Optimizing the distribution of road space for urban multimodal congested networks

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INTRODUCTION - MOTIVATION

As cities around the world grow rapidly and more people through different modes compete for limited urban road infrastructure to travel, there is an increasing need to understand how this space is used for transportation and how it can be managed to improve accessibility for everyone. This research seeks to shed some light in the macroscopic modeling of traffic flow for overcrowded cities with multimodal transport. Ultimately, the goal of the proposed work is to develop modeling and optimization tools, which will contribute on how to redistribute city space to multiple transportation modes and to understand what sustainable level of mobility cities of different structures can achieve.

Management strategies can be implemented to partition a city so that road space is deliberately allocated between competing modes. Although the allocation of this space is eminently political, it should be informed by the correct physics. The present paper speaks to these physics. This would allow for the analysis of the performance of different modes using the same road space under different management strategies, such as mixing traffic or separating modes by special-use lanes. Transportation planners are faced daily with the task of evaluating and selecting between different operational strategies. This research will provide the tools and analytical framework to provide answers to these questions based on data that can be readily observable and describe their respective roadway networks. In addition, this research will provide new performance measures not only for transit planners but also for traffic engineers responsible for optimizing arterial traffic control. It will switch the interest from the currently inefficient vehicle throughput based optimization to the more efficient for networks and society, passenger throughput optimization. In this paper, we present a macroscopic approach for optimizing road space allocation for multimodal transport systems.

Space should be allocated taking into account spatiotemporal differences in the demand, the topology and the control characteristics. These spatiotemporal decisions are important because, if they're made incorrectly, space could be wasted. If this wasted space could be productively used by low-occupancy vehicles without affecting the more productive modes, mobility is being restricted. For example, recent studies in Californian freeways, have questioned the effectiveness of high-occupancy lanes (HOVs) and have shown that HOV lanes are underutilized and the passenger capacity of freeways has decreased, resulting in heavier congestion levels (Chen et al., 2005).

Despite the different features of these modes in terms of passenger occupancy, driving characteristics, duration of travel and scheduled vs. non-scheduled service, a common characteristic is the following: All of these vehicles when moving to an urban environment make stops related to traffic congestion (e.g. red phases at traffic signals) and *other* stops, which also cause delays: buses stop to board/alight passengers; taxis or delivery trucks stop frequently and randomly when they search/pick up/deliver passengers or goods. While there is a good understanding and vast literature of the dynamics and the modeling of congestion for congestion-related stops, the effect of *service* stops in the overall performance of a transportation system still remains a challenge. The effect of these stops during light conditions in the network capacity is almost negligible, but nowadays city centers experience high level of congestion and the frequency in time and space of the *service* stops is high.

A transportation system can be treated as an interconnected network of “reservoirs” with one or more modes moving, where each reservoir represents the streets in a neighborhood. In this extension, different parts of a city can be subject to different management strategies (see for example figure 1). Perhaps bus-only streets are allocated only in the central business district while other parts of the city allow vehicles to operate in mixed traffic. The effect of changes in one reservoir on the behavior of adjoining reservoirs will also be considered with this model. While recent findings in the macroscopic modeling and dynamics of traffic in cities have provided knowledge of single-mode, single- or multi-reservoir cities (Geroliminis and Daganzo, 2007, 2008 and others), the understanding of multi-mode, multi-reservoir cities is limited.

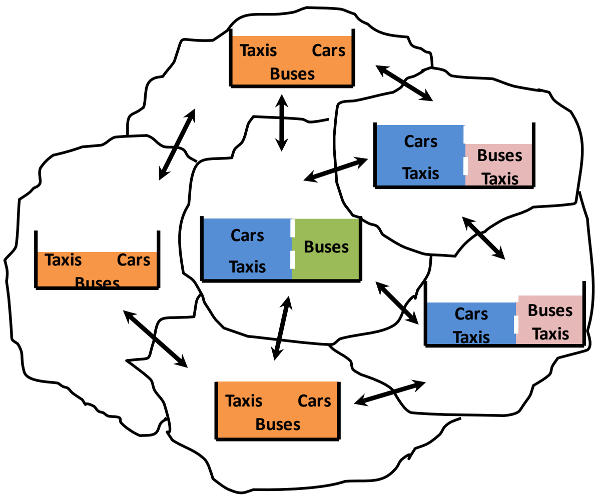

Figure 1 A multi-reservoir, multimodal system.

