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Evaluating the robustness effects of infrastructure projects based on their topological and geometrical roadway designs

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ABSTRACT

When infrastructures projects are evaluated, it is not only important to evaluate them with models that represent the average daily situation, but also to evaluate them in case of irregular situations like incidents. This becomes especially relevant when various project alternatives are expected to show significantly different scores in case of incidents. Project alternatives and their road sections have different topological and geometrical characteristics. The focus of this paper is on the following characteristics: hard shoulders, the number of lanes, parallel road structures and weaving sections. The main question that this paper addresses is how these network characteristics affect both the risk of different types of incidents occurring and the effects of those incidents on the network performance (robustness). In order to answer this question, analytical examples are presented for small theoretical networks that give insight into how the selected characteristics affect the total delay caused by incidents and its dependence on the traffic volume, capacity, severity and duration of incidents. A marginal simulation based method is presented that can be used to compute the robustness effects of project alternatives, given their geometrical and topological characteristics, on a network level. A case study for an infrastructure project in the Netherlands is presented that illustrates how the robustness effects of infrastructure projects can be computed given their topological and geometrical characteristics.

1. Introduction

In many urbanized areas, incidents and other disturbances can cause large delays. In the Netherlands incidents are responsible for 20–25% of the total travel time delay (Snelder et al., 2013) and roadworks are responsible for 4% of the total travel time delay. In the United States of America, 39% of the total travel time delay is caused by traffic incidents, 18% by different weather conditions and 1% by work zones (TRB, 2013). Therefore, when infrastructures projects are designed and evaluated, it is not only important to perform this for an average daily situation, but also to do that for disturbances like incidents, roads works, bad weather conditions, demand fluctuations and special events. This becomes especially relevant when different project alternatives are expected to have significantly different scores when disturbances are considered. Project alternatives have different topological and geometrical characteristics, which affect the network performance when disturbances occur. Often decisions have to be made on the utilization of scarce available space. For instance, if a hard shoulder is replaced by a regular lane, the throughput is higher under regular conditions, but if an incident occurs more lanes have to be closed and more traffic is affected. Therefore, it is important to understand how different topological and geometrical characteristics affect the performance of road networks in case of disturbances.

The term robustness is directly related to the performance of road networks in case of disturbances. Robustness is defined as the extent to which, under pre-specified circumstances such as incidents, roadworks, bad weather conditions, demand fluctuations and special events, a network is able to maintain the function for which it was originally designed (Snelder et al., 2012). An increasing amount of work has been performed on the assessment of the robustness of a network or the vulnerability of links (e.g. Murray-Tuite, and Mahmassani, 2004; Jenelius, 2010; Sullivan et al., 2010; Knoop et al., 2012; Snelder et al., 2012; Calvert and Snelder, 2015). However, little is known on how topological and geometrical characteristics affect network performance and consequently the robustness of a road network.

The main question that this paper addresses is how topological and geometrical characteristics affect both the risk of different types of incidents occurring and the effects of those incidents on network

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performance (robustness). The focus of this paper is on the following characteristics: hard shoulders, the number of lanes, parallel road structures and weaving sections. With respect to disturbances, the focus of this paper is on incidents. However, the presented method can also be used for other disturbances that cause local capacity reductions (e.g. roadworks). This paper contributes to the existing literature by giving an overview of how hard shoulders, the number of lanes, parallel road structures and weaving sections affect the risk, duration and capacity reduction of incidents and the delays caused by these incidents and therewith the robustness of a network. This paper also shows how the robustness effects of infrastructure projects can be computed given their topological and geometrical characteristics.

Section 2 presents theoretical insights into how the number of lanes, hard shoulders, parallel road structures and weaving sections affect the delays that are caused by incidents on a single road stretch. Section 3 presents a method that can be used to compute the robustness of project alternatives, given their topological and geometrical characteristics, on a network level. Section 4 presents a case study in which the method is applied. Finally, in Section 5 general conclusions are presented.

2. Theoretical insights: delays caused by incidents and roadworks

This section gives analytical insights into how the number of lanes, hard shoulders, parallel road structures and weaving sections affect the robustness of a single road stretch in case of incidents. These insights can be used to understand the effects that occur on a network level as explained in more detail in Sections 3 and 4.

In Olmstead (1999) and Knoop (2009) it is shown that the total delay that is caused by an incident can be computed using Eq. (1). Both assume homogeneous and stationary traffic, no spillback to other roads, and a constant capacity reduction during the duration of the incident.

$$D = \max\left(0,\ \frac{t^2(rC - C)(I - rC)}{2(I - C)}\right) = \max\left(0,\ \frac{t^2(r-1)(rC - I)}{2(1-\frac{I}{C})}\right) \tag{1}$$

in which D=total delay for all vehicles caused by an incident [vehicle hours]; t= incident duration [hour]; r=capacity reduction factor [-](e.g. 0.9 implies a capacity reduction of 10%); I=traffic volume [vehicles/h] and C=capacity [vehicles/h].

