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# Optimization method of alternate traffic restriction scheme based on elastic demand and mode choice behavior

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ABSTRACT

As a countermeasure to urban traffic congestion, alternate traffic restriction (ATR) involves a certain proportion of automobiles being prohibited from entering pre-determined ATR districts during specific time periods. The present study introduces an optimization method for ATR schemes in terms of both their restriction districts and the proportion of restricted automobiles. As a Stackelberg game between traffic policy makers and road users, the ATR scheme optimization problem is established using a bi-level programming model, with the upper-level examining an ATR scheme aimed at consumers' surplus maximization under the condition of overload flow minimization, and the lower-level synthetically optimizing elastic demand, mode choice (private car, public transit and park-and-ride) and multi-class user equilibrium assignment. A genetic algorithm based on the graph theory is also proposed to solve the bi-level programming model with a gradient project algorithm for solving the lower-level model. To our knowledge, this study represents the first attempt to theoretically optimize an ATR scheme using a systematic approach with mathematical model specification.



## 1. Introduction

Urban traffic congestion is a growing problem for cities in which traffic demand has increased rapidly and/or road capacity has seriously degraded. Various countermeasures have been developed and implemented in order to cope with serious recurrent traffic congestion, including congestion charges (Pigou, 1920; Yang and Huang, 2005; Lawphongpanich et al., 2006; Lindsey, 2006, 2010; Tsekeris and Voss, 2009), parking charges (Brown and Lambe, 1972;Gillen, 1977a; Peng et al., 1996;Hensher and King, 2001; Hess, 2001;Yang et al., 2004), public transit priority systems (Gillen, 1977b;Peng et al., 1996; Hess, 2001;Hensher and King, 2001; Watters et al., 2006;Li et al., 2009), vehicle quota systems (Chin and Smith, 1997;Seik, 1998), and travel credit systems (Akamatsu, 2007; Yang and Wang, 2011;Nie, 2012; Wang et al., 2012;Wu et al., 2012). The present study focuses on another method: alternate traffic restriction (ATR), also known as road space rationing (Daganzo, 1995) or vehicle restriction (Grange and Troncoso, 2011). Although almost all available countermeasures to traffic congestion are subject to certain limitations - and some are even controversial - they can also be effective under certain circumstances, especially when several are employed in combination. In comparison to most of the above-mentioned methods, ATRP is an obligatory yet effective approach able to promptly reduce congestion associated with rapid traffic demand increase and serious road capacity degradation. Under ATR, a certain proportion of automobiles are prohibited from entering pre-determined ATR districts during specific time periods. In other words, all automobile users are restricted alternately into ATR districts according to the ATR scheme in question.

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As a congestion-mitigation approach, ATR has been put into practice (largely successfully) in cities such as Athens, Santiago, México City, São Paulo, Bogotá, La Paz, San José, countrywide in Honduras, Quito (En.wikipedia.org, 2012), and Milan (Wantedinmilan.com., 2011). In Bogotá, Colombia, traffic restrictions were initially set in place in 2000 and extended in 2008 for the hours of 6am to 8pm (En.wikipedia.org, 2011), with the system restricting private vehicle use based on the last digit of license plate numbers. The scheme resulted in a 40% reduction in daily private automobile use, and has thus been extended to other Colombian cities such as Medellín, Armenia, Barranquilla, Bucaramanga, Cali, Cartagena, Manizales, Pereira, and Envigado (Picoyplaca.info., 2012). During the 2008 Beijing Olympic Games (7/1/2008 to 9/2/2008), an even–odd license plate method was adopted in order to prevent urban traffic congestion (Xinhuanet.com., 2008); immediately after the Games had finished, this temporary method was replaced by a permanent ATR scheme: in peak hours of each working day, one fifth of automobiles are restricted from downtown areas (within the Fifth Ring Road) according to the last number on the license plate. As a result of this scheme, 800,000 cars have been taken off the road each restricting day (Btv.org, 2008).

