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Modeling the day-to-day traffic evolution process after an unexpected network disruption

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ABSTRACT

Although various approaches have been proposed for modeling day-to-day traffic flow evolution, none of them, to the best of our knowledge, have been validated for disrupted networks due to the lack of empirical observations. By carefully studying the driving behavioral changes after the collapse of I-35W Mississippi River Bridge in Minneapolis, Minnesota, we found that most of the existing day-to-day traffic assignment models would not be suitable for modeling the traffic evolution under network disruption, because they assume that drivers' travel cost perception depends solely on their experiences from previous days. When a significant network change occurs unexpectedly, travelers' past experience on a traffic network may not be entirely useful because the unexpected network change could disturb the traffic greatly. To remedy this, in this paper, we propose a prediction–correction model to describe the traffic equilibration process. A "predicted" flow pattern is constructed inside the model to accommodate the imperfect perception of congestion that is gradually corrected by actual travel experiences. We also prove rigorously that, under mild assumptions, the proposed prediction–correction process has the user equilibrium flow as a globally attractive point. The proposed model is calibrated and validated with the field data collected after the collapse of I-35W Bridge. This study bridges the gap between theoretical modeling and practical applications of day-to-day traffic equilibration approaches and furthers the understanding of traffic equilibration process after network disruption.

1. Introduction

Prediction of day-to-day traffic flow evolution is vital for the prioritization of traffic restoration projects after a network disruption, such as the unexpected collapse of the I-35W Mississippi River Bridge in Minneapolis, Minnesota. From the traffic management's perspective, for a disrupted network, it is essential to understand how the traffic pattern evolves from a disequilibrium state toward a new equilibrium, before traffic restoration projects can be planned accordingly.

Day-to-day (or inter-periodic) traffic assignment methods are believed to be most appropriate for analyzing traffic equilibration processes because of their flexibility to accommodate a wide range of behavior rules, levels of aggregation, and traffic models (Watling and Hazelton, 2003). Watling (1999) classified day-to-day traffic assignment models into four types, by whether they are continuous or discrete, and deterministic or stochastic. Existing continuous time day-to-day dynamics employ differential equations to describe traffic evolution. In this category, Smith (1984), Friesz et al. (1994), and Zhang and Nagurney (1996) proposed three dynamical systems. These three systems adopted the assumption of perfect perception of travel cost and developed deterministic traffic assignment processes over a continuous temporal dimension. In discrete

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time day-to-day traffic dynamical systems, travelers' route choice behavior is assumed to be repeated daily, in accordance with daily changes in traffic flows. Specifically, Friesz et al. (1994) employed a projection-type discretization algorithm, given by Bertsekas and Gafni (1982), to approximate the continuous traffic trajectories in the dynamical system developed therein. Nagurney and Zhang (1997) specified their continuous model in a discrete temporal space with fixed demand and applied Euler's method to solve the projected dynamical system. To accommodate the drivers' route choice stochasticity, existing stochastic day-to-day traffic assignment models followed Markov processes, as those in Cascetta (1989) and Hazelton and Watling (2004). To solve these models, Davis and Nihan (1993) provided a particular Gaussian multi-variant autoregressive process and Hazelton et al. (1996) proposed a Markov Chain Monte Carlo method.

As noted by Mahmassani (1990), it is difficult to obtain observational evidence of real-world traveler choice behaviors to verify a day-to-day traffic assignment model. Most studies on day-to-day dynamic traffic modeling (e.g., Mahmassani et al., 1986; Jotisankasa and Polak, 2005) rely on experimental approaches rather than field data. Other studies (Chang and Nojima, 2001; Hunt et al., 2002, e.g.,) provide empirical observations of traffic fluctuation under network disruption but no mathematical models are established. Due to the lack of data, very few studies have compared the outcomes of a day-to-day traffic assignment model against reality, and thus the quality of existing models has not been verified. As noted by Friesz and Shah (2001), the urgent need for day-to-day traffic dynamic modeling is neither to establish delicate mathematical formula nor to develop computational tools, but rather "to gather data which allows construction and calibration of the kind of day-to-day adjustment dynamics". There clearly exists a gap between day-to-day traffic flow evolution models and their practical applications, especially for disrupted networks that are appealing to traffic management authorities.