Eq. (1) represents the dashed surface in Fig. 1a. The Equation can also be derived from Fig. 1b by multiplying the number of vehicles in the queue (density * queue length) with the delay of those vehicles integrated over all time periods. Fig. 1b shows a space time plot for a road section The traffic drives from the bottom of the figure to the top. The dashed area shows the congestion that is caused by an incident. The queue length varies over time (vertical cross section of the dashed area) and the queue moves upstream over time.

Knoop (2009) shows how the above mentioned theory can be extended to compute the total delay [vehicle hours] caused by incidents near convergent and divergent points by taking spillback effects and secondary bottlenecks into account that occur at junctions when the incident queues solve. Below we use Eq. (1) and the extended theory from Knoop (2009) to give insights into the influence of the number of lanes, hard shoulders, parallel road structures and weaving sections on the robustness of a road network. The assumptions on capacity reductions and durations of incidents that are used in the examples below are based on Table 2 and are presented in Section 4.2.

2.1. Example number of lanes

In this example, we assume that an incident occurs on a road with 2, 3, 4, 5 or 6 lanes with a capacity of respectively 4200, 6300, 8200, 10,000 and 11,500 vehicles per hour. Two lanes are assumed to be closed and the capacity of the remaining lanes is assumed to be 80% of the original lane capacity. For the road with 2 lanes, we assume a capacity reduction of 90% instead of 100%. The duration of the incident is assumed to be 34 min. The total delay caused by an incident can be computed using Eq. (1). Fig. 2 shows the delay caused by the incident of different traffic volumes. From Fig. 2 it can be concluded that for identical traffic volumes, having more lanes available results in a lower delay per incident, which can be explained by the fact that there is more spare capacity. However, motorways with more lanes can accommodate more traffic. Therefore, when severe incidents occur that block the entire road for instance, the total delay caused by that incident will be higher on a road with more lanes.

2.2. Example hard shoulder

In this example, we assume that a car breakdown on a road with 3 lanes and a capacity of 6000 vehicles/h reduces the capacity by 10% (factor 0.9) for 30 min. This implies that although the car is on the hard shoulder, the capacity of the other lanes is reduced by 10% due to rubbernecking where drivers slow down to look at the vehicle on the hard shoulder. If the hard shoulder is not present, the car blocks an entire lane and the traffic on the other lanes slows down as well, which results in a capacity reduction of 40% (factor 0.6). Furthermore, we

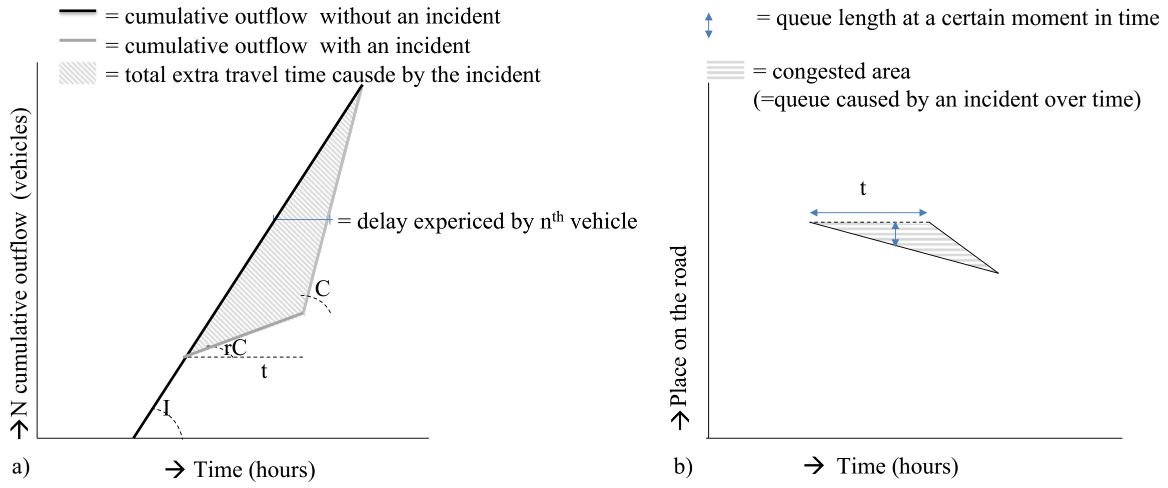

Fig. 1. a) Cumulative link outflow without an incident and with an incident; b) space-time plot with congestion caused by an incident.