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A gravity model integrating high-speed rail and seismic-hazard mitigation through land-use planning: Application to California development

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A B S T R A C T

California high-speed rail (CalHSR) will be changing the current regional and urban structure because of the improved transportation mobility and accessibility. It has been a focus of interest to see whether high-speed rail will enhance the polarization of first-tier station cities or reduce the gap between those and lower-tier cities. In California, the two largest cities (i.e., San Francisco and Los Angeles) are under great seismic threat. Planners should be able to assess CalHSR impacts and the resulting seismic risks because of disproportionally allocating future growth to seismic hazardous locations. Urban models can help develop knowledge about urban and regional system behavior, since CalHSR does not yet exist. A gravity model, TELUM, is therefore used to understand the effects of CalHSR and seismic hazard mitigation on the allocation of future development over six 5-year increments from 2015 to 2040. Several scenarios are considered: 1) natural growth; 2) impact of CalHSR; 3) impacts of both seismic hazard mitigation and CalHSR. The first scenario shows that TELUM tends to result in spatial polarization. Under the second scenario, CalHSR enhances the polarization of San Francisco, Los Angeles, and Fresno metropolitan areas, due to their economic strength. The third scenario is to examine whether CalHSR effects increase seismic risks. The results show that a seismic mitigation plan with zero-development policy can improve urban resilience. From the perspective at the regional level, possible seismic mitigation approaches are discussed, through land-use and transportation planning, to guide future growth to more seismic-resistant locations.

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1. Introduction

Transportation investment is an important consideration in land-use planning. The California high-speed rail project (CalHSR), for instance, will be changing the regional and urban landscape of California (Ewing & Bartholomew, 2009; Sands, 1993). With speed of 200 miles per hour (mph), it will be able to link San Francisco to Fresno in 1.5 h, and to Los Angeles in 3 h (Sands, 1993). Because of this improved transportation network, HSR is likely to provide urban regeneration opportunities for the station cities (Garmendia, Ribalaygua, Ureña, 2012). An issue is whether CalHSR will enhance the polarization of San Francisco and Los Angeles, the two major growth cores in the state, or be beneficial to all the intermediate station cities, particularly in the Central Valley, due to reduced travel time. In addition, the two largest metropolitan areas are under great seismic threat. It is therefore important to assess CalHSR impacts on economic activities and the seismic risks resulting from a disproportional allocation of future growth to seismic hazardous locations.

Modern metropolitan areas can be seen as highly complex systems. Models have been used to better understand their behavior (Iacono, Levinson, & El-Geneidy, 2008). Gravity models, which represent the transportation interactions between locations, as functions of activities and travel costs/times (Iacono et al., 2008), could be helpful to analyze the impacts of CalHSR on urban and regional change. A GIS-based system successor of the DRAM/EMPAL

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gravity model, TELUM (Transportation Economic and Land Use Model), is used in this study. TELUM has been applied to numerous cities in the world, with a particular focus on the interaction between transportation network changes and the resulting allocation of economic activities (Casper, O'Brien, Lupa, Dimitrijevic, & de Araujo, 2009; Pozoukidou, 2014). In TELUM, the DRAM residential model and the EMPAL employment model are linked to a transportation model (Putman, 2010).

TELUM is used to better understand the effects of CalHSR and seismic-hazard mitigation on population, employment, and land-use allocation over six 5-year increments between 2015 and 2040. Several scenarios are considered: 1) natural growth; 2) impact of CalHSR; 3) impacts of both seismic hazard mitigation and CalHSR. The results show how these impacts shape the future of California and provide technical and policy insights for a seismic-resilient development.

The remainder of the paper is organized as follows. Section 2 consists in a literature review. The methodology is presented in Section 3. The data are described in Section 4. The simulation results and their analysis are presented in Section 5. Section 6 discusses how CalHSR can be used to enhance seismic-resilient development. Section 7 presents conclusions and outlines areas for future research.

2. Background

2.1. High-speed rail

High-speed rail (HSR), defined as a system operating daily at speed of 150 mph (240 km/h) or more, is designed to improve intercity transportation by reducing travel time (Sands, 1993). As compared to aviation, HSR has proved to be more effective for distances of up to 425 miles (700 km), because of more frequent service, lower cost, easier station access, greater reliability, and increased safety (Levinson, 2012; Sands, 1993; Sanuki, 1979; Ureña, Menerault, & Garmendia, 2009). Therefore, HSR systems have been built in many countries, starting in Japan (Shinkansen), followed by European countries (French TGV and German ICE), and currently East Asian countries (Taiwanese THSR, Chinese CRH, and South Korea KTX) (Garmendia et al., 2012; Sands, 1993).