This paper is devoted to bridging the gap by developing and validating a new discrete-time deterministic day-to-day traffic assignment model, based on the observations collected after the collapse of I-35W Mississippi River Bridge on August 1, 2007. Since the I-35W highway bridge is a major artery in the Twin Cities highway network, its collapse constitutes a significant disruption to the trip-making patterns in the region. While catastrophic to those affected by the collapse in terms of fatalities, injuries, and loss of personal property, it provides a rare research opportunity to observe the traffic flow evolution process empirically. Therefore, the main goal of this work is to gain insights into the traffic flow evolution process given the real-world example.

Based on the loop detector data from the Twin Cities freeway system, we found that most of the existing day-to-day traffic assignment models would not be suitable for modeling the traffic evolution under network disruption, because they assume that drivers' cost perception depends solely on their experiences from previous days. For instance, the perception updating process in Nagurney and Zhang (1997) and Yang and Liu (2007) assumes that travelers' route choice depends on their experienced travel costs on the previous day only; other studies, e.g., Chang and Mahmassani (1988), Cascetta (1989), Davis and Nihan (1993), adopt a weighted average based cost updating mechanism. Such cost updating mechanisms can be considered as cost correction processes, but cannot be applied directly to a traffic network with a significant unexpected disruption. When a significant network change occurs unexpectedly, travelers' past experience on a traffic network may not be entirely useful because the unexpected network change could disturb the traffic pattern greatly. An additional component is needed inside the perception update process to take care of the disturbance from disruption.

The proposed day-to-day traffic assignment model differs from the traditional ones in that the cost updating process considers driver's forward-looking behavior responding to network disruption. We assume that drivers make predictions of future traffic conditions due to network topology changes. The forward-looking responses can be modeled by introducing a predictive component into cost perception, such that the perceived cost pattern involves driver's anticipated congestion resulting from network disruption. The predictive flow patterns are then corrected with driver's actual experiences. We name this cost updating procedure as a "prediction–correction" process. Meanwhile, the proposed model belongs to a more general day-to-day dynamic framework proposed by Cantarella and Cascetta (1995). Under the framework, we specify the forecasted cost filter and the initial conditions by introducing the additional prediction component, which models drivers' anticipation of congestion from an unexpected event. By comparing the model results against field data observed before and after the I-35W Bridge collapse, we demonstrate that the prediction component in the model plays a crucial role in replicating the traffic recovery characteristics due to unexpected events.

In addition, this paper also devotes significant theoretical effort to analyzing the stability of the proposed model. Stability is an important mathematical property of day-to-day assignment models that is critical for real-world applications. In the literature, Smith (1984) analyzed the stability of a continuous day-to-day traffic evolution model using the Lyapunov theorem. Horowitz (1984) considered the stability of a discrete time day-to-day assignment model under different perception update processes. Zhang and Nagurney (1995) proposed regularity conditions to ensure local and global convergence to stationary points of the projected dynamical system. Cantarella and Cascetta (1995) discussed the stability conditions for general networks. Stability in their research requires that the corresponding Jacobian matrix, when evaluated at the equilibrium point, has eigenvalues (real or complex) all within the unit circle. Later, by applying the bifurcation theory for nonlinear dynamical system, Cantarella and Velona (2003) showed that different attractors (implying different types of flow evolution trajectories) may be present when parameters of a model change, and thus the stability of equilibrium cannot be guaranteed. Most recently, Bie and Lo (2010) applied the attraction domain to study the asymptotic stability of day-to-day traffic evolution. In this paper, we will provide a comprehensive analysis of the stability properties for the proposed link-based day-to-day assignment models.

The remainder of this paper is organized as follows. The next section describes the empirical observations we collected after the collapse of the I-35W Bridge. The empirical data inspires us to develop the "prediction–correction" framework,