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Speed limits, speed selection and network equilibrium

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ABSTRACT

This paper investigates the local and global impact of speed limits by considering road users' non-obedient behavior in speed selection. Given a link-specific speed limit scheme, road users will take into account the subjective travel time cost, the perceived crash risk and the perceived ticket risk as determinant factors for their actual speed choice on each link. Homogeneous travelers' perceived crash risk is positively related to their driving speed. When travelers are heterogeneous, the perceived crash risk is class-specific: different user classes interact with each other and choose their own optimal speed, resulting in a Nash equilibrium speed pattern. With the speed choices on particular roads, travelers make route choices, resulting in user equilibrium in a general network. An algorithm is proposed to solve the user equilibrium problem with heterogeneous users under link-specific speed limits. The models and algorithms are illustrated with numerical examples.

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1. Introduction

Speed limit schemes have been ubiquitous around the world owing to effectiveness in enhancing safety, reducing emissions and/or saving energy consumption in a straightforward manner. However, imposing speed limits will undoubtedly affect travel time and mobility on the roads. Previous studies have overwhelmingly focused on the local impacts of speed limits on performance such as safety and vehicle emissions of the road where the speed limit is imposed; but unfortunately the system-wide impacts of speed limits on a general network have received only very limited attention in both the theoretical and empirical literature (Yang et al., 2012). Although McKnight and Klein (1990), Lave and Elias (1994, 1997) and Grabowski and Morrisey (2007) realized the traffic reallocation effect of speed limits, their studies focus on only local impacts without systematic investigation. Taylor (2000), Woolley et al. (2002) and Madireddy et al. (2011) applied microscopic traffic simulation tools to examine the system-wide impacts of speed limits, and it was reported that traffic reallocation was observed and the travel time disproportionately increased with reduced speed limits. It was not until recently that Yang et al. (2012) made the first attempt to theoretically investigate the traffic reallocation effect of link-specific speed limit schemes on a general network from the viewpoint of macroscopic user equilibrium. The uniqueness conditions of the UE link travel times and link flows were investigated, and the feasibility of using the speed limits as a flow management toll was discussed. In the same spirit, Yang et al. (2013) and Wang (2013) undertook further analysis of the network performance with speed limits. Yang et al. (2013) established the tri-objective, bi-level optimization problem, aiming to minimize the travel time, accident occurrence and emission simultaneously. Wang (2013) also considered the efficiency and equity issues in the implementation of speed limits.

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Nomenclature

A	set of directed links
a	link $a \in A$
M	set of user classes
m	user class $m \in M$
v	aggregate flow on a representative link
v^m	flow of user class $m \in M$ on a representative link
v_a	aggregate flow on link $a \in A$
v_a^m	flow of user class $m \in M$ on link $a \in A$
$\bar{s}$	speed limit on a representative link
$\bar{s}_a$	speed limit on link $a \in A$
$\hat{s}$	optimal speed on a representative link with homogeneous travelers
$\hat{s}^m$	optimal speed of user class $m \in M$ on a representative link
$\hat{s}_a^m$	optimal speed of user class $m \in M$ on link $a \in A$
s^m	speed adopted by user class $m \in M$ on a representative link
s_a^m	speed adopted by user class $m \in M$ on link $a \in A$
s^{ave}	average speed on a representative link
s_a^{ave}	average speed on link $a \in A$
l_a	length of link $a \in A$

A key assumption in Yang et al. (2012) and subsequent studies (Yang et al., 2013; Wang, 2013) is road users' perfect compliance with the speed limits, which is restrictive in practical situations, as reported in many studies (Kanellaidis et al., 1995; Tarko, 2009; Yannis et al., 2013). For an individual traveler, a higher driving speed may weaken control of car and require a longer stopping distance, naturally raising the possibility of crash involvement. The relationship is described by either power functions (Maycock et al., 1998; Quimby et al., 1999) or exponential functions, with the crash risk increasing faster at higher speeds (Fildes et al., 1991; Kloeden et al., 1997, 2001). Besides absolute speed, speed variance among vehicles on a road is also a main factor for crash involvement. Earlier and recent studies found an increased crash risk for vehicles driving faster than the surrounding vehicles. However, the findings diverge for vehicles driving slower than average. An increased risk was reported in earlier studies (Solomon, 1964; Cirillo, 1968; RTI, 1970) but it was not reconfirmed in more recent studies (Kloeden et al., 1997, 2001). It was reported later that the crash frequency at the road section level increases with average speed (Finch et al., 1994; Nilsson, 1982, 2004) and speed variance (Garber and Gadiraju, 1989). Comprehensive reviews of previous studies on the relationship between crash rate and speed can be found in Aarts and van Schagen (2006) and McCarty (1998).

This paper is intended to make a useful and substantial extension of the traffic equilibrium model with speed limits, as proposed by Yang et al. (2012), in order to capture road users' speed selection behavior. The rest of the paper is organized as follows. In Section 2, the traffic equilibrium model with obedient users in Yang et al. (2012) is reviewed. Section 3 analyzes the speed selection of non-obedient, homogeneous users. Section 4 extends this speed selection model to the case with heterogeneous users by including the crash risk increment caused by the speed variance among different user classes. The network-wide user equilibrium problem with speed selection is proposed in Section 5, together with an iterative solution algorithm and some numerical examples for demonstration. General conclusions are provided in Section 6.

2. Traffic equilibrium under speed limits with obedient users

Consider a general network $G = (N, A)$ with a set N of nodes and a set A of directed links. Denote W as the set of origin-destination (OD) pairs. Each OD pair $w \in W$ is connected by a set R_w of simple routes serving a given and fixed travel demand d_w. Let $f_{r,w}$ denote the flow on path $r \in R_w$ between OD pair $w \in W$, and $v^A = (v_a, a \in A)^T$ denote the vector of link flows with v_a representing the traffic flow on link $a \in A$. For a specific link, the speed-flow relationship and the travel time-flow relationship are depicted in Fig. 1. Like most static traffic assignment models, only the normal flow regime is considered in this study, so for any link $a \in A$, the travel time function $\tilde{t}_a(v_a)$ is assumed to be separable, continuous, differentiable and strictly increasing with link flow v_a. Let $\bar{s}_a$ denote the link-specific speed limit on link $a \in A$. If no speed limit is imposed on link a, we can simply set $\bar{s}_a$ to be the free-flow speed on link a.

Yang et al. (2012) investigated the properties of traffic equilibrium under a speed limit law by assuming that all travelers strictly adhere to the speed limit on each link. In this case, the speed-flow relationship on link $a \in A$ under speed limit $\bar{s}_a$ is altered, as shown in Fig. 2(a), where C is the road capacity and s^c is the vehicle speed when the link flow rate reaches capacity. Correspondingly, the travel time function $t_a(v_a)$ on link $a \in A$ under speed limit $\bar{s}_a$ takes the following form:

$$t_a(v_a) = \begin{cases} \bar{t}_a, & 0 \leqslant v_a \leqslant \bar{v}_a \\ \tilde{t}_a(v_a), & \bar{v}_a < v_a \leqslant C_a \end{cases} \tag{1}$$

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