffic Crashes in Baghdad with an Emphasis on Road Network Topology Metrics'.

Methodology

The methodological framework was implemented as a continuous pipeline from data preparation of Baghdad city in 2024-2025 to model estimation and

reporting. First, the official boundary of Baghdad was defined as the study extent and, to ensure spatial comparability, the entire area was tessellated into a regular 1×1km grid. All processing was conducted in WGS84/UTM Zone 38N (EPSG: 32638) to ensure that distance/area calculations were metrically reliable and that the computation of road lengths, densities, and distances was robust. Baghdad, Iraq's capital and largest city, straddles both banks of the Tigris River. The metropolitan area is characterized by dense mixed-use fabrics, a strong arterial hierarchy, and rapid demographic and vehicular growth. Expressways, radial connectors, and major east-west bridges structure flows, creating corridors of heavy movement that concentrate potential conflicts. Climatic and hydrological conditions, land-use mosaics, and the river's bifurcation shape the distribution of built-up areas and open spaces that, in turn, influence operating speeds and visibility. These features provide a pertinent laboratory to examine interactions among network topology, built form, exposure, and crash occurrence [Ali, 2022; Encyclopedia Britannica, n.d.; Climate-Data.org, n.d.; GLTN, 2024] (Figure 1).

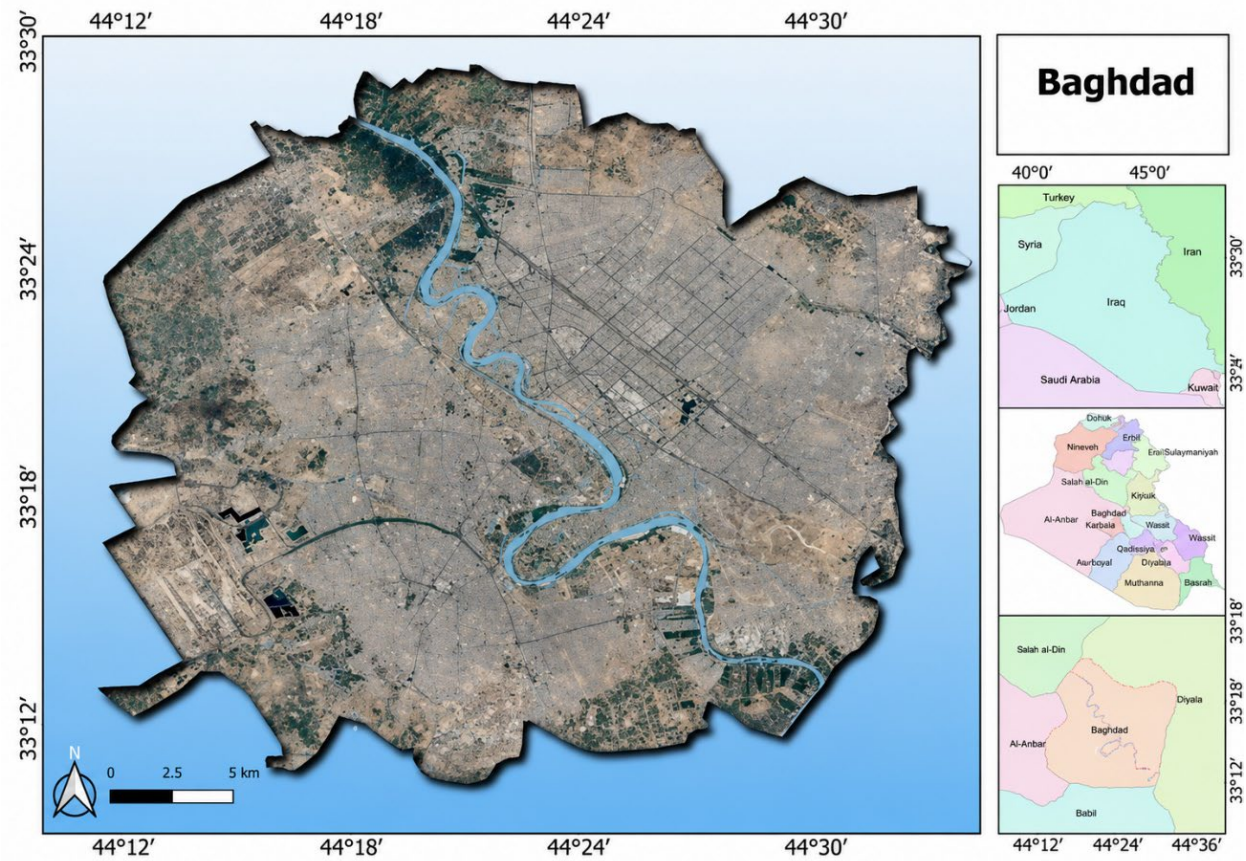

Figure 1. Study area

Four data families were then assembled either directly from counts or via locally consistent estimation procedures and spatially allocated to grid cells (All variables were aggregated to a 1×1km grid in WGS84/UTM Zone 38N for comparability):

1. Crashes: Crash records for 2024-2025 (or the nearest available period) were harmonized in terms of time and severity. Duplicates were removed; Events were snapped to the nearest network edge (e.g., 50-100m tolerance).
2. Road network: OSM streets are cleaned (dangles/breaks resolved), converted to a drivable graph, and topology is ensured prior to metric computation.
3. Built form: Microsoft Building Footprints provide per-cell building area; Openness is derived as 1−(built-up/cell area).
4. Exposure (AADT): From official counts or consistent local proxies, AADT is spatially allocated to the grid; if using a count model, $\log_{(\text{AADT} \times \text{road length})}$ serves as an offset.

