Transportation Research Part A 44 (2010) 676–696

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Pareto-improving ramp metering strategies for reducing congestion in the morning commute

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ARTICLE INFO

Article history:
Received 5 February 2009
Received in revised form 24 June 2010
Accepted 4 July 2010

Keywords:
Ramp metering
Pareto-improving
Externality
Morning commute

ABSTRACT

This paper presents an alternative approach to internalize congestion externality during the morning commute. We consider a linear freeway with multiple on-ramps and a downstream bottleneck and commuters accessing the freeway via different on-ramps try to arrive at work on time. Rather than charging congestion tolls as widely suggested by economists, we show that the old-fashioned engineering approach – ramp metering – can be a powerful tool to affect travelers' departure time choice and thereby alter the congestion externality distribution among travelers. With carefully designed time-dependent metering plans, travelers from different origins can be channelized and will access the freeway bottleneck in different time periods, resulting in less total cost for the system compared to the no-metering case. The metering strategies are Pareto-improving, with travelers from the on-ramp with the highest priority having the smallest individual costs and travelers from the on-ramp with the lowest priority having their costs equal to those in the no-metering scenario. By changing the priority order of the ramps periodically, the benefit of the Pareto-improving metering strategies can be distributed evenly among all travelers. Numerical experiments show that the total user cost can be reduced by up to 40% with the proposed metering strategies. This study offers researchers and policy makers a different angle of looking at congestion externality, and the results provide an overview of the potential long term benefits that dynamic ramp metering strategies can achieve.

1. Introduction

In a congested transportation network, a traveler's trip can cause additional delays to other travelers who enter the network later. Due to the presence of this congestion externality, the departure time and route choices of travelers who seek to optimize their own travel experience usually lead to inefficient temporal and spatial traffic distribution in a transportation network in terms of social welfare. This 'welfare gap' between the Wardropian user equilibrium (a product of selfish choices) and system optimum traffic patterns can be, in theory, eliminated by internalizing the congestion externality via *marginal cost pricing*.

Considerable effort has been devoted to the understanding, characterization and more importantly elimination of (or narrowing) this welfare gap in the so-called *morning commute* problem (e.g., Vickrey, 1969; Hendrickson and Kocur, 1981; Mahmassani and Herman, 1984; Smith, 1984; Daganzo, 1985; Newell, 1987; Arnott et al., 1990, 1993; Kuwahara, 1990), where a fixed number of travelers make their departure time and route choices by balancing the tradeoff between travel cost and schedule delay cost (i.e., the cost of early or later arrival). The seminal work by Vickrey (1969), which focuses on a single route with one bottleneck and assumes all the travelers have the same desired arrival time, delineates the first dynamic

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0965-8564/$ - see front matter © 2010 Published by Elsevier Ltd.
doi:10.1016/j.tra.2010.07.002

economic model for congestion pricing in the morning commute. A time-dependent toll equal to the cost of the waiting time is derived to drive the user equilibrium pattern toward a system optimum. Later, Newell (1987) extends the equilibrium analysis to situations where different travelers may have different value of time for queuing and schedule delays and shows that a time-dependent tolling plan capable of completely eliminating the queue at the bottleneck still exists. Arnott et al. (1990) explores the problem in a network with two parallel routes, combining travelers' departure time choice with route choice. It is found that the route splits of the two alternatives at user equilibrium and system optimum are identical and the system optimum can be decentralized by employing a time-dependent toll affecting only departure times.

