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Estimating the spatiotemporal impact of traffic incidents: An integer programming approach consistent with the propagation of shockwaves

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A R T I C L E I N F O

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A B S T R A C T

A fundamental issue in estimating the spatiotemporal impact of an incident is to ensure that the shape of the affected region in the speed map is consistent with the propagation of shockwaves. In this research, we develop an integer programming model with a set of novel constraints to guarantee such consistency, which is new to the literature. The input to our model includes the historical speed on a given road as well as the location and starting time of a known incident. The model then outputs the spatiotemporal region impacted by this incident. We prove that our model produces results that are consistent with the propagation of shockwaves. We then show that our model is computationally more efficient than the current state-of-the-art model because ours requires substantially fewer constraints. Numerical experiments using both simulation and real data demonstrate that the reduction in computational time can be as large as 95–98% on average.

1. Introduction

When traffic incidents, such as accidents or vehicle breakdowns, occur on the road, they disrupt the smooth movement of vehicles and slow down the traffic (Ng et al., 2013; Xiong et al., 2014). There has been a proliferation of studies that leverage historical vehicle travelling speed and incident reports (which record the starting times and locations of incidents) on a road, to estimate the spatiotemporal impact of traffic incidents (Chung, 2011; Chung and Recker, 2012; Chung, 2013; Chung and Recker, 2015). Such information can be used to quantify the delay caused by the incident, estimate its maximum spatial extent or maximum congestion time, or estimate traffic state in non-recurrent situations (Duret and Yuan, 2017). It can also be used to build models that predict the spatiotemporal evolution of incidents using factors such as the type of the incident, the geometry of the road, the time of day, the weather condition, and so on (Chung and Recker, 2015; Hojati et al., 2016).

The spatiotemporal impact of an incident can be conveniently visualized using a speed map (Tian et al., 2015; 2016). Take the road segment shown in Fig. 1(a) as an example. The road is divided into 10 sections labelled as l_1, l_2, $\cdots$, and l_{10}, and vehicles travel from sections l_1 to l_{10}. Suppose that an incident occurs at 8:05 AM on section l_9 and is cleared at 8:35 AM. The speed map for this road segment between 8:00 AM and 9:00 AM is shown in Fig. 1(b), where the horizontal axis indicates the sections along the road and the vertical axis represents the time intervals. Given a road section and a

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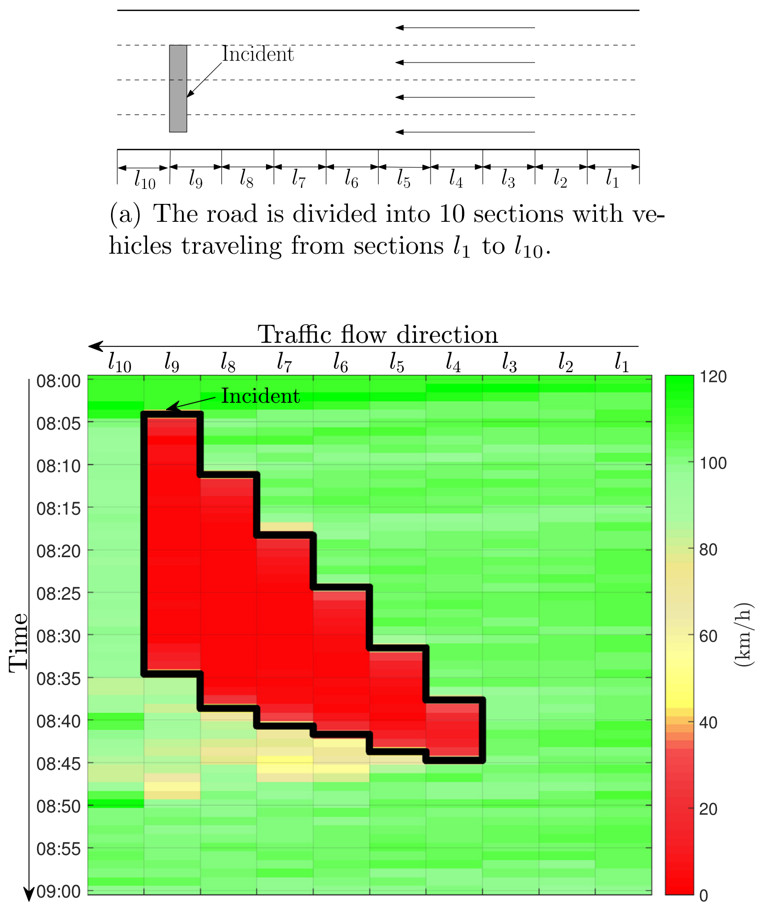

(a) The road is divided into 10 sections with vehicles traveling from sections l_1 to l_{10}.

(b) The impacted region is colored in red.

Fig. 1. Illustration of the spatiotemporal impacted region of a traffic incident.

time interval, they define a rectangular cell in the speed map and the color of this cell indicates the travelling speed at the corresponding location and time interval. When the incident takes place, its impact propagates upstream and the colors in the cells become red, reflecting the reduction in vehicle speed. When the incident clears, the colors in the cells return to green, suggesting that the vehicle speed recovers. The boundary of the spatiotemporal impact caused by this incident is highlighted by the thick black line.

A fundamental issue in estimating the spatiotemporal impact of incidents is to ensure that the shape of the affected region is consistent with the propagation of shockwaves (Chung and Recker, 2012; Chung, 2013; Chung and Recker, 2015). Although existing studies all attempt to accomplish this goal, there has not been one that can guarantee such consistency. According to Chung and Recker (2012), this consistency requirement can be translated into three rules, that is Rules 1 through 3 detailed later in Section 2.1, that govern the shape of the affected region. However, as is shown by the example in Appendix A, the integer programming models developed in Chung and Recker (2012) and Chung (2013), later used by Chung and Recker (2015), may produce results that violate Rule 3. The study based on artificial neural networks (Du et al., 2016) suffers from the same problem. To ensure consistency, there are studies using quadrilaterals (Chou and Miller-Hooks, 2009) or parallelograms (Snelder et al., 2013) to approximate the shape of the impacted region, however, these approaches are very restrictive because they can only accommodate specific shapes of the impacted region. Chen et al. (2016) use K-Nearest Neighbor to determine the spatiotemporal impacted region, which is later extended by Yang et al. (2017) using Fuzzy c-means. However, the output of these models may violate Rule 1. Other remotely related literature includes those based on the Kinematic Wave Theory (KWT) (Lighthill and Whitham, 1955; Martin and Wohl, 1967; Chow, 1976; Wirasinghe, 1978; Heydecker, 1994). These models require additional data input such as traffic density and road capacity on all affected upstream sections. The work by Anbaroglu et al. (2014, 2015) is also loosely related to ours since the authors attempt to detect non-recurrent traffic congestion using link journey times.

In this paper, we develop an integer programming model with a set of novel constraints to guarantee the consistency with the propagation of shockwaves. The input to our model includes the historical speed on a given road and the location

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