In the pre-processing step, crash data were cleansed for duplicates using a combined space-time-severity matching (thresholded by spatial proximity and temporal separation), and events were snapped to the nearest network edge using a defined spatial tolerance (e.g., 50-100m, depending on input accuracy) so that each crash could be unambiguously associated with the corresponding segment of the network. The OSM network underwent topology cleaning: Dangling arcs and breaks were resolved; Consistent node creation at intersections was enforced; Edge directionality was harmonized; and road classes were encoded for speed/cost weighting.

This yielded a final graph suitable for computing both path-based metrics (e.g., betweenness) and local connectivity indicators. For buildings, overlapping/embedded polygons were dissolved and geometries corrected so that the total building area per cell could be obtained; Openness was then computed as:

$$\text{Openness}_i = 1 - \frac{\text{Built-up Area}_i}{1\ \text{km}^2}$$

Network indicators were divided into path-based and connectivity-based classes. Betweenness centrality (edge/node) was computed under two weighting scenarios for sensitivity analysis: 1) equal/length weighting, and 2) travel-time weighting (length/class-based speed). Edge/node betweenness was subsequently aggregated to the 1 km cells (e.g., length-weighted means of edges lying within each cell). Meshedness was calculated—using the planarized local sub-graph—as an indicator of cycle-richness/grid-ness (i.e., the extent of independent cycles relative to a planar maximum), and assigned to cells. Intersection density was defined as the number of nodes with degree ≥3 per square kilometer, and road-length density as the sum of drivable edge lengths per square kilometer. All explanatory variables were Z-standardized so that differing units and scales would not unduly affect estimation or interpretation.

For the response, a crash rate normalized by exposure was defined. For each cell i, daily VKT (Vehicle-Kilometers Traveled) was computed by summing across edges within the cell:

$$\text{VKT}_{i,\text{day}} = \sum_{e \in i} \text{AADT}_e \times L_e$$

Where L_e is the length (km) of edge e and AADT_e is its daily volume. Annual VKT followed as $\text{VKT}_i = 365 \times \text{VKT}_{i,\text{day}}$, and the crash rate was:

$$\text{Crash Rate}_i = \frac{\text{Crashes}_i}{\text{VKT}_i} \times 10^8$$

i.e., per 100 million VKT. If only a cell-mean AADT surface was available, it was proportionally allocated to the cell's road edges by length so that VKT_i remained consistent with the network geometry.

