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Efficiency and equity of speed limits in transportation networks

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ABSTRACT

This paper examines the impact of speed limits on network efficiency, in terms of total travel time of all road users, and equity among road users from different origin–destination (OD) pairs, in terms of the change of travel time after imposing a speed limit scheme. We find that after imposing a speed limit scheme, the total travel time of all road users may decrease or increase; road users of some OD pairs may experience longer travel time, while other OD pairs may have shorter travel time. In view of the importance of speed limits on network efficiency and equity, we subsequently develop a bi-level programming model for designing the optimal speed limit scheme that maximizes the network efficiency while considering the equity issue. A global optimization approach that is suitable for bi-level programming models with finite discrete upper-level decision variables is proposed. Moreover, a conic quadratic mixed-integer linear programming approach is developed to solve relaxed models of the bi-level formulation of speed limit design. Two numerical examples are carried out.

1. Introduction

Speed limits are imposed worldwide to reduce the fatal crash rates. In 1987 the US federal government allowed states to raise speed limits from 55 mph to 65 mph on rural interstates. Of the 47 states with rural interstate roads, 40 adopted the higher speed limit within a year (Greenstone, 2002). As a result, the fatality rates on the rural interstates increased dramatically in most states (Garber and Graham, 1990). The higher speed limit may lead to an increase, as is the case in Illinois (Brown et al., 1990) and Alabama (Rock, 1995), little change, as is the case in Washington States (Ossiander and Cummings, 2002) or a decrease, as is the case in New Mexico (Gallagher et al., 1989), in the number of crashes. However, a higher speed undoubtedly increases the fatal crash rate by increasing the severity of crashes. For example, compared to the risk of an occupant fatality following involvement in a crash at 40 mph, the risk of a fatality is 2.5 times greater at 60 mph, 6 times greater at 70 mph, and approximately 20 times greater at 80 mph (Joksch, 1975).

In addition to safety considerations, imposing speed limits also affects fuel consumption and emissions (Eerens et al., 1993; Qu et al., 2013). Nevertheless, the analysis of the environmental impacts of speed limits is a complex issue because both vehicular emissions and fuel consumptions are non-monotonic functions of vehicular speeds (Yin and Lawphongpanich, 2006; Chen and Yang, 2012) and related to other aspects of vehicle operation such as acceleration and deceleration (Panis et al., 2006). Still, imposing speed limits could be used as a tool for reducing emissions at least in some scenarios. For example, Woolley et al. (2002) found that for short street section lengths, emissions are reduced under a 40 km/h speed limit compared to 60 km/h. The case study of Madireddy et al. (2011) showed reductions in CO_2 and NO_X emissions of about 25% if speed limits are lowered from 50 to 30 km/h in the residential area. In 2003, in order to reduce traffic emissions of NO_X and PM_{10}, a pilot speed limit of 80 km/h with "strict enforcement" was implemented on an urban motorway in Rotterdam

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and now has been applied to an increasing number of motorway sections (Keuken et al., 2010). Yang et al. (2012) pointed out that in comparison with the toll and rebate schemes, a speed limit scheme may have overwhelming advantages in emission reduction due to its direct control on vehicular speeds.

Despite enhancing traffic safety and the possibility of reducing fuel consumption and emissions, imposing speed limits will inevitably impact the mobility of transportation network users. Raising the speed limits from 55 mph to 65 mph on rural interstates in US in 1987 is a consequence of a number of studies that have investigated the tradeoff between travel time and fatality rate, vehicle emission and/or fuel consumptions. Most previous studies of speed limits simply focus on the local impacts, for example, the shift of traffic from rural non-interstates to 65 mph rural interstates (e.g, McKnight and Klein, 1990; Lave and Elias, 1994, 1997; Grabowski and Morrisey, 2007). Taylor (2000), Woolley et al. (2002) and Madireddy et al. (2011) have applied microscopic traffic simulation tools to examine system-wide impacts of speed limits. Their simulation shows the traffic reallocation phenomenon and demonstrates that travel time increases with reduced speed limits but not in a direct proportion to the change of speed limits. Yang et al. (2012) made the first attempt to investigate how a link-specific speed limit scheme reallocates traffic flow in an equilibrium manner at a macroscopic network level. They found that, although the link travel time–flow relationship is altered after a speed limit is imposed, the standard traffic assignment method still applies. However, whereas the uniqueness of link travel times at user equilibrium (UE) remains valid, and the UE flows on links may not be unique.

