Physica A 419 (2015) 537–545

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Locating inefficient links in a large-scale transportation network

Li Sun [a,1], Like Liu [a,b,1], Zhongzhi Xu [a], Yang Jie [a], Dong Wei [a], Pu Wang [a,*]

[a] *School of Traffic and Transportation Engineering, Central South University, Changsha, Hunan, 410000, PR China*
[b] *Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL 32611, United States*

HIGHLIGHTS

- Braess's paradox in a large transportation network under realistic travel demand.
- The variation of total travel time $|\Delta T|$ follows a power-law distribution.
- Heterogeneous travel demand may be the origin of the power-law distributed $|\Delta T|$.
- Inefficient link clusters can be located using a genetic algorithm.

ARTICLE INFO

Article history:
Received 20 May 2014
Received in revised form 3 September 2014
Available online 19 October 2014

Keywords:
Transportation network
Network flow
Transportation efficiency
Braess's paradox

ABSTRACT

Based on data from geographical information system (GIS) and daily commuting origin destination (OD) matrices, we estimated the distribution of traffic flow in the San Francisco road network and studied Braess's paradox in a large-scale transportation network with realistic travel demand. We measured the variation of total travel time ΔT when a road segment is closed, and found that $|\Delta T|$ follows a power-law distribution if $\Delta T < 0$ or $\Delta T > 0$. This implies that most roads have a negligible effect on the efficiency of the road network, while the failure of a few crucial links would result in severe travel delays, and closure of a few inefficient links would counter-intuitively reduce travel costs considerably. Generating three theoretical networks, we discovered that the heterogeneously distributed travel demand may be the origin of the observed power-law distributions of $|\Delta T|$. Finally, a genetic algorithm was used to pinpoint inefficient link clusters in the road network. We found that closing specific road clusters would further improve the transportation efficiency.

1. Introduction

Many transportation networks, from road networks to the Internet and power-grids, are characterized by complex topologies and time-variant flows. As vital infrastructures in modern cities, transportation networks play a crucial role in people's daily life. Their performance is of great importance and has attracted widespread attention in scientific and engineering fields [1–5]. The most straightforward method to improve the efficiency of a transportation network is to increase its capacity [2,3], for example, building new roads in a road network. However, theoretical analysis [5–8] and practical observations [9,10] indicate that adding new links to a transportation network may decrease its efficiency; this is known as Braess's paradox [11].

---

[*] Corresponding author.
E-mail address: wangpu@csu.edu.cn (P. Wang).

[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.physa.2014.10.066

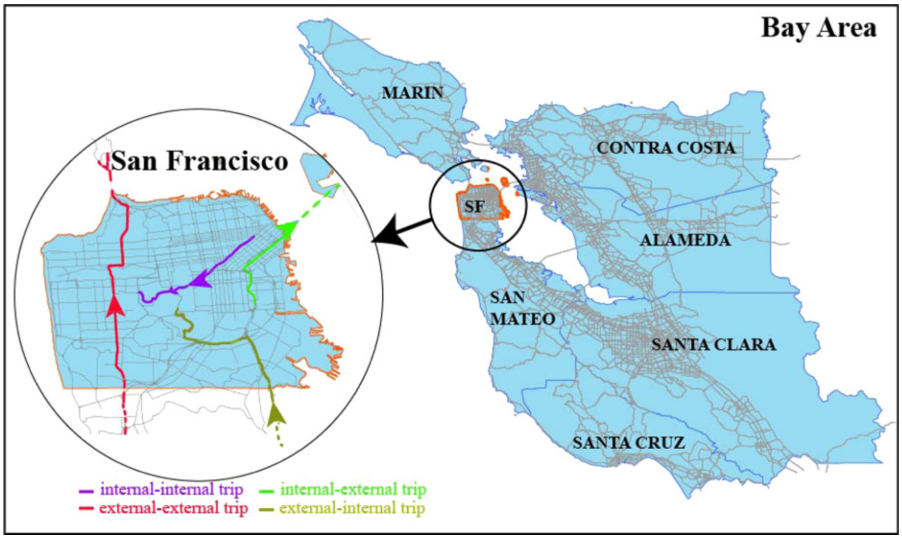

Fig. 1. The San Francisco road network and four types of trips. The San Francisco road network was extracted from the Bay Area road network. From the Bay Area commuting OD data, we extracted 42,018 internal–internal trips, 43,650 internal–external trips, 48,435 external–internal trips and 17,523 external–external trips during the morning peak and 51,050 internal–internal trips, 58,983 internal–external trips, 53,093 external–internal trips and 21,378 external–external trips during the evening peak.

Braess's paradox is caused by agent's selfish routing and has been shown to occur in, for example, mechanical and electrical networks [12], water-supply networks [13], and queuing networks with fixed [14] or dynamic routing schemes [15]. In the field of transportation engineering, studies have shown that the occurrence of Braess's paradox depends on the link cost function and travel demand [16]. The paradox disappears as travel demand increases [16,17]. An explanation for this observation is that high travel demand prevents travelers from selfishly selecting routes [8]. Previous investigations on Braess's paradox were commonly based on the classical, symmetric four-link network proposed by Braess [18–20]. Recently, Braess's paradox was studied in simplified road networks of New York, London and Boston, with only one pair of origin and destination considered [3]. There are few studies on Braess's paradox in practical large-scale transportation networks with realistic transport demand [21].

In this work, we first estimated the morning and evening peak (rush-hour) travel demand in San Francisco. Next, we studied Braess's paradox in the San Francisco road network and located inefficient links. We analyzed the properties of the inefficient links and explored the generality of the results in three theoretical complex networks. Finally, using a genetic algorithm, we located inefficient link clusters whose closure could further improve transportation efficiency in comparison with the closure of a single link.

2. Data and methods

2.1. Transportation network and travel demand estimation

The San Francisco road network was used in this study. The data were extracted from the Bay Area road network [22], which consists of 1148 intersections and 2823 road segments (see Fig. 1). The road segments include highways and arterial roads. For each road segment, the speed limit, capacity, number of lanes and direction were extracted from the database.

The Bay Area home-work commuting OD data were also used in this study [23]. The OD data record the number of trips from residents' home locations to work locations at a street-block level. We identified the census tract each street block belongs to and generated the OD at a census tract resolution. The vehicle usage rate (*VUR*) of each census tract was estimated using the mode split data provided by TransCAD 5.0 [24]: $VUR\,(i) = P_{\text{drive}}\,(i) + P_{\text{carpool}}(i)/S$. Here, $P_{\text{drive}}(i)$ is the probability that residents in census tract i drive alone and $P_{\text{carpool}}(i)$ is the probability that residents share a car. The average carpool size in California $S = 2.25$ was used in the calculations [25]. We randomly assigned residents in each census tract to a transportation mode (vehicle or non-vehicle) according to the vehicle usage rate and eliminated trips that were not made by vehicles.

Cross-Classification Analysis was used to estimate the total number of trips. In this method, the annual income of a household was used to determine the vehicle trip production rate [26] (Table 1). By extracting the numbers of different classes of households in each census tract, we estimated the total number of trips in the Bay Area (17,297,493 in total) using the Cross Classification method provided by TransCAD 5.0. We further calculated the average hourly trip production in the morning (6:00–10:00 a.m.) and evening (4:00–8:00 p.m.) period based on the daily distribution of traffic volume [27]. Consequently, we generated morning and evening peak hourly commuting OD matrices.