Before model fitting, exploratory and diagnostic analyses were performed: variable distributions were examined for skewness/kurtosis, and mild transformations, such as log1p, were applied to strictly positive variables (e.g., AADT, building area) where appropriate. All predictors were then Z-standardized. VIF was computed to screen for multicollinearity (with a conventional threshold, e.g., 5). Moran's I for the crash rate was estimated with permutation tests to assess spatial autocorrelation in the response.

The baseline model was OLS with heteroskedasticity-robust (HC) standard errors, providing the signs and magnitudes of linear, global effects. Post-estimation diagnostics included residual normality and heteroskedasticity checks and, crucially, spatial autocorrelation in residuals (residual Moran's I). Where residual spatial structure was significant, a suite of spatial econometric models—SLM (spatial lag), SEM (spatial error) and SDM (spatial Durbin with lagged covariates)—was fitted. Model selection drew on a combination of LM tests (lag/error) and information criteria (AIC/BIC). In the selected spatial model, beyond coefficient estimates, direct, indirect (spillover), and total effects were derived (using the partial-derivatives approach of LeSage-Pace) to quantify spillovers. The spatial weights matrix W was specified as Queen contiguity over grid cells, with an alternative kNN specification (e.g., k=6) and row standardization considered. Sensitivity to W was examined in the robustness section.

To reveal spatial non-stationarity in effects, GWR with an adaptive kernel (bi-square weighting) was employed. The bandwidth was optimized internally by minimizing AICc. GWR outputs included the spatial distribution of local coefficients β_i, local R^2 and sign/significance maps. GW-VIF diagnostics were used to assess local multicollinearity; Where necessary, overlapping indicators were reduced or adjusted. This enabled reporting on the share of the urban area in which each metric exhibited significant positive/negative effects, thereby informing place-specific policy design.

For mapping and reporting, local coefficient maps (from GWR) and sign/significance overlays were prepared and stacked on contextual layers (network, buildings, hospitals) to support intuitive, evidence-based spatial interpretation. In addition, the percentage of area with significant positive/negative effects for each metric was computed, and hotspots were identified from the exposure-normalized crash rate surface, motivating policy levers such as traffic calming, junction re-design, and speed management in more open environments.

For robustness, multiple sensitivity scenarios were executed: Altering the grid resolution (500m vs 1km), switching the spatial weights (Queen vs kNN with different k), and modifying the rate/offset definition (e.g., using offset=$\log_{(\text{VKT})}$ in count models, or alternatively using road length as a normalizer). In each scenario, the sign and significance of key coefficients and model fit indices (R^2/AIC for OLS; AIC/BIC for spatial models) were monitored to ensure the stability of results. Finally, reproducibility was ensured through comprehensive documentation. The OSM extract date and the version of building-footprint layers, software/library versions (QGIS/GeoPandas/OSMnx/NetworkX/libpysal/mgwr), key settings (CRS, snapping tolerance, kernel type/parameters in GWR, and the form of W), the random seed, and all scripts were recorded in a

version-controlled repository. This level of documentation enables full replication, cross-study comparability, and periodic updates of results for Baghdad's urban safety policy.

Findings

The spatial context maps for the street network (Figure 2), building footprints and openness (Figure 3a), and hospitals (Figure 3b) were prepared.

