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Spatial Panel Analysis of Road Traffic Restrictions on the Spatiotemporal Dynamics of COVID-19 in Kurdistan Province

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Abstract

Background and Objective: Despite the widespread implementation of road traffic restrictions in Iran during the COVID-19 pandemic, there is little quantitative evidence regarding the spatial effectiveness of these policies at the intra-provincial scale. The present study aimed to analyze the impact of traffic restrictions on the spatiotemporal dynamics of COVID-19 in Kurdistan Province and to test five quantitative hypotheses.

Methodology: In this study, a balanced panel of 10 counties of Kurdistan Province was constructed for the period 2019–2022, and spatial autocorrelation was examined using the Global Moran's I index. A spatial lag panel model with random effects and a K-nearest neighbor weight matrix was estimated. The policy variable (the proportion of months with travel bans) was extracted from the announcements of the National COVID-19 Taskforce and entered into the model in the form of interaction terms with traffic and migration variables. Direct, indirect, and total effects were calculated through matrix inversion $(I - \lambda W)^{-1}$, and the robustness of the results was assessed using six different spatial weight matrices.

Results and Findings: The Global Moran's I index was non-significant for all years (p-value > 0.05); however, the spatial lag model revealed a strong and significant spatial autoregressive coefficient ($\lambda = 0.812$, $p < 0.001$) (confirming H2). The coefficient for "bus travel" was positive and significant ($\beta = 0.100$, $p = 0.004$), whereas the coefficient for "private car travel", contrary to expectations, was negative and significant ($\beta = -0.0073$, $p < 0.001$) (partially confirming H1). The interaction terms of restrictions with car and bus traffic were nonsignificant (rejecting H3). The "restrictions × migration" interaction was positive and significant ($\beta = 0.271$, $p = 0.045$) (confirming H4). Hypothesis H5 was not tested due to the absence of daily mortality data. For all variables, spillover effects outweighed direct effects (for main road density: direct effect = 2.275 versus indirect effect = 5.706). The results remained robust across the six weight matrices. Hence, uniform road traffic restrictions, in the absence of essential travel management, shifted the disease transmission pathway from public travel to exempted migrations. The strong spatial autocorrelation and the predominance of spillover effects necessitate the design of regional and coordinated inter-county interventions. Policy evaluation in regions with a small number of spatial units requires advanced spatial models, and simple tests such as Moran's I are insufficient.

Keywords: COVID-19; spatial panel model; spatial lag; spatial spillover effects; spatial weight matrix; Kurdistan Province.

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EXTENDED ABSTRACT

Introduction

The COVID-19 pandemic exposed profound spatial heterogeneities in disease transmission, often driven by human mobility and regional connectivity. In Iran, the National COVID-19 Taskforce imposed widespread intercity travel restrictions from early 2020, yet quantitative evidence on the spatial effectiveness of these interventions at the intra-provincial (county) scale has been scarce. Kurdistan Province, located in western Iran with a 230 km border with Iraq, recorded over 74,000 infections and 4,759 deaths by February 2022, making it one of the high-burden provinces. Its mountainous terrain, severe climatic variability, and unevenly distributed road infrastructure create a complex spatial dynamic where both contiguous spread and long-distance migration shape transmission. Previous studies in Iran have largely remained descriptive or employed geographically weighted regression, but none have utilized spatial panel models capable of simultaneously capturing temporal dynamics and spatial spillovers of policy variables. This study aims to fill that gap by employing a spatial lag panel model to quantify the direct and indirect effects of road traffic restrictions on COVID-19 incidence across Kurdistan's 10 counties. Five hypotheses are tested regarding the role of bus/private car travel, spatial autocorrelation, the moderating effect of restrictions on traffic, the enhanced role of migration under restrictions, and behavioral response to mortality.

Methodology

A balanced panel of 10 counties over 4 years (2019–2022) was constructed, yielding 40 observations. The dependent variable is the annual total of confirmed COVID-19 cases per county, obtained from the Kurdistan University of Medical Sciences. Independent variables cover main and secondary road density, daily bus and private car trips, number of vehicles, net migration rate, and postal parcel volume. The policy variable (restrict_ratio) represents the proportion of days under severe travel restrictions per year, coded from official taskforce announcements. All absolute variables were transformed to rates per 1,000 population to avoid multicollinearity (VIF < 5 for all variables). Six spatial weight matrices were constructed: K-nearest neighbor (k=3, used as baseline), queen contiguity, rook contiguity, inverse distance, distance threshold, and Gabriel graph. Spatial autocorrelation was assessed annually via Global Moran's I. A spatial lag panel model with random effects (Hausman test: $p = 0.104$) was estimated using the spml function in the splm package in R. Interaction terms between the restriction ratio and traffic/migration variables were added to a second model. Direct, indirect, and total effects were computed through matrix inversion. Robustness was checked by re-estimating the model across all six weight matrices.

Results and discussion

Yearly Global Moran's I values were non-significant ($p > 0.05$), suggesting no univariate spatial autocorrelation. However, the spatial lag model revealed a strong latent spatial dependence: $\lambda = 0.812$ ($p < 0.001$), confirming H2. This implies that 81% of the variation in a county's cases is attributable to the weighted average of cases in neighboring counties. Among traffic variables, bus travel had a positive and significant coefficient ($\beta = 0.100$, $p = 0.004$), while private car travel showed an unexpected negative and significant effect ($\beta = -0.0073$, $p < 0.001$), partially confirming H1. The interaction terms of restrictions with bus and car travel were not significant, rejecting H3. In contrast, the interaction between restrictions and net migration was positive and

significant ($\beta = 0.271$, $p = 0.045$), confirming H4. The large positive coefficient of the restriction variable itself ($\beta = 10.570$, $p < 0.001$) reflects reverse causality: tight restrictions were imposed exactly when the epidemic peaked, making the variable endogenous. Decomposition of effects demonstrated that indirect (spillover) effects outweighed direct effects for all variables. For main road density, the direct effect was 2.275 and the indirect effect 5.706. This pattern proved robust across all six spatial weight matrices. The findings reveal a "policy-induced mobility substitution": when rigid travel bans curtailed public and private transport, essential, exempted migration became the dominant channel of inter-county transmission. The center-periphery spatial pattern with Sanandaj as the persistent hotspot underscores the need for coordinated, regional interventions. Compared to international studies, the magnitude of spatial autocorrelation ($\lambda = 0.812$) is remarkably high, reflecting Kurdistan's specific geographic and infrastructural context. The ineffectiveness of the univariate Moran's I test in small panels ($N = 10$) further warns against relying on simple spatial tests for policy evaluation in regions with few spatial units.

Conclusion

This study provides the first spatial panel evidence at the county level in Iran that uniform road travel restrictions, without complementary management of essential mobility, fail to disrupt transmission chains and instead reroute the epidemic through exempted migration corridors. The strong spatial autoregressive coefficient and the dominance of spillover effects call for multi-county coordination, targeted screening at origin/destination points during holidays, and the integration of real-time road traffic data into adaptive restriction systems. The concept of "policy-induced mobility substitution" enriches spatial health econometrics and highlights the danger of ignoring behavioral adaptation to geographic interventions. Future research should apply dynamic spatial panels with time-varying weight matrices, extend the analysis to other border provinces, and use agent-based simulations to optimize restriction designs. The study also demonstrates that in small panels, advanced spatial models are indispensable—simple indicators like Moran's I can be misleading.

Declarations

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Authors' Contribution

Both authors contributed to the conceptualization, analysis, and writing of the article.

Conflict of Interest

The authors declare no conflict of interest.

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