Transportation Research Part C 86 (2018) 245–262

Contents lists available at ScienceDirect

Transportation Research Part C

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

A resource allocation problem to estimate network fundamental diagram in heterogeneous networks: Optimal locating of fixed measurement points and sampling of probe trajectories

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ARTICLE INFO

Keywords:
Network Fundamental Diagram (NFD)
Macroscopic Fundamental Diagram (MFD)
Heterogeneous networks
Probe trajectories

ABSTRACT

Network Fundamental Diagram (NFD) or Macroscopic Fundamental Diagram (MFD) represents dynamics of traffic flow at the network level. It is used to design various network-wide traffic control and pricing strategies to improve mobility and mitigate congestion. NFD is well defined when congestion distribution in the network is homogenous. However, in real world networks traffic is often heterogeneously distributed and initiated from an asymmetric and time-varying origin-destination (OD) demand matrix. In this paper, we formulate a resource allocation problem to find the optimal location of fixed measurement points and optimal sampling of probe trajectories to estimate NFD accounting for limited resources for data collection, network traffic heterogeneity and asymmetry in OD demand in a real-world network. Data from probe trajectories are used to estimate space-mean speed while data from fixed detectors are used to estimate traffic flow. Thus, the proposed model does not require an aggregate penetration rate of probe vehicles to be known a priori, which is one of the main contributions of this study. The proposed model is a mixed integer problem with non-linear constraints known to be NP-hard. A heuristic solution algorithm (Simulated Annealing) is implemented to solve the problem. Using a calibrated simulation-based dynamic traffic assignment model of Chicago downtown network, we present successful application of the proposed model and solution algorithm to estimate NFD. The results demonstrate sensitivity of the NFD estimation accuracy to the available budget, namely number of fixed measurement points and probe trajectories. We show that for a fixed proportion of OD trajectories, the increase in the proportion of fixed detection points increases the accuracy of NFD estimation as expected. However, when the proportion of fixed detection points is set to be constant, the increase in the proportion of OD trajectories does not necessarily improve the estimated NFD. Results hold true when varying demand is used to emulate variation in day-to-day traffic patterns. The robustness of the proposed methodology to the initial solution and trajectory availability for each OD pair is demonstrated in the numerical results section. We also found that a uniform distribution of selected links and ODs for NFD estimation across the network may not necessarily result in an optimal solution. Instead, distribution of links and OD pairs should follow the same distribution of links and OD pairs in the network.

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https://doi.org/10.1016/j.trc.2017.11.017
Received 1 June 2017; Received in revised form 9 October 2017; Accepted 15 November 2017

Nomenclature

T	Number of time intervals over the horizon for NFD estimation
t	time interval index
ζ	weight factor in objective function for minimizing deviation of estimated average flow from the ground-truth average network flow
η	weight factor in objective function for minimizing deviation of estimated average density from the ground-truth average network density
Q_t	ground-truth average network flow at time interval t
$\widehat{Q}_t$	estimated average network flow by fixed detectors at time interval t
K_t	ground-truth average network density at time interval t
$\widehat{K}_t$	estimated average network density at time interval t
I	number of links in the network
i	Link number index
q_i^t	flow at link i at time interval t
l_i	lane-length of link i
s_i^t	space-mean speed at link i at time interval t
x_i	binary variable associated with fixed detection at link i
J	number of origin-destination pairs in the network
j	origin-destination pair index
$K(j)$	number of trajectories available for origin-destination pair j
k	Trajectory index for origin–destination pairs
p_{ijk}^t	binary parameter specifying if kth trajectory of origin-destination pair j includes link i at time interval t
$\widetilde{tt}_{ijk}^t$	experienced travel time at link i and time interval t by k^{th} trajectory of origin-destination pair j
$\widehat{tt}_i^t$	experienced average travel time at link i and time interval t by available trajectory of selected origin-destination pairs
$\hat{s}_i^t$	Estimated space-mean speed from mobile probe trajectories at link i at time interval t
z_i^t	binary variable specifying if there is any trajectory from selected origin-destination pairs that includes link i at time interval t
M	a large number
w_i^t	binary variable specifying if estimated speed is available through at least one trajectory from selected origin-destination pairs including link i at time interval t, and estimated flow is available through the detector at link i
y_j	Binary variable associated with the probe trajectory data for origin–destination pair j
c_i	data collection or acquisition cost if there is a fixed detector at link i
f_j	data collection or acquisition cost for probe trajectory data of origin-destination pair j
B	total available budget for data collection or acquisition

1. Introduction

The network-wide relationship between average flow, average density, and average speed, known as Network Fundamental Diagram (NFD) or Macroscopic Fundamental Diagram (MFD), is a powerful tool for representing traffic dynamics in large-scale networks (Godfrey, 1969; Mahmassani et al., 1984, 1987; Geroliminis and Daganzo, 2008). NFD can be used to design and implement specific control and pricing strategies to improve mobility at the network level (Haddad and Geroliminis, 2012; Zheng et al., 2012; Geroliminis et al., 2012; Keyvan-Ekbatani et al., 2012; Ramezani et al., 2015; Yildirimoglu et al., 2015; Haddad and Mirkin, 2016; Mariotte et al., 2017). NFD is well defined and has low scatter when congestion distribution in the network is homogenous (Buisson and Ladier, 2009; Ji et al., 2010; Mazloumian et al., 2010; Daganzo et al., 2011; Gayah and Daganzo, 2011; Geroliminis and Sun, 2011; Saberi and Mahmassani, 2012; Mahmassani et al., 2013; Saberi and Mahmassani, 2013; Knoop et al., 2012; Zockaie et al., 2014b). Estimating NFD in real-world networks, when data collection budget is limited and network traffic is heterogeneous and initiated from an asymmetric and time-varying origin-destination (OD) demand matrix, is a challenging task.

Analytical methods to estimate NFD based on variational theory developed previously by Daganzo and Geroliminis (2008) and later refined by Geroliminis and Boyaci (2012) and Leclercq and Geroliminis (2013) are limited to urban corridors in stationary conditions and cannot be applied to large-scale heterogeneous networks. A recent study by Leclercq et al. (2014) evaluated existing estimation methods for NFD focusing only on homogenous network loading. They suggested that using the complete population of vehicle trajectories to estimate NFD is the only estimation method with no bias agreeing with recent findings of Saberi et al. (2014). However, availability of the entire population of trajectories is still limited in urban networks and will continue to be limited even when connected vehicles are deployed in near future. Gayah and Dixit (2013) proposed a method to estimate average network density using probe vehicles combined with NFD. Leclercq et al. (2014) suggested that combining information from probe vehicles and traffic loop detectors can also provide fairly accurate estimation of NFD in stationary conditions even for sample rates as low as 10%. Other studies by Ortigosa et al. (2014) and Nagle and Gayah (2014) estimate NFD using combined mobile probes and traffic loop detector data. Ortigosa et al. (2014) studied the optimal number and location of measurement points by minimizing the error in estimated average network density. However, they overlooked the potential of the application of probe trajectory data in NFD estimation. Nagle and Gayah (2014) proposed a method to estimate average network density and flow using data from mobile probes given a constant and known penetration rate of probes across a network. In a later study, Du et al. (2015) extended the method to varying penetration rates with heterogeneous demand in an idealized square grid network. A limitation of this method is that the penetration rates of probes must be known a priori. More recently, Ambuhl and Menendez (2016) proposed a fusion algorithm that decomposes the network into two sub-networks and uses both loop detector data and floating car data to estimate NFD.