Although increasing numbers of cities have employed ATR as a ready-to-use measure for traffic congestion mitigation, there remains a distinct lack of theoretical investigation of the approach. To our knowledge, most previous studies have involved the qualitative evaluation of ATR practice or traffic impact analysis (Li et al., 2008;Su et al., 2009; Vytautas and Gražvydas, 2009; Gao et al., 2011), while relatively few have undertaken a comprehensive examination of the formulation and optimization of ATR schemes. Daganzo (1995) and Daganzo and Garcia (2000) investigated congestion reduction schemes involving a hybrid strategy of road pricing and rationing, with these then applied by Nakamura and Kockelman (2002) in the traffic management of the San Francisco Bay Bridge. However, the method was effected on only a single road bottleneck rather than a whole road network. More recently, Han et al. (2010) analyzed the efficiency of the plate-number-based traffic rationing theoretically by establishing the bounds of the reduction in the system cost associated with the restricted flow pattern at user equilibrium in comparison with the system cost at the original user equilibrium. Wang et al. (2010) analyzed the effect of road rationing in both the short-term, based on the original traffic assignment model (Beckmann et al., 1956), and on long-term traffic equilibrium, taking into account public self-adjustment activities such as car purchase and disposal. However, the study was limited by a lack of theoretical investigation into different ATR districts, and as such the combinatory optimization of ATR proportion and district could not be obtained. Liu et al. (2012) developed a simple equilibrium model for a linear monocentric city to investigate the effects of rationing and pricing on morning commuters' travel cost and modal choice behavior in each location, and finds that Pareto-improving rationing and pricing scheme might be obtained as a combination of the rationing degree and the toll associated with rationing. Song et al. (2013) presented the mathematical formulations for Pareto-improving pure road space rationing and hybrid policies including congestion pricing and road space rationing considering two mode automobile and transit.

The problem of ATR scheme optimization can be simplified and described in a scientific manner. Assume a geographically closed region with elastic traffic demand and three travel modes available, i.e. private car, public transit and park-and-ride (P&R). In order to relieve serious road congestion, the ATR scheme regulates that all private cars are alternately restricted by day from entering traffic restriction districts according to the preset traffic restriction proportion. Note that P&R users are possibly restricted as their routes by driving to transfer site of public transit could also be restricted. For certain O–D pairs, if all automobile travel paths are blocked by restriction districts, the restricted users shift to public transit or P&R in order to reach their destinations. In other words, there exist a group of automobile users who travel by public transport or P&R and a group of P&R users who travel by public transit on certain days if their travel paths are blocked by restriction areas. Because these mode-shifted users are used to drive by themselves, the travel costs for them are assumed to be a little higher than those of general public transit users at the same public transit links. Considering urban rail transit, bus rapid transit and bus priority lanes etc., constant travel times and unlimited transportation capacity are assumed for all public transit systems.

The overall objective of ATR optimization is not only to maintain a non-congested traffic condition, but also to meet potential travel demand. In scientific terms, the problem can be defined as the search and evaluation of alternate ATR schemes by comprehensively considering elastic demand, mode choice and the respective route choices of unrestricted and restricted users. Optimization of the ATR scheme therefore requires the solution of three key research problems: determining the search strategy, solving for the equilibrium state considering elastic demand, modal split and route choice, and finally evaluating the effects on overall traffic condition as well as on road users' travel convenience.

Owning to non-restriction on capacity and invariable travel time of public transit, we assume that only one fixed-cost transit path is available to connect each O–D pair, so the route choice equilibrium analysis is merely for private car users and P&R users. ATR models must consider the specific case in which a proportion of private cars are restricted from ATR districts, thus automobile users and P&R users are divided into unrestricted and restricted groups with respective route sets. In such a case, multi-class user equilibrium analysis can be applied. For example, Dafermos (1973) took both vehicle and network types into consideration before dividing users into different classes in order to investigate traffic system optimization, while Yang and Huang (2004) divided users into two classes according to a value of time in their study of traffic network equilibrium. It should be noted that the ATR method deviates from typical multi-class user equilibrium in that it includes a special class of automobile travelers whose possible travel paths are all blocked by traffic restriction districts. During particular restriction days, some have to shift from private car to P&R or public transit, and some others have to shift from P&R to public transit, which result in changes of travel costs.