The effects of HSR systems on future development have been analyzed at different spatial levels. At the regional level, a major concern is whether HSR projects result in spatial concentration or dispersal of population and economic activities around station cites, due to the improved mobility and accessibility (Garmendia et al., 2012; Hall, 2009; Sands, 1993). An increasing concentration (polarization) may result in substantial spatial disparities between metropolitan areas and more remote places, also called peripheralization (Hall, 2009). New development could be inconsistent across station cities, and determined by their economic strengths (Sands, 1993).

At the urban level, a city with a HSR station is likely to have higher growth rates of population, employment, and land uses (Nakamura & Ueda, 1989; Sands, 1993). Examples from Europe also show that HSR stations can act as catalysts for urban development (Hall, 2009; Loukaitou-Sideris, 2013). HSR service may offer the possibility to have a denser and more focused development around the station cities, using the theory of transit-oriented development (TOD) (Dittmar, Belzer, & Autler, 2004; Zhong, Bel, & Warner, 2014). Unfortunately, there are no empirical studies to date on HSR effects in the US, as these services do not yet exist (Levinson, 2012).

2.2. Urban models

Linking first-tier cities to one another and to second-tier cities, CalHSR would increase mobility and accessibility (Garmendia et al., 2012; Levinson, 2012), resulting in changes in the physical landscapes and economies around station cities (Geng, Bao, & Liang, 2015; Loukaitou-Sideris, 2013). However, few studies discuss these impacts in terms of population, employment, and land uses. An urban model would therefore be helpful to better estimate the impacts of transportation investments (i.e., CalHSR).

Various urban models have been developed to integrate land-use and transportation based on different planning objectives and methodologies. Several theoretical frameworks for urban models have been reviewed by Iacono et al. (2008) and Waddell (2002): (1) Gravity-Based Models (e.g., Model of Metropolis by Lowry and Garin in the 1960s; ITLUM by Putman in the 1980s); (2) Econometric Models (e.g., MUSSA by Martinez in the 1990s; PECAS by Hunt and Abraham in the 2000s); (3) Spatial Input-Output Models (e.g., TRANUS by de la Barra in the 1980s; MEPLAN by Echenique et al. in the 1990s); and (4) Microsimulation models (e.g., UrbanSim by Waddell in the 2000s). The first three modeling frameworks specify interactions of aggregate activities between locations over a transportation network, while microsimulation disaggregates population into individual agents, redefining the nature of actors in the model (Iacono et al., 2008). Zhou, Kockelman, and Lemp (2009) also summarize several applications of the above-mentioned models, including PECAS (Abraham & Hunt, 2003; Hunt et al., 2008), MUSSA (Martinez, 1996), and UrbanSim (Borning, Waddell, & Förster, 2008; Waddell et al., 2003).

Lowry's gravity model, using the economic base theory, is the oldest of this kind of urban models, addressing the mobility and accessibility improvement, while estimating future development locations (Ewing & Bartholomew, 2009; Prato, Clark, Dolle, & Barnett, 2007; Putman, 1983; 2010). Gravity models have several advantages: simple model structure, moderate data demands, and relatively straightforward estimation (Duthie, Kockelman, Valsaraj, Zhou, 2007; Zhou et al., 2009). TELUM (Transportation, Economic, and Land-Use Model) is a widely used integrated interactive software package for evaluating the impacts of transportation improvement projects on population, employment, and land uses (Casper et al., 2009; Zhou et al., 2009). Urban models, such as TELUM, allow planners to consider the potential consequences of a wide range of policies for regional sustainable development (Casper et al., 2009).

Casper et al. (2009) demonstrated a TELUM application that predicts land-use development for the Colorado Springs region over six 5-year increments between 2005 and 2035. Similarly, Zhou et al. (2009) used TELUM to analyze sustainable transportation policies for Austin, Texas. In their study, three scenarios were considered: business-as-usual, congestion pricing plus carbon tax, and urban growth boundary. The simulated results revealed that the imploration of road pricing had no significant effect on land-use predictions, but resulted in the same vehicle miles travelled (VMT) reduction as the urban growth boundary policy. These TELUM applications focus on the interactions between land use and transportation when considering different growth policies. However, there is a need, often neglected in past studies, to incorporate safety elements when considering policies for future growth in areas with natural hazards (Nelson & French, 2002). In the operation of TELUS, land control policies could include land-use restrictions to limit future development within natural hazardous zones, while transportation policies could refer to the HSR project for California.

2.3. Seismic hazard and urban vulnerability

In addition to mobility and accessibility, sustainability and affordability have also been discussed in recent HSR studies (Garmendia et al., 2012). However, seismic vulnerability also

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