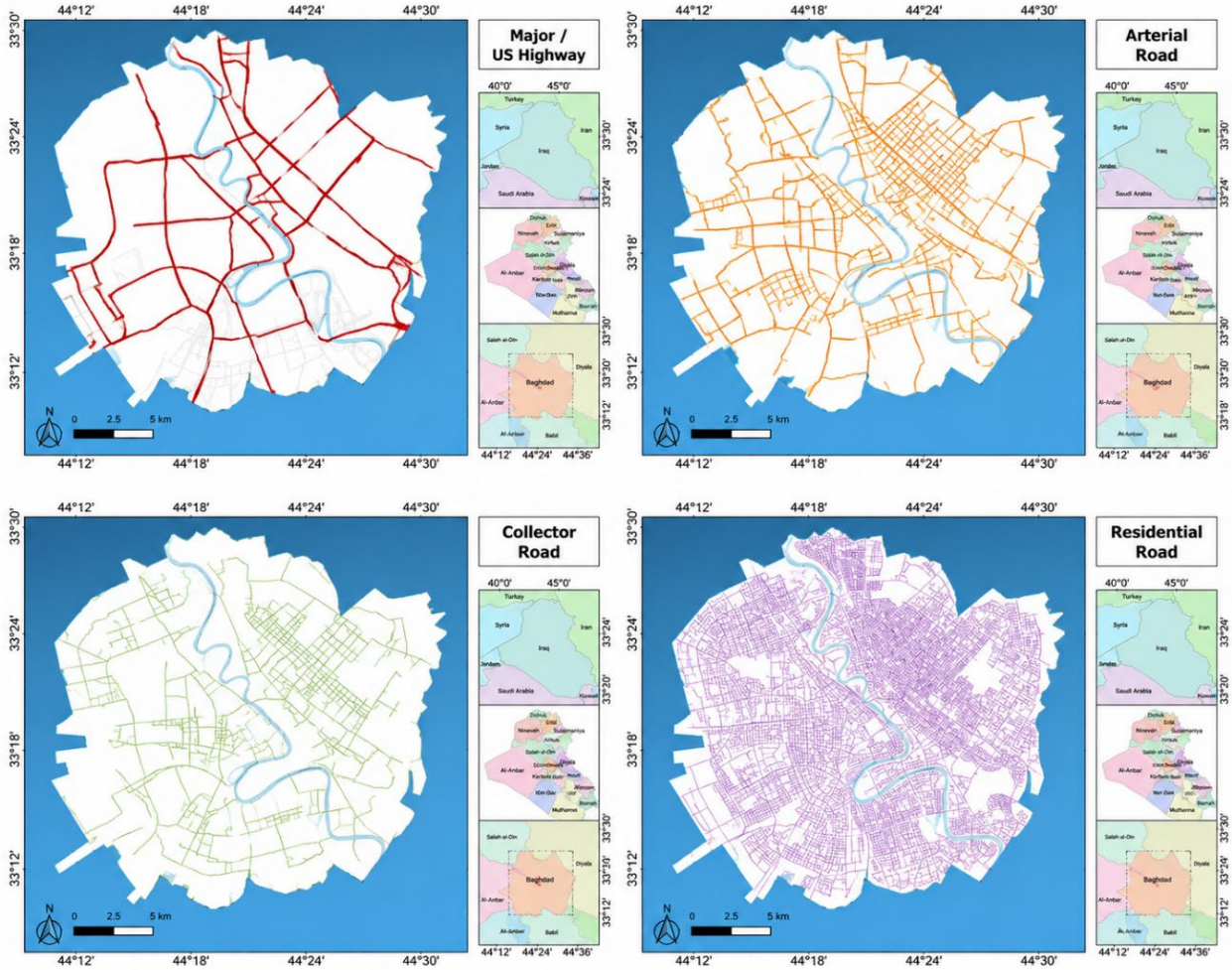

Figure 2. OSM-derived street network by functional class and linear density

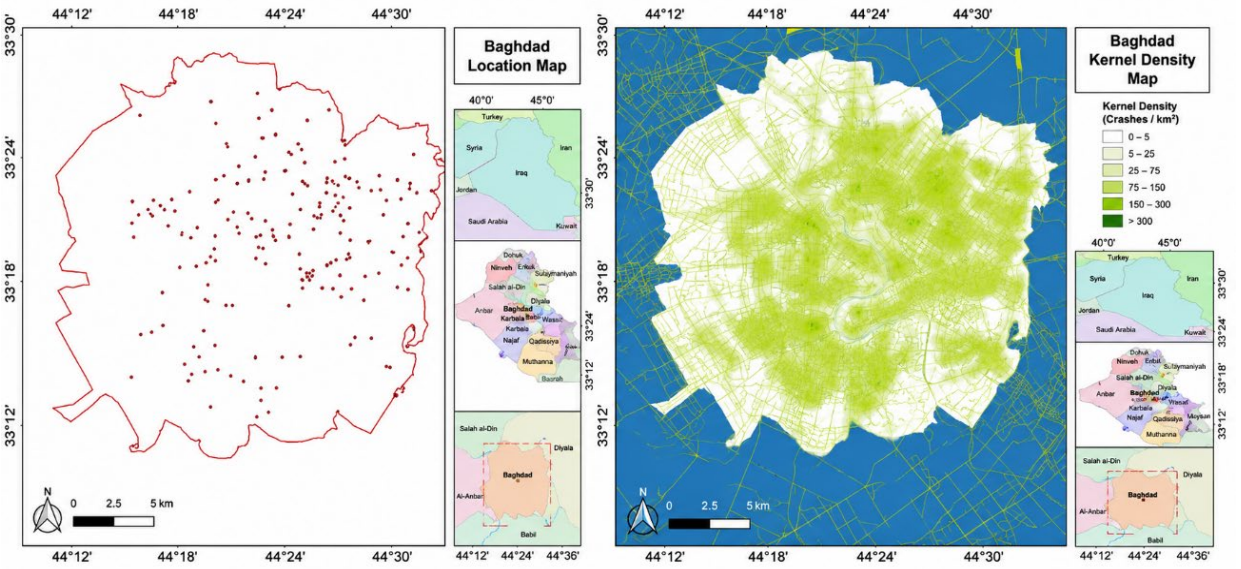

Figure 4a. Crash points.

Figure 4b. Estimated kernel density of crash points.

Figure 3. a) Building-area density and openness (1-built-up share) per 1km cell; b) Hospital locations with 1/3/5km buffers for accessibility overlays

