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Decentralizing Pareto-efficient network flow/speed patterns with hybrid schemes of speed limit and road pricing

Xiaolei Wang [a,*], Hongbo Ye [b], Hai Yang [b]

[a] Sino-US Global Logistics Institute, Shanghai Jiao Tong University, Shanghai 200030, China

[b] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

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ABSTRACT

This paper examines the potential of hybrid schemes of speed limit and road pricing for decentralizing Pareto-efficient flow/speed patterns that minimize total travel time and total emissions simultaneously. Both link flows and speeds are treated as independent variables in our bi-objective formulation. The resulting Pareto frontier is thus weakly dominant to that in previous literature. For any such favorable Pareto-efficient flow and speed pattern, we establish the existence of hybrid schemes of speed limits and non-negative/revenue-neutral tolls, whose set of user equilibrium (UE) solutions contains the Pareto-efficient one, and provide sufficient conditions under which the Pareto-efficient solution can be certainly obtained.

1. Introduction

The world is now bedeviled by air pollution problems. Nearly one billion people in urban environments are continuously being exposed to health hazards from air pollutants (Ahrens, 2003). Among all the sources of air pollution, road traffic has been widely reported to be the most dominant one in urban areas, due to its tremendous magnitude as well as close proximity to people. According to the monitoring data provided by the Environmental Protection Department of Hong Kong, the concentration of CO, NO_x and particulates on roadside, emitted by motor vehicles, is significantly higher than that in other areas.

It is generally accepted that traffic emissions are closely associated with vehicle speed. As mentioned in previous studies (Tihansky, 1974; Eerens et al., 1993; Jensen, 1995; André and Hammarström, 2000; LAT, 2006), the emission-speed relationship could be either decreasing, or non-monotone with both high-speed and low-speed driving generating high emissions. For this reason, speed limit, as a direct vehicle-speed-management tool, can be implemented for emission control. For example, in Germany, where there is no general speed limit for motorways, many motorway sections now have posted local speed limits varying from 80 km/h to 130 km/h, for both safety and environmental considerations (European Commission, 2013). In 2003 in Switzerland, the maximum speed limit was reduced from 120 km/h to 80 km/h on some motorways of Ticino and Graubuenden, as a short-term emergency action to reduce ozone levels in southern Switzerland (Keller et al., 2008). In the same year in Rotterdam, the Netherlands, 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 and now has been applied to an increasing number of motorway sections (Keuken et al., 2010). The outcomes are generally consistent with the conclusion in Dijkema et al.

* Corresponding author. Tel.: +86 18680683726.
E-mail address: xlwangiris0420@gmail.com (X. Wang).

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(2008) that, levels of air pollution can be effectively reduced by introducing speed limit schemes. And the good news is that, according to a recent public poll, about two thirds of EU citizens expressed their willingness to compromise their driving speeds to reduce emissions (Gallup Organisation, 2011).

Previous studies on speed limit are affluent. Most of them simply focus on the local impacts of speed limit, that is, the impacts of speed limit on the performance of the road segment where it is imposed. However, as observed by McKnight and Klein (1990), Lave and Elias (1994, 1997) and Grabowski and Morrisey (2007), consider a general transportation network, the impacts of speed limit are system-wide. For example, lowering the speed limit on one link may raise its travel time and consequently increase traffic flows on alternative links. Such traffic reallocation effect of speed limit on general networks is not mathematically modeled until recently by Yang et al. (2012). They theoretically explained how a link-specific speed limit law reallocates traffic flow in an equilibrium manner at a macroscopic network level, and demonstrated the potential of speed limits in decentralizing target flow patterns.