BACKGROUND

Traffic in real cities is complex, with many modes sharing streets, and congestion evolving as demand patterns change over the course of a day. Existing literature on the physics of urban mobility can be divided generally into city-scale (macroscopic) efforts and street-scale works. City-scale investigations have thus far looked only at the behavior of <u>one</u> mode and the involved dynamics of traffic congestion. Studies of multiple modes, on the other hand, have only been made at the street-level scale for unrealistic time-independent scenarios. Some planning studies have looked at public transport on a city scale, particularly buses on idealized road networks. Making road space allocation decisions, however, requires consideration of multiple modes. To date, such considerations have been made only at the much finer street scale and still in a time-independent (unrealistic) environment. Thus, the existing body of work leaves a gap to be filled—a physically realistic time-dependent, city-scale model including multiple modes is much needed.

On the public transport side, city-scale modelers have looked at how systems should be designed. Wirasinghe et al. (1977) considered how to design a bus transit system for an idealized city with centralized demand, by ignoring the interactions with cars. Work has also been done to look at how multiple modes can share the road, but only on the street-scale level. Researchers (e.g. Sparks and May, 1971, Dahlgren, 1998, Daganzo and Cassidy, 2008) have studied how different modes use freeways, recognizing that these modes serve different numbers of passengers. But these works are limited to small scale systems. Their consideration of different occupancies between vehicles and total passenger travel time is important, because it recognizes that some modes are more productive than others. The importance of considering passengers rather than vehicles has further voiced by Vuchic (1981), but only at the street scale.

Researchers have looked at allocating street space between more than one mode whether it be through the dedication of a freeway lane to high occupancy vehicles or a lane for buses on a city street (Radwan and Benevelli, 1983, Black at al., 1992, Currie et al, 2004, Cameron et al, 2003). These methods have limited applicability, because either they ignore demand fluctuations and spill-over effects that typically characterize urban traffic congestion or rely on intensive planning travel data and micro-simulation that are typically unreliable or unavailable. The quantitative treatment of the transit process (network route design, scheduling) is reflected in a considerable effort in other publications (e.g. Ceder, 2007, Ceder and Wilson, 1986), and will not be addressed here. Quantifying the impact of road space allocation on the performance of a congested multimodal transport system remains exclusive.

This gap is firstly due to the lack of a traffic model, which represents flow dynamics of a multimodal system as a result of road space allocation. While various theories have been proposed to macroscopically model urban networks (Godfrey, 1969, Herman and Prigogine, 1979, Daganzo, 2007), Geroliminis and Daganzo (2007, 2008), recently demonstrated the existence of a fundamental model (the Macroscopic Fundamental Diagram - MFD) on congestion dynamics of single-mode system. An MFD is a plot between network space-mean flow and density. These references showed that (1) the MFD is a property of the network itself (infrastructure and control) and not very sensitive to demand, i.e. the MFD should have a well-defined maximum and remain invariant when the demand changes both with the time-of-day and across days and (2) the space-mean flow is maximum for the same value of critical density of vehicles, for many origin-destination tables. Nevertheless, MFDs should not be universally expected. Properties of well-defined MFDs, stability and scatter analysis and other simulation and experimental tests can be found in Buisson & Ladier (2009), Ji et al. (2010), Mazloumian et al. (2010), Daganzo et al. (2011), Geroliminis and Sun (2011), Knoop et al. (2012) and others. Recently, Gonzales et al. (2011) observed through simulation an MFD for multimodal systems of cars and buses in the city center of Nairobi, Kenya.

To evaluate topological or control-related changes of the network flows (e.g. due to a re-timing of the traffic signals or a change in infrastructure), Daganzo and Geroliminis (2008) have derived analytical theories for the shape of the MFD as a function of network and intersection parameters, using Variational Theory (VT). In VT, streets can also have any number of time-invariant and/or time-dependent point bottlenecks with known capacities. The bottlenecks are modeled as lines in the (t, x) plane on which the “cost” per unit time equals the bottleneck capacity. For the multi-modal case extension of this theory provides an approximation of the MFD, by considering that bus service related stops interact with traffic (Boyaci and Geroliminis, 2011). The above broad applicability of VT gives us the flexibility to model many different types of conflicts in traffic movements as hypothetical traffic signals with periodic characteristics. The operational characteristics of this hypothetical signal-bus stop depend on the dwell times and the frequencies of buses, while the capacity during service stops is *smaller* as buses might block traffic.