Higher-order corridors and dense fabrics around the urban core tended to concentrate traffic flows and potential points of conflict. The crash-rate surface (per 100million VKT; Figure 4) showed clear clustering along these corridors and in more open sections where higher speeds were likely.

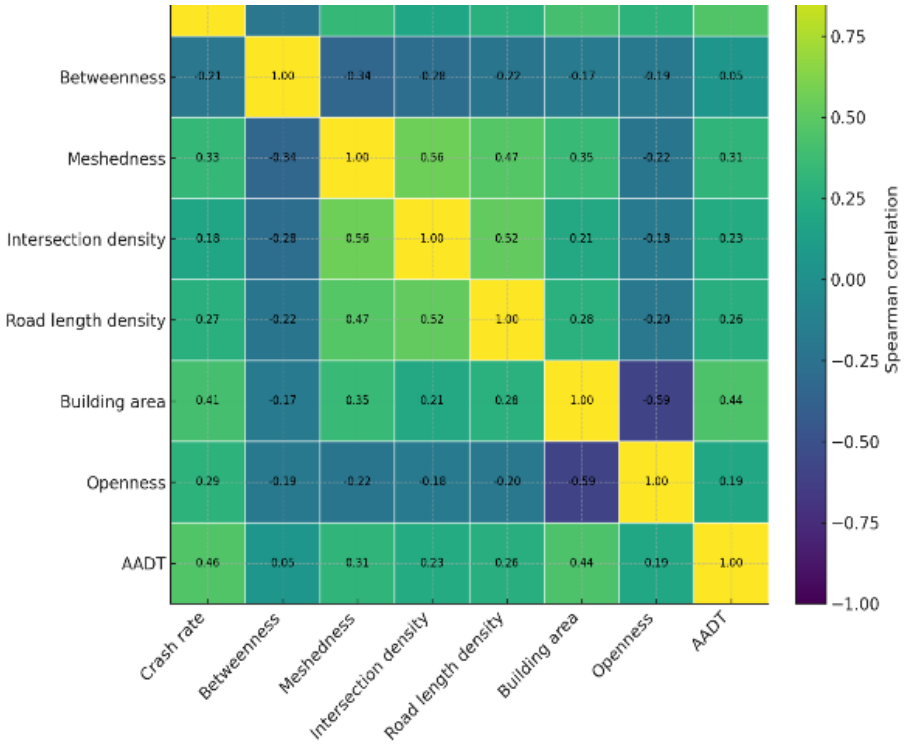

Figure 4. Correlation matrix (Spearman)