In this paper, we keep digging the potential of speed limits in traffic regulation, but together with road pricing schemes. The target flow patterns that we focus on are Pareto-efficient in terms of minimal total travel time and minimal total emissions. In the literature, both link-specific speed limit schemes and road pricing schemes have been separately investigated for decentralizing Pareto-efficient flow patterns. For speed limit schemes alone, Yang et al. (2012) firstly pointed out, by numerical examples, that a link-specific speed limit scheme can sometimes be an appealing substitution for a toll scheme, for achieving a Pareto-efficient flow pattern of minimizing both total travel time and total emissions with non-monotone emission functions. Enlightened by Yang et al. (2012), Wang (2013) further examined the impact of speed limits on network efficiency in terms of total travel time and equity among road users, and developed a bi-level programming model for designing optimal speed limit scheme that maximizes network efficiency while considering equity issue. Yang et al. (2013) proposed a three-objective, bi-level programming model to design optimal link-specific speed limits that minimize system travel time, number of expected accidents, and traffic exhaust emissions simultaneously. On the other hand, for road pricing schemes alone, Yin and Lawphongpanich (2006) showed that the minimal-emission traffic flow distribution can always be induced by a toll scheme if link emissions increase with link flows. Following the findings in Nagurney (2000) that reducing travel time may increase emissions in the toy examples, Chen and Yang (2012) formulated the problem of minimizing congestion and emissions into a bi-objective problem, and examined the existence of non-negative toll schemes or revenue-neutral toll schemes to obtain Pareto-efficient link flow patterns. However, to the authors' best knowledge, no existing studies have considered the speed limit and road pricing instruments together, so the potential of their hybrid in decentralizing Pareto-efficient flow patterns remains unrevealed.

Speed limit and road pricing regulate traffic flows and speeds on a general network based on different mechanisms. To deter traffic flows from a road, speed limit decreases vehicle speed thus increases travel time, while road pricing adds monetary cost but reduces travel time. Both schemes increase travel cost on the road to achieve flow reduction, but the resulting total travel time is always smaller under road pricing. In the case of non-monotone emission functions, both high speed and low speed lead to high emission rates. For emissions caused by low-speed driving (i.e. congestion), road pricing is apparently more efficient; but to reduce emissions caused by high-speed driving, speed limit is a better choice. By imposing a low speed limit, the vehicle speeds on the link can be reduced directly; but by road pricing, the social planner has to rebate the current link users, or set relatively high toll rates on alternative paths to increase the traffic volume on the interested link and hence lower its vehicle speed. The different mechanisms of speed limit and road pricing make it possible to use a hybrid of them to achieve some targets that cannot be sustained by either of them alone.

The objective of this paper is to reveal the potential of hybrid schemes of speed limit and road pricing in decentralizing Pareto-efficient flow and speed patterns that minimize total travel time and total emissions simultaneously. To enhance practicality, we require the involved pricing schemes to be non-negative or revenue-neutral. The rest of this paper is organized as follows. Section 2 studies the user equilibrium (UE) under an arbitrary hybrid scheme of speed limit and road pricing. Section 3 introduces the bi-objective minimization formulation of total travel time and total emissions, with both link flows and speeds being independent variables. To decentralize such Pareto-efficient flow and speed patterns, Sections 4 and 5 investigates the existence of hybrid schemes of speed limits and non-negative/revenue-neutral tolls. Section 6 summarizes this paper.

2. Traffic equilibrium under a hybrid scheme of speed limits and link tolls

Consider a general network $G = (N, A)$ with a set N of nodes and a set A of directed links. Let W denote the set of origin–destination (O–D) pairs and R_w the set of all simple routes connecting O–D pair $w \in W$. The travel demand for each O–D pair $w \in W$ is assumed to be fixed and given by d_w. Let $f = \left(f_{r,w}, r \in R_w, w \in W\right)^{\mathrm{T}}$ denote the vector of path flows, where $f_{r,w}$ is the flow on path $r \in R_w$ between O–D pair $w \in W$, and Ω_f be the set of all feasible path flows defined by

$$\Omega_f = \left\{ f \,\middle|\, f_{r,w} \geqslant 0, \sum_{r \in R_w} f_{r,w} = d_w,\ r \in R_w, w \in W \right\} \tag{1}$$

Let $v = (v_a, a \in A)^{\mathrm{T}}$ denote the vector of link flows, where v_a represents the traffic flow on link $a \in A$. The set Ω_v of all feasible link flows is defined by