Although the idea of using dynamic road tolls to internalize congestion externality is theoretically sound, its actual effect in practice may be dramatically deviated from the ideal situation. In practice, the continuously changing toll usually need to be converted to a coarse step toll, which may not precisely internalize travelers' actual congestion externality. Toll stations can only be built on a limited number of links, instead of all links as desired by the first-best tolling criterion. If not all tolls are paid electronically which is still the case for many toll stations in practice, physical toll booths can potentially form new bottlenecks causing additional delays in an already congested route. The idea of congestion pricing may also be accompanied with public reluctance. As reported by surveys conducted in different metropolitan areas (e.g., Texas Oswald, 1995, Washington State's Puget Sound area Pacific Rim Resources, 2004 , Austin Texas Podgorski and Kockelman, 2006, etc.), the public support of using toll for congestion alleviation is typically below 50%. Although some studies (e.g., Schweitzer and Taylor, 2008) show that compared to using sales taxes to fund transportation projects, low-income residents actually pay less with congestion pricing, it is often still regarded as a regressive policy which disproportionately burden impoverished drivers.

Internalizing externalities by congestion pricing is the direct but not the only recipe for improving efficiency. One alternative option is to use traffic management strategies (e.g., tolling, traffic control, etc.) to channelize travelers into several groups so that congestion externality only occurs among travelers in the same group and no interactions exist across different groups of travelers. (See Fig. 1 for a detailed illustration.) With carefully designed *externality redistribution* strategies, the total congestion impact to the entire system can be reduced. Compared to using marginal cost pricing for congestion externality internalization, this idea of externality redistribution is far less investigated. Daganzo and Garcia (2000) explore a similar concept which they call *rationing*. Time-dependent toll is launched during a time window and some users are exempted from paying it. The classification of road users is such that the fraction of days that a user is free to use the road is the same for all the users in the long run. Lago and Daganzo (2007) also mention the possibility of controlling the access of one approach of a merge network during the middle of the morning rush hour to attain system improvement but do not provide detailed analysis.

According to this key concept, one old-fashioned engineering approach – *ramp metering* – may potentially be a powerful tool for altering the distribution of congestion externality: Freeway on-ramps are ideal locations for channelizing traffic, and a dynamic scheme can be easily implemented by varying the metering rates. Unfortunately, despite of its frequent use in practice, ramp metering is usually treated as a *short term* management device whose primary role is to improve freeway mainline flow capacity by avoiding potential capacity drop due to traffic breakdowns (Cassidy and Bertini, 1999). Its *long term* role in affecting the distribution of externality by affecting travelers' departure time choice has been overlooked, although practical evidence shows that travelers do react to metering by rescheduling their trips and even changing routes

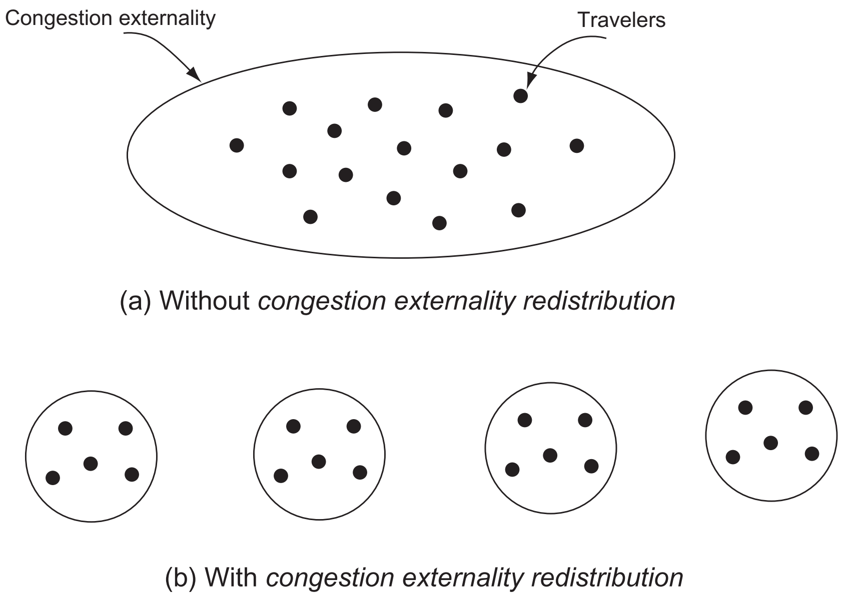

Fig. 1. Illustration of congestion externality redistribution.