Building in the knowledge of the single-mode macroscopic modeling, developing the dynamics of multimodal systems is promising. Treatment of mode conflicts is the second issue. All modes when moving to an urban environment make stops (e.g. red phases at traffic signals, buses stop to board/drop passengers). Road space allocations determine the magnitude of mode conflicts, which significantly influences the performance of the system. With proper treatments of mode conflict and congestion dynamics, system performance can be estimated and then road space can be optimized. A multimodal Macroscopic Fundamental Diagram model is developed in this paper to estimate the dynamics of congestion and the effect of mode conflicts and interactions. We will show that (i) the proposed model captures the operational characteristics of each mode, (ii) the resulting system performances are consistent with the physics of traffic given different road space strategies, e.g. with or without dedicated bus lanes, (iii) based on the resulting system performance, allocation of road space can be readily optimized.

METHODOLOGICAL FRAMEWORK

The goal for road space optimization of a multi-modal city is to minimize the total passenger hours travelled (PHT) to serve the total initial demand by redistributing the road space in different areas of a city. Suppose a city is partitioned in regions as in figure 1. Any region i is partitioned in j sub-areas, each one containing a specific type of usage, e.g. j can be bus-only lanes, mixed traffic lanes, car-only lanes or any other special usage lane. The strategy of determining $j$and allocating fraction of space to each j is represented by variable π_i^j. Mathematically the optimization problem reads as follows:

$$\min_{\pi_i^j} Z = \sum_{t,i,j,m} PHT_{t,i,j,m}\left(\pi_i^j\right) \qquad (1)$$

subject to

$$\frac{dn_i^{jm}}{dt} = \sum_k Q_{i\to k}^{jm} + \sum_{k\neq i} O_{k\to i}^{jm}\left(\pi_k^j, NV_k^j, I_k^j, PT_k^j\right) - \sum_k O_{i\to k}^{jm}\left(\pi_i^j, NV_i^j, I_i^j, PT_i^j\right) \qquad (2)$$

$$Q_{i\to k}^{jm} = U\left(Q_{i\to k}, F_i^{jm}\left(dn_i^{jm}, \pi_i^j\right)\right) \qquad (3)$$

All variables in equations (2) and (3) involve a time variable that has been omitted for simplicity. Equations (2) reflect the flow dynamics of each mode m in region i and sub-area j. $Q_{i\to k}^{jm}$ is the generated demand at a region i with destination k, which chooses to travel in sub-area j with mode m. $O_{k\to i}^{jm}$ is the incoming flow of mode m from region k while $O_{i\to k}^{jm}$ is the outgoing flow of mode m to region k (outgoing flow $i \to i$ is the trip completion rate within region i.) They are estimated based on a multimodal MFD (as described in Boyaci and Geroliminis, 2011), which is in function of space allocation variables $\boldsymbol{\pi}$, network variables $\boldsymbol{NV}$, intersection variables $\boldsymbol{I}$ and public transport related variables $\boldsymbol{PT}$. Mode choice $Q_{i\to k}^{jm}$ in equation 3, is related to the-unconditional-to-mode demand, $Q_{i\to k}$, travel cost F_i^{jm} of mode m which depends on π_i^j and dn_i^{jm}. All the related functions and variables will be described in more details in the full paper. The above optimization problem is highly non-linear and the large search space of the decision variables makes the solution procedure not straightforward. We plan to explore different methods and heuristics.

PRELIMINARY RESULTS

In this example we estimate the performance of a city with two regions, where mixed traffic of buses and cars occurs in the outside region, while a fraction of roads in the center region is dedicated to buses. The dynamics of the system are described by equations (1) and (2), while MFDs for different sub-areas are estimated with Variational Theory using (Daganzo and Geroliminis, 2008 and Boyaci and Geroliminis, 2011). Speed of buses in mixed traffic lanes integrates the effect of dwell times and bus stops. A mode choice model based on the utilities of each mode is introduced. Utility of car depends only on travel time, while utility of bus depends on travel time, dwell times and a discomfort term for standing passengers or limited accessibility. Passenger Hours and Kilometers travelled are estimated per unit time during a time-dependent peak hour demand profile.The results of Scenario 0, where buses and cars share the whole network without special bus lane and Scenario 1, where 10% of the space in Region 1 is dedicated only to buses, are shown in Figure 2. It is clear that the system performance of a