The OLS model showed that AADT and building area were the strongest positive predictors of crash rate, while meshedness and openness were also positively associated. Betweenness centrality was negatively associated with crash rate. Although the model explained a moderate share of the variance, the residuals still exhibited significant spatial autocorrelation (Figure 5).

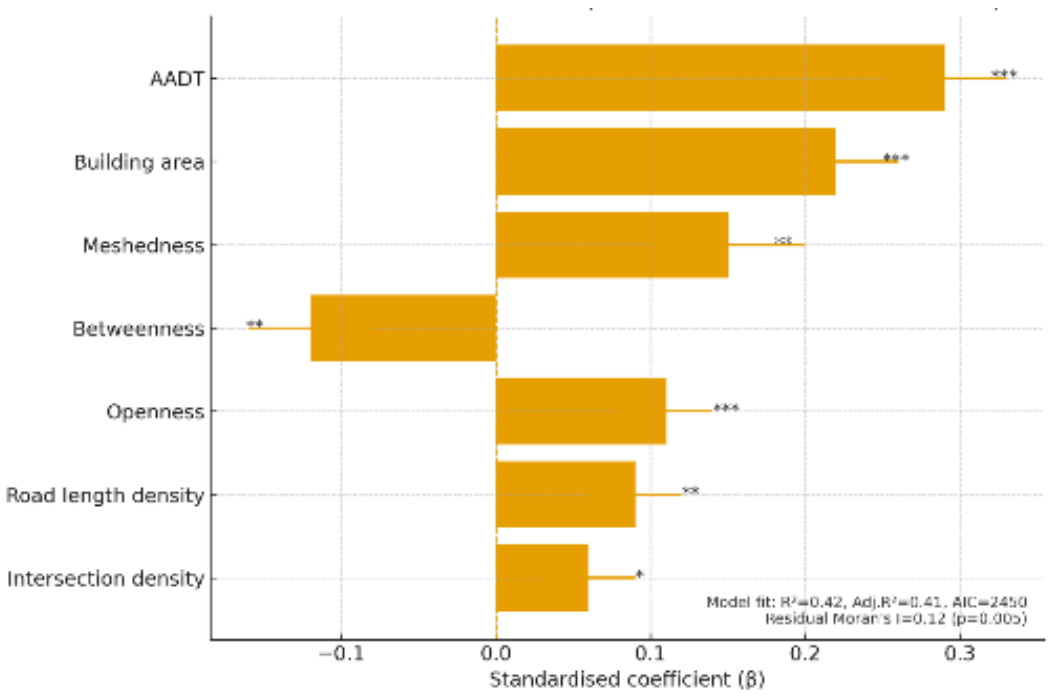

Figure 5. OLS regression (standardized coefficients; Robust SE in brackets)

When the spatial lag (SLM), spatial error (SEM), and spatial Durbin (SDM) models were compared, the SDM provided the best overall fit. In this model, AADT (0.36; Direct: 0.28, Indirect: 0.08) and building area (0.26; Direct: 0.18, Indirect: 0.08) had the largest total effects on crash rate, and betweenness centrality had a negative effect (-0.12; Direct: -0.09, Indirect: -0.03). The significant spatial parameter confirmed that spatial spillovers were an important feature of Baghdad's crash risk (Table 1).

Geographically weighted regression improved model fit compared with the global models and revealed marked spatial variation in effects. Betweenness centrality had negative local coefficients across much of the city, whereas AADT and building area had positive coefficients over large areas (Table 2).

