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Multimodal crash frequency modeling: Multivariate space-time models with alternate spatiotemporal interactions

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ABSTRACT

Enhancement of safety for all transportation mode users plays an essential role in the implementation of multimodal transportation systems. Compared with crash frequency models dedicated to motorized mode users, the use of these models has been considerably scarce in the multimodal literature. To fill this research gap, the authors aimed to develop and evaluate three multivariate space-time models with different temporal trends and spatiotemporal interactions. The model estimates justified the use of mode-varying coefficients for explanatory variables as the impact of these factors varied across different crash modes. Largely, a similar set of influential covariates was generated by the three models which indicate their robustness. However, notable differences were observed from the assessment of evaluation criteria pertaining to predictive accuracy based on criteria assessing the training and test errors. The model with time-varying spatial random effects demonstrated superior performance for training and test errors. However, due to the significant increase in number of effective parameters that were utilized for model development, this model appeared to have the largest value of deviance information criterion (DIC). In terms of the comparison between models based on site ranking performance, the time-varying spatial random effects model demonstrated the best performance in both site consistency and method consistency. In other words, the superiority of the model's predictive performance could be transferred to yield more accurate result at site ranking.

1. Introduction

Urban mobility and safety for all modes of transportation are key elements in the development of safer traffic environment. This goal may be realized with the implementation of multimodal approaches which allows the flexibility to simultaneously determine the injury risk of different travel modes. Compared with other modes, the non-motorized transportation modes generate health, environmental and social benefits, such as decreasing energy consumption, reducing congestion, keeping healthy and improving livability (Berrigan et al., 2006; Frank et al., 2010; Giles-Corti et al., 2010; Insall, 2013; Wanner et al., 2012). Albeit with the enormous advantages, the non-motorists are more vulnerable due to the lack of protective structure or "armor" like a car. Therefore, safety enhancement for all mode users (especially the pedestrians and bicyclists) plays an instrumental role in the implementation of multimodal transportation and resolving multiple long-term issues related to sustainability and efficiency of travels in urban environments (Tasic and Porter, 2016).

The traffic safety research has addressed the concerns pertaining to multimodal transportation by investigating the non-motorized crash modes (Lee and Abdel-Aty, 2005; Moudon et al., 2011; Beck et al., 2007; Wardlaw, 2002). Some studies explored the inter-relationship of pairs of motorized and non-motorized crash modes for the better understanding of influential factors and eventually design better safety improvement program, such as vehicle and pedestrian crashes (Shankar et al., 2003; Lee and Abdel-Aty, 2005; Pulugurtha and Sambhara, 2011), bicycles and vehicles (Wang and Nihan, 2004; Schepers et al., 2011; Strauss et al., 2013) and multiple vehicle crashes (Abdel-Aty and Radwan, 2000; Wang and Huang, 2016). However, the realization of safe traffic environment from the multimodal perspective demands joint estimation of multiple modes of crashes as an effort to account for the inter-relationship among crash modes. This unobserved heterogeneity may be addressed by the development of multivariate crash frequency models which reduce the bias associated with the ignorance of such correlation structures (Huang et al., 2017). The multivariate models have been extensively employed for the joint estimation of vehicle crashes on crash types (Ye et al., 2009; El-Basyouny et al., 2014; Aguero-Valverde et al., 2016; Cheng et al., 2017a) or severity levels

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(Park and Lord, 2007; El-Basyouny and Sayed, 2009; Aguero-Valverde and Jovanis, 2009; Gill et al., 2017a). However, the use of these models has been considerably scarce in the multimodal literature.

The study by Conway et al. (2013) employed a bivariate model to investigate the locations of conflict occurrence between bicycles and other mode users such as pedestrians, freight, passenger cars, and cabs. The study area was an urban setting as the interactions among such multiple modes are relatively more common. The characteristics which influenced the conflicts between these modes were also explored. This study recommended the development of a multivariate regression model for prediction of multimodal conflicts provided the availability of robust crash data and explanatory variables. Recently, the study by Huang et al. (2017) employed a multivariate Poisson lognormal model to jointly analyze the occurrence of motor vehicle, bicycle, and pedestrian crashes at urban intersections. This model specification allowed the flexibility to account for the unobserved heterogeneity due to the correlation among different modes involved in crashes at individual intersections. The results confirmed the presence of significant correlations among heterogeneous residuals among the crash risk of three modes considered in the study.

