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Analytical evaluation of flexible sharing strategies on multi-modal arterials

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Abstract

This paper examines strategies that share road space capacity in a flexible manner at a given element of the arterial (e.g. intersections) to move buses in front of the car queues without continuously banning cars from using one full lane. We build a generalized analytical framework with fixed set theory to evaluate bi-modal arterials with any kind of flexible sharing strategies. These strategies are modelled parsimoniously using a single parameter to describe their effectiveness. This parameter can be estimated analytically, empirically, or with simulations. Overall, the mathematical formulation is versatile, as it applies to both intuitive cases when the arterial capacity is shared in a fixed manner, and non-intuitive cases when flexible sharing strategies are installed. This framework can provide practitioners both analytical and graphical tools to systematically and quantitatively evaluate any given bi-modal arterial. Moreover, the requirements to efficiently install flexible sharing strategies along the arterial are established. Lastly, one particular flexible sharing strategy, the pre-signal, is illustrated as an example both mathematically and with a calibrated simulation.

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Keywords: Multi-modal; Capacity; Bus priority; Arterial; Traffic flow; Pre-signal

1. Introduction and background

Improving public transportation operations is important because more people can be moved within limited road space. Buses are promoted with various bus priority strategies in many cities around the world to encourage people to switch from cars. This could lead to a more sustainable transportation system in the long run. One common bus priority strategy is to implement dedicated bus lanes. However, the discrete nature of traditional dedicated bus lanes (i.e. either one full lane is reserved for buses or none) is problematic because such sharing of capacity between buses and cars is likely sub-optimal. Bus flows in most urban arterials are much lower than the capacity of a lane, while car flows could often be higher than the capacity of the remaining lanes. The reduction in car capacity is especially detrimental on signalized arterials, where growing car queues during peak hours could eventually spillback

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to upstream intersections (Daganzo (2007); Liu and Chang (2011)). This can impact the traffic performance of the whole network. Moreover, sharing the arterial capacity between modes in such a fixed manner cannot respond to the variation in traffic demand throughout the day. Therefore, a continuously dedicated bus lane along an arterial is often undesirable, especially when the bus flow is low or the car demand is high.

This paper considers strategies that share road space capacity in a flexible manner at a given element of the arterial (e.g. the intersection) to move buses in front of the car queues without continuously banning cars from using one full lane. These strategies use flexible space allocation to combine the advantages of mixed lanes (the elements' capacity can be fully utilized if buses are not present) and dedicated bus lanes (the buses receive priority). These strategies will be referred to as flexible sharing strategies hereafter. Some examples of such strategies could be queue jumper lanes (Nowlin and Fitzpatrick (1997); Zhou and Gan (2009)), or pre-signals (Wu and Hounsell (1998); Guler and Menendez (2014a,b); He et al. (2016)). Excluded from the list are pre-signals which use the opposite direction lane (Guler et al. (2016)), dynamic bus lanes which must be implemented on multiple elements along the arterial (Eichler and Daganzo (2006); Chiabaut et al. (2013)), and transit signal priority which changes how capacity is allocated at the intersection between different approaches (Baker et al. (2002); Smith et al. (2005)).

There are various measures to assess the operation of a transportation system, for example capacity, accessibility, equality, reliability, economical costs, and environmental impacts. Among them, capacity is one of the most important parameters which describes the maximum sustainable quantity of vehicles that can pass through the system over a period of time. Systems with lower capacities are more prone to congestion, which results in decrease of labor productivity, reduction of system reliability, increase in transportation cost of goods, and higher environmental impacts. Therefore, this paper aims to provide a theoretical framework to systematically analyze the capacity of a multi-modal arterial, which could aid in policy-making. Single-mode transportation systems are often assessed in terms of capacity on the link/node level (Greenshields (1935); Lighthill and Whitham (1955); Allsop (1972); Guler and Cassidy (2012)), on the arterial level (Transportation Research Board (1997); Eichler and Daganzo (2006); Wu et al. (2011)), or on the network level (Mahmassani et al. (1984, 1987); Geroliminis and Daganzo (2008); Daganzo and Geroliminis (2008); Geroliminis and Sun (2011); Mahmassani et al. (2013)).

When multi-modal transportation systems are assessed in terms of capacity, the difficulty arises because bus and car performance need to be respectively analyzed and compared. Therefore, most literature analyzes the car capacity at specific levels of bus demands (e.g. Boyac and Geroliminis (2011); Geroliminis et al. (2014); Arnet et al. (2015)). The main drawback of analyzing bus and cars separately is that the improvement of one mode usually comes at the cost of another. To overcome this, researchers have tried to compute a single representative value for the system, for example the passenger capacity (Geroliminis et al. (2014); Chiabaut et al. (2014); Chiabaut (2015); Loder et al. (2017)), or the average person travel time (Zheng and Geroliminis (2013); Christofa et al. (2016)). The problem with analyzing transportation systems in terms of travel times is that it requires either elaborate calculations or simulations. This is especially problematic because many different cases need to be considered when more innovative strategies are introduced. Therefore, most works on innovative bus priority strategies have been restricted to the isolated intersection level (Nowlin and Fitzpatrick (1997); Wu and Hounsell (1998); Guler and Menendez (2014a,b); He et al. (2016); Zhou and Gan (2009)). Some have tried to analyze the problem at the arterial level, but with some assumptions which might limit their generality and applicability in practice (Eichler and Daganzo (2006); Truong et al. (2015); Christofa et al. (2016)). Moreover, when various strategies are combined on an arterial, or different systems need to be compared, the analysis becomes very tedious.

In order to add to the set of existing tools for the quantitative evaluation of multi-modal arterials, in this paper we build a new analytical framework which is: i) robust: consistent with single-mode interpretations yet easily expandable to more modes, ii) versatile: applicable to both intuitive cases when the arterial capacity is shared in a fixed manner, and non-intuitive cases when flexible sharing strategies are installed, iii) generalized: applicable to all flexible sharing strategies, iv) parsimonious: with as few additional parameters as possible, v) practical: all parameters are easy to calculate in practice. This mathematical framework is formulated for a bi-modal arterial in Section 2. Based on this framework, mathematical definitions for improving bi-modal arterial capacity are discussed in Section 3. These two sections build the foundation for Section 4, where a graphical tool and mathematical principles are established to efficiently install flexible sharing strategies along an arterial. In Section 5, a pre-signal strategy is examined as an example of a flexible sharing strategy. Improvements in traffic operation, when pre-signals are installed according to