Table 1. Global spatial models and spillovers (SDM selected)

Model	Spatial parameter	Value	p-Value	AIC	pseudo-R^2
SLM (Lag)	ρ	0.17	0.004	2378	0.48
SDM (selected)	ρ	0.19	0.002	2371	0.49
SEM (Error)	λ	0.21	0.002	2385	0.47

Table 2. Geographically weighted regression summary (AICc=2362; Pseudo-R^2=0.56; Local R^2=0.38)

Parameter	Median β_i	Q1-Q3	Significant +	Significant –	Max
Betweenness	−0.10	(−0.18, −0.03)	6%	48%	0.42
Meshedness	0.12	(0.04, 0.21)	52%	8%	0.47
Intersection density	0.05	(−0.02, 0.12)	23%	11%	0.31
Road length density	0.08	(0.02, 0.16)	34%	5%	0.29
Building area	0.19	(0.11, 0.28)	61%	3%	0.52
Openness	0.09	(0.01, 0.17)	39%	4%	0.33
AADT	0.24	(0.15, 0.34)	68%	2%	0.55

Crash rates were highest in grid cells within a few kilometers of hospitals and lower at greater distances. After adjusting for network metrics, however, risk remained heterogeneous, and areas with high meshedness and low betweenness close to hospitals still showed elevated crash rates (Table 3).

Table 3. Crash rates by distance to hospitals and network indicators

Distance to hospital (km)	Crashes/year	Crash rate (per 100 M VKT)	Median betweenness	Meshedness (median)	Road length dens. (km/km^2)
0-1	420	260	0.41	0.38	9.1
1-3	980	310	0.46	0.41	8.2
3-5	720	220	0.52	0.33	6.9
>5	390	170	0.37	0.28	5.1

Sensitivity tests that varied the grid size and the form of the spatial weights matrix produced similar signs and significance patterns for the main predictors (Table 4).

Table 4. Robustness to unit of analysis and spatial weights in SDM model

Scenario	R^2/AIC (OLS)	Spatial AIC	Δ-sign (key coefficients)	Change in mean β
500m grid; Queen	0.42/2450	2371	0	6%
1km grid; Queen	0.39/1960	1894	0	8%
500m grid; kNN (6)	0.41/2442	2380	1 (intersection density)	9%

Discussion

This study examined spatial patterns of road traffic crashes in Baghdad using a targeted set of network-topology metrics and exposure controls. Three principal findings stand out. First, betweenness centrality shows a negative association with crash rates in the global models and remains negative in the spatial Durbin model's total effects, while GWR indicates significantly negative local coefficients across roughly half of the city. This accords with a growing body of research suggesting that higher betweenness—when interpreted as efficient through-movement along shortest paths—can reduce local turbulence and opportunities for conflict by concentrating movement into predictable corridors [Clemente *et al.*, 2024]. In other words, well-connected arterial spines may channel flows in ways that reduce random weaving and U-turns on minor streets, even at high volumes [Cui *et al.*, 2025]. The Baghdad results therefore align with prior evidence that "structural efficiency" is not synonymous with greater risk; On the contrary, predictable routing and clear hierarchy can be protective when geometric design and speed management are adequate.

Second, meshedness, building area, and openness exhibit positive associations with crash rates—globally in OLS and SDM, and locally across large swathes in GWR—again mirroring recent findings in European and North American cities [Clemente *et al.*, 2024]. Mechanistically, meshedness and intersection density proxy conflict point intensity and turning opportunities. Denser grids facilitate accessibility but multiply decision points and angle conflicts; Depending on control type and visibility, the net effect ranges from neutral to harmful [Liu *et al.*, 2024]. Our mixed results for intersection density are consistent with this: Where four-way stops and short-sight triangles prevail, the effect tends to be positive; Where signal coordination and protected phases exist, it weakens or becomes ambiguous. Openness (1-built-up share) is positively associated with crash rates, which is consistent with the well-

documented speed-injury mechanism in more open, straighter, and wider environments [Chaudhuri *et al.*, 2022]. Building area likely captures both activity density (footfall, parking, kerbside friction) and exposure to side-friction, raising the probability of conflicts despite any "traffic calming" that frontage activity might produce. These patterns align with the meta-narrative that network complexity and higher operating speeds increase risk unless matched by appropriate geometric design, signal control, and speed management [Wang *et al.*, 2013].

