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A Pareto-optimization approach for a fair ramp metering

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ABSTRACT

This paper deals with a fair ramp metering problem which takes into account average travel delay distribution among on-ramps for an expressway system comprising expressways, on-ramps and off-ramps. A novel spatial equity index is defined to measure the evenness of travel delay distribution among on-ramps within the predefined on-ramp groups. An ideal fair ramp metering problem therefore aims to find an optimal dynamic ramp metering rate solution that not only minimizes the total system delay, but also maximizes the equity indexes associated to the groups. Some of these objectives, however, contradict with each other, and their Pareto-optimality is explored. The fair ramp metering problem proposed in this paper is formulated as a multiobjective optimization model incorporating a modified cell-transmission model (MCTM) that captures dynamic traffic flow pattern with ramp metering operations. The MCTM then is embedded in the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to solve the multiobjective optimization model. Finally, the Interstate I-210 W expressway-ramp network in the United States is adopted to assess the methodology proposed in this paper.

1. Introduction

Ramp metering is an application that regulates vehicles at on-ramps entering to expressways by means of a proper ramp metering rate solution. It is a practical traffic control strategy to mitigate traffic congestion on an expressway-ramp system, which consists of expressways' mainline sections, on-ramps and off-ramps. A field study carried out by Cambridge Systematics (2000) has demonstrated some benefits of ramp metering, such as, increasing expressway's throughput, reducing total system travel time and enhancing traffic safety. Papageorgiou and Kotsialos (2002) performed a comprehensive overview on how and why ramp metering improves traffic flow conditions.

Over years, researchers have neglected one vital issue concerning the performance of ramp metering, namely the ramp metering inequity issue. Although this issue has been raised in the literature as early as 1960s (Pinnel et al., 1967), it has been neglected. Only until recently when this lack of consideration of user equity has adversely affected public acceptance and handicapped the widespread adoption of ramp metering, researchers start to realize its importance. The public resistance is evident in research studies carried out on the drivers in Portland (Alkadri, 1998) and Twin Cities (Levinson and Zhang, 2006) in America. Levinson and Zhang (2006) reported that the ramp metering algorithm used in Twin Cities provoked the inequity issue, in which long trips drivers are favored compared to short trips drivers. Hence, it is urgent that the inequity issue should be addressed and considered in the future ramp metering research studies. According to Levinson and Zhang (2006), there are two types of ramp metering equity, namely the temporal and spatial inequity. Temporal inequity measures the difference of travel time, delay or speed among drivers who travel on the same route but arrive at the on-ramp

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at different times. Spatial inequity measures these differences among drivers who arrive at different on-ramps at the same time.

From a system manager's point of view, the key objective to implement ramp metering is to improve the efficiency of the expressway-ramp systems. Usually, this is measured by a system efficiency index, such as total system travel time or delay. However, the system-wide benefits of ramp metering should not be achieved at the expense of some individuals, thereby causing user inequity in the allocation of ramp metering benefits. Therefore, it is important to develop a methodology that can compromise both objectives in determining a ramp metering rate solution.

1.1. Literature review

Since the pioneering work by Wattleworth and Berry (1965), there have been considerable ramp metering studies. These studies can be, in general, classified into two categories – with and without taking into account the equity constraints. Because this paper is concerned with equity in ramp metering, more emphasis is placed on it as compared to the latter category.

1.1.1. Ramp metering without the equity constraints

Static and dynamic ramp metering have been the two main approaches adopted in the past. Under static traffic flow conditions, linear programming and bi-level programming models were built to determine an optimal ramp metering rate solution (e.g., Iida et al., 1989; Yang and Yagar, 1994). To consider dynamic nature of ramp metering, more emphasis has been put on algorithm design and analysis to obtain the optimal dynamic ramp metering rate solution. A variety of optimal control theories coupled with proper dynamic traffic simulation models have been applied for expressway or expressway-corridor systems (e.g. Papageorgiou et al., 1990; Stephanedes and Chang, 1993; Zhang et al., 1996; Zhang and Recker, 1999; Zhang et al., 2001; Kotsialos et al., 2002; Bellemans et al., 2003; Hegyi et al., 2002; Gomes and Horowitz, 2006). The objective for these studies is to minimize the total system travel time including ramp delay. The studies are differing by the research methodologies adopted. Some researchers attempted to employ a better traffic flow model to describe dynamic traffic flow conditions while others aimed to improve efficiency of ramp metering by applying various advanced optimal control theories.

The state-of-practice for the ramp metering on the other hand, tends to be focused on the operational algorithms such as, BOTTLENECK (Jacobson et al., 1989), FLOW (Jacobson et al., 1989), ALINEA (Papageorgiou et al., 1991), ZONE (Lau, 1997), METALINE (Papageorgiou et al., 1997), HELPER (Lipp et al., 1991) and SWARM (Paesani et al., 1997). Most of these operational algorithms lack the proper optimization techniques in identifying a better ramp metering rate solution. Hence, microscopic traffic simulation models such as INTEGRATION, MITSIM and PARAMICS were adopted to evaluate effectiveness of these algorithms; for example Hellinga and Van-Aerde (1995), Hasan et al. (2002), Chu et al. (2004), and Beegala et al. (2005).

1.1.2. Ramp metering with the equity constraints

There were a few studies dealing with the ramp metering equity issue. Benmohamed and Meerkov (1994) were the pioneers in investigation of this issue. They gave an intuitive example with three on-ramps showing that average travel delays experienced by drivers on two on-ramps are dramatically different, ranging from zero to two time periods of interest, if dynamic ramp metering rate solution follows the feedback law suggested by Papageorgiou et al. (1990). To distribute the average travel delay incurred on the interested on-ramps more evenly, Benmohamed and Meerkov (1994) proposed a dynamic traffic control architecture that needs to calculate ramp metering rate based on the decentralized control law and local measurements for the benefit of individual expressway's segment. This is inspired by a data network flow control mechanism. Unfortunately, this dynamic traffic control architecture is not applicable in practice because its assumption on traffic flow conditions is unrealistic (refer Section 1 and Section 2.1 of Benmohamed and Meerkov (1994)).

Papageorgiou and Kotsialos (2001) defined an equity constraint for each on-ramp that aims to keep queuing length at the on-ramp within a desired threshold. They also built an optimization model to determine the optimal ramp metering rate solution, in which the objective function includes a penalty term defined by the ramp metering equity constraints with different predetermined weight factors. These weight factors have significant impact on the ramp metering rate solution. Nevertheless, it is a challenging issue to determine these weights in practice. Kotsialos and Papageorgiou (2004) continued to develop an optimal freeway network-wide ramp metering strategy, termed as Advanced Motorway Optimal Control (AMOC), for the ring-road of Amsterdam, the Netherlands. In AMOC, ramp metering control coordination is formulated as a dynamic optimal control model that can be numerically solved for given traffic demands and vehicle turning rates over a time horizon. They found that by imposing a maximum queue requirement to the model, burden of ramp queuing needed to reduce the total system travel time is distributed among the on-ramps. They further mentioned that the equity is achieved at the expense of further improvement of the traffic conditions, proving that equity and efficiency are two partially competing objectives of ramp metering operations.

The new ramp metering algorithm, implemented in the expressway system between Twin Cities of Minneapolis and St. Paul, Minnesota, has imposed a maximum ramp delay constraint that ensures a delay of less than 4 min per vehicle on local ramps and less than 2 min per vehicle on expressway to expressway ramps (Cambridge Systematics, 2000). All of these practical equity constraints can balance the efficiency and equity to some extent. However, as Zhang and Levinson (2005) pointed