Scenario with dedicated lanes improves: The highly congested part disappears, total person hours traveled (PHT) during peak hours reduces significantly, meanwhile PKT increases when demand is at its maximum value (compare (a) and (d), (b) and (e), and (c) and (f) respectively). Furthermore, we elaborate more in Scenario 1 and examine the parameters of the model. Figure 3 shows the resulting mode utility, mode choice, bus occupancy and the effect of bus stop on bus speed, given a peak demand profile. They reflect the expected dynamics of a multimodal system. Note that the effect of increased dwell times with the number of bus passengers is reflected in Fig. 3d, where buses do not travel full. A methodological optimization framework will be described in the full paper to identify the optimal allocation of road space.

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Figure 2 An illustration of the efficency of space allocation to buses for Scenario 0 (left) and Scenario 1 (right): (a)(b) The MFD states of cars in city center, (c)(d) PHT over time, (e)(f) PKT over time

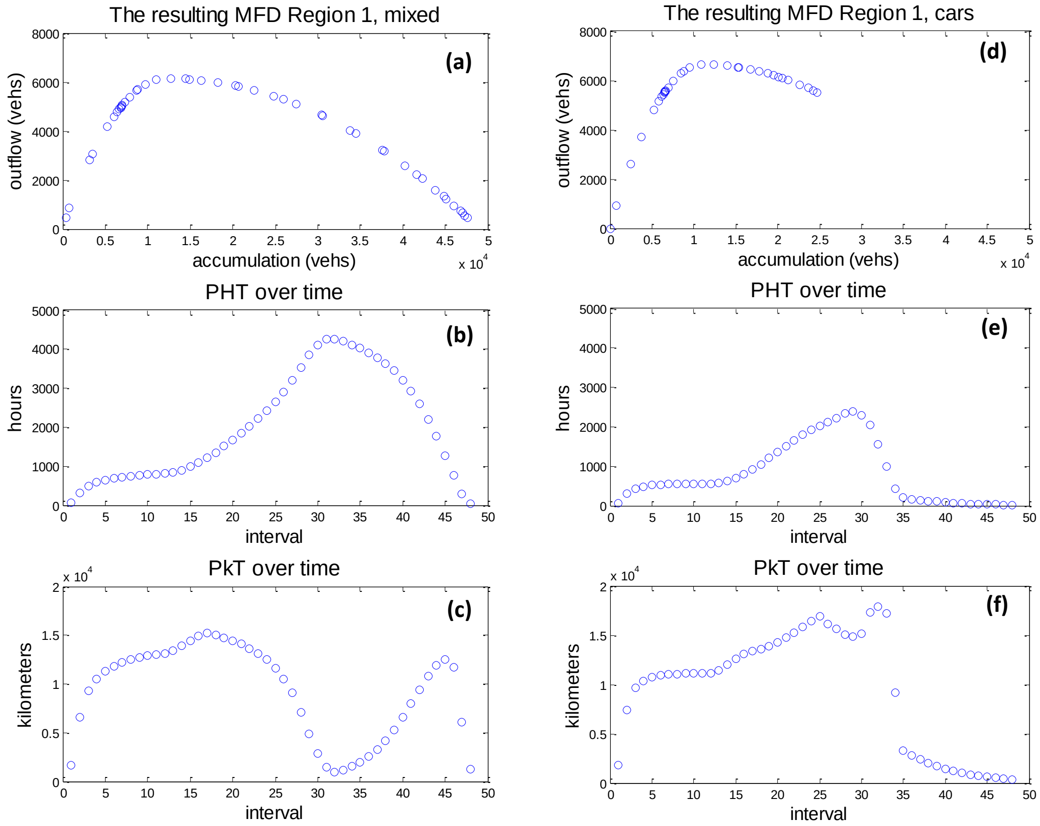

Figure 3 System performance measures for 10% space allocation: (a) Demand [pax/hour] and mode share [%] over time, (b) Ratio of average bus over vehicle speed, (c) Utility of each mode over time (green for bus, blue for car) (d) Average bus occupancy [pax per bus] and average bus dwell time [seconds per bus stop] over time