Similar to the multivariate specification which allows correlations among crash modes (also crash types and severity levels), spatial and serial correlations have also been explored in crash data. Accommodation of spatially unstructured (serial) correlations has been found to enhance the model fitness and precision by numerous research studies focused on vehicle crashes (Andrey & Yagar, 1993; Hay & Pettitt, 2001; Cheng et al., 2017b). Likewise, the significance of incorporating spatial correlations was also highlighted by many studies (Guo et al., 2010; Abdel-Aty & Wang, 2006) which noticed consistently superior performance of the spatial models over those accounting for heterogeneity random effect only. Some multimodal studies incorporated the spatial correlations among entities for improved estimation of crash risk as such correlation structures render the capability to "pool strength" from neighboring entities (Aguero-Valverde and Jovanis, 2008) and also act as surrogate for the unmeasured spatial confounding factors related to sites of interest which are not incorporated in the model (Chiou et al., 2014). Cai et al. (2016) incorporated the spatial spillover effects to develop dual-state models for analysis of pedestrian and bicycle crashes at the macro-level of Traffic Analysis Zones (TAZs). It was observed that consideration of spatial effects improved the performance of model while highlighting the impact of certain traffic, roadway and sociodemographic characteristics on bicycle and pedestrian crashes at the planning level. The study by Tasic and Porter (2016) incorporated spatial random effects on the level of census tracts within the negative binomial model to evaluate the relationship multimodal infrastructure and traffic safety outcomes. A significant association was observed between motorized and non-motorized crashes, and variables pertaining to socio-economic, land use, road network, travel demand. Amoh-Gyimah et al. (2016) employed the CAR (conditional autoregressive) specification into the negative binomial model for estimation of pedestrian and bicycle crashes at the macro-level of statistical area. The study by Wang et al. (2017) focused on the motor vehicle, bicycle, and pedestrian crashes at the intersection level but incorporated the zonal factors (TAZ level) as a measure of spatial dependence. It was observed that the inclusion of zonal factors elevated the performance of the model in case of non-motorized crashes while their omission resulted in biased parameters, which indicates the role of macro-level factors for estimation of crash risk for non-motorized crash modes. It should be noted that aforementioned multimodal spatial studies mostly focused on the macro-level as such higher levels of spatial entities better fits to account for the area-wide explanatory factors for the safety of multimodal environment (Tasic and Porter, 2016). However, the above multimodal studies did not employ a previously discussed multivariate model for simultaneous estimation of multiple crash modes although such multivariate spatial models have been employed to estimate various crash severities or outcomes (Aguero-Valverde, 2013; Cheng et al., 2017a). The recent paper by Huang et al. (2017) proposed a spatial multivariate Poisson lognormal model for joint modeling of three transportation modes at intersection level, namely: motor vehicle, bicycle, and pedestrian crashes. It was observed that the proposed model outperformed the univariate spatial and the multivariate models which accounted only for spatial correlation among sites and correlation among modes, respectively. The variance estimates for spatial correlation of the three modes were noted to be statistically significant.

Given the benefits associated with temporal and spatial correlations, some studies of crash severity incorporated the interaction of space and time for better precision of estimates. Aguero-Valverde and Jovanis et al., 2006 developed spatiotemporal models for analysis of fatal and injury crashes at the county level under the Full Bayesian framework which allowed the flexibility to accommodate hierarchical nature of crash data. The space-time interactions, along with spatial correlation and time trend were observed to be significant for injury counts. A recent study by Ma et al. (2017) proposed multivariate spatiotemporal models which accounted for the unobserved heterogeneity by incorporating spatial, temporal, space-time, and correlations among different severity levels. The results confirmed the superiority of space-time model over the alternative random effects and spatial models.

The aforementioned sophisticated space-time models, which combine the immense benefits associated with spatial and temporal correlations, are scarce in studies focused on multimodal literature. To fill this research gap, the authors aim to develop three multivariate spatial-temporal models to analyze the modal crash data at the macro-level of counties. The three alternate models share the common aspects of the multivariate spatial specifications but differ on the assignment of temporal trends and spatiotemporal interaction. The model formulations are presented in order of complexity: (1) the linear time trend with fixed spatial; (2) the quadratic time trend with fixed spatial; and the more sophisticated (3) the time-varying spatial model. Given that the external influential factors may not have an equal impact on different modes, the mode-varying intercept and model parameters, rather than fixed ones, were chosen which allow the flexibility to estimate different coefficients for each of the four modes (motor-vehicle only, pedestrian-involved, bicyclist-involved and motorcyclist-related). This study serves two broad objectives: (a) to examine the benefits of alternative models associated with model fit and goodness-of-fit, which is assessed by employing DIC (deviance information criterion), and LPML (log pseudo marginal likelihoods), and (b) to quantify the transferability of better model fitness and crash estimation to site ranking, which is evaluated by employing SCT (site consistency test) and MCT (method consistency test) at different threshold levels.

2. Methodology

This study analyzed four different transportation mode users-involved crashes aggregated at the 58 counties of California over a period of eight years. The models were developed assuming the Poisson-lognormal distribution, unlike the alternate Negative Binomial, as the heavier tails associated with the lognormal distribution renders the capability of better handling the small sample size (Lord and Miranda-Moreno, 2008) and overdispersion (Lord and Mannering, 2010) in crash data. To reduce the bias associated with the ignorance of dependency within crash modes, the multivariate error term was incorporated in the models for simultaneous estimation of crash rates for all four modes (Park and Lord, 2007). Finally, the random effects were incorporated to account for the spatial correlations and spatiotemporal interactions from different perspectives. To account for the unobserved heterogeneity from different perspectives, the Full Bayesian (FB) framework was employed due to its flexibility and effectiveness to incorporate complex correlations with a hierarchical structure of data (Pawlovich et al., 2006; Miranda-Moreno, 2006). The traditional approach of maximum likelihood estimation relies on the point estimates for

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