According to the above literature review, there is no study that systematically investigates the impact of speed limit on the mobility of the transportation network users. In particular, it seems that speed limits would adversely affect the mobility. Therefore, the first interesting question is, is it possible that a speed limit improves the overall transport mobility? Moreover, to ensure community acceptance of speed limits, the travel time of road users cannot be dramatically increased. Otherwise it may be difficult to rally public support and easy to invoke opposition to the setting of speed limits. Consequently, the second problem that is worth exploring is, which group of road users will be affected by speed limits and to what extent; in particular, are speed limits detrimental only to users that traverse the roads? Based on the above two questions, a natural third question is, how to design a speed limit scheme that ensures both the efficiency of transport network and the equity among different origin–destination (OD) road users? Triggered by the questions posted above, we investigate the impact of speed limits on the efficiency and equity of transport networks. Note that this paper focuses on the impact of speed limit over a longer time horizon at the macroscopic network level in contrast to dynamic speed limit analysis or control (Lee et al., 2006; Carlson et al., 2011; Heydecker and Addison, 2011; Weng and Meng, 2011) and ramp metering (Kotsialos and Papageorgiou, 2004; Meng and Khoo, 2010; Papamichail et al., 2010) at the microscopic level.

The rest of the paper is organized as follows. Section 2 analyzes the impact of speed limits on efficiency and equity of transport networks. Section 3 investigates the relation between speed limit, capacity reduction and toll pricing. Section 4 develops an optimization model to design speed limits considering efficiency and equity. Section 5 presents a global optimization method. In Section 6, two numerical experiments are reported. Section 7 concludes the paper.

2. Impact of speed limits on efficiency and equity

2.1. Travel time functions under speed limits

Like the standard static traffic assignment models (Sheffi, 1985, Yang et al., 2012), we assume the speed-flow relationship to be within the normal flow regime where speed decreases when traffic flow increases. Consider a road segment with length L. The travel time $t(v)$ on the segment increases with traffic flow v, as shown in Fig. 1a, where t_0 is the free flow travel time. If a speed limit s is imposed, then the minimum travel time would be $\bar{t}_0 := L/s$. Therefore, the new link travel time function is

$$\bar{t}(v) = \max\{\bar{t}_0, t(v)\} \tag{1}$$

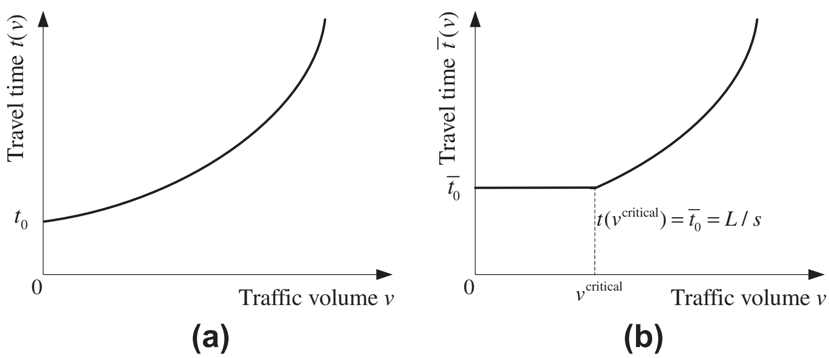

Fig. 1. Travel time function before and after imposing a speed limit of s.