Third, exposure (AADT) shows a positive association with crash rates across all specifications, with large total effects in SDM and high spatial consistency in GWR. This agrees with long-standing evidence and recent city-scale studies that treat AADT (or variants such as flow or VKT) as the dominant exposure control in crash modeling [Chaudhuri *et al.*, 2022; Cui *et al.*, 2025]. Notably, the spatial spillover parameter ($\rho \approx 0.19$) is significant in the SDM, implying that shocks to risk factors in one cell propagate to neighbors (e.g., diversion, speed adaptation, or signal coordination effects). This validates the shift from OLS to spatial econometric models and justifies reporting direct, indirect, and total effects rather than raw coefficients alone [LeSage & Pace, 2009]. From a policy standpoint, this means interventions on one corridor may yield neighborhood-level benefits or disbenefits, underscoring the need for corridor-scale design rather than purely local fixes.

The hospital-distance overlay adds a demand-and-operations perspective. Crash rates peak within 1-3 km of hospitals and decline beyond 5 km, but remain heterogeneous even after controlling for network structure. A plausible interpretation is that hospitals tend to lie near busy urban fabrics with intense flows and complex access patterns, where ambulance routes, drop-offs, and frontage frictions co-exist. Internationally, similar proximity effects have been reported near major generators (campuses, malls, stations) where concentrated activity and turning traffic elevate conflict probability unless access management and signal priority are in place [Clemente *et al.*, 2024]. For Baghdad, targeted measures near hospitals—protected turns, kerbside management, short crossing distances, and enforced speed limits—are therefore justified.

Limitations warrant caution. First, crash data in many LMIC settings are prone to under-reporting and severity misclassification; Although snapping to edges reduces spatial error, positional uncertainty persists. Second, AADT surfaces may rely on partial counts or modeled proxies; While our VKT-based normalization mitigates bias, exposure misallocation remains possible. Third, OSM completeness and building-footprint accuracy vary across districts; Residual measurement error could attenuate some effects [Boeing, 2017]. Fourth, the analysis is cross-sectional; Unobserved time-varying factors (enforcement, fuel price, post-event learning) are not captured. Finally, any grid-based study faces the modifiable areal unit problem (MAUP); our robustness checks (500 m vs 1 km; Queen vs kNN W) reduce but do not eliminate scale sensitivity.

Despite these caveats, the convergence of signs, the selection of SDM, the significant spillover parameter, and the GWR-based spatial consistency collectively strengthen internal validity. The correspondence with recent comparative studies further supports external validity: Baghdad's patterns reflect general mechanisms—exposure, conflict points, and speed opportunity—mediated by the particularities of its network hierarchy and built form [Clemente *et al.*, 2024; Cui *et al.*, 2025].

Conclusion

Baghdad's crash landscape was shaped by the combined influence of network structure, built form, and exposure. Higher betweenness centrality is associated with lower crash rates, whereas meshedness, openness, building area, and AADT are associated with higher risk once spatial dependence is accounted for. These patterns indicate that corridor-scale, network-oriented safety strategies are needed, with priority given to speed management, protected intersection design and access control in high-exposure, highly meshed and more open sections, especially around hospitals.

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Authors' Contribution: Khudhair HH (First Author), Introduction Writer/Methodologist/Statistical Analyst (30%); Azizi Z (Second Author), Discussion Writer/Methodologist/Statistical Analyst (30%); Neshat AR (Third Author), Discussion Writer/Methodologist (20%); Imani Harsini J (Fourth Author), Discussion Writer/Methodologist (20%)

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