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Applying variational theory to travel time estimation on urban arterials

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ABSTRACT

The Variational Theory (VT) expresses the LWR model as a least cost path problem. Recent researches have shown that this problem can be simply applied on a graph with a minimal number of nodes and edges when the fundamental diagram is triangular (sufficient variational graph – SVG). Such a graph accounts for traffic signal settings on an urban arterial and leads to mean traffic states for the total arterial in free-flow or congested stationary conditions. The Macroscopic Fundamental Diagram (MFD) can then be directly estimated. In this paper, we extend this method to provide the complete distribution of deterministic travel times observed on an arterial. First, we will show how to obtain a tight estimation of the arterial capacity by properly identifying the most constraining part of the SVG. Then, we will show that a modified version of the SVG allows the exact calculation of the cumulative count curves at the entry and exit of an arterial. It is finally possible to derive the full travel time distributions for any dynamic conditions.

1. Introduction

Travel times and traffic conditions are key components of any traffic monitoring system. Their estimation is crucial for urban traffic managers, especially when the network becomes congested. They are also useful to evaluate traffic control policies and to provide traffic information to users for guidance purposes.

Different sources of data can be used. Some studies focus on probe vehicles (Lagrangian sensors) such as buses, smartphones in cars or taxis (Bertini and Tantiyanugulchai, 2003; Herrera et al., 2010; Zhan et al., 2013). They directly give access to travel times and allow deriving travel time patterns and distributions (Ban et al., 2009; Ramezani and Geroliminis, 2012; Hofleitner et al., 2012). However, such data are not yet very common. That is why the large body of existing methods is based on fixed (Eulerian) sensors like loop detectors that provide speed and flow measurements at fixed points along the arterial. The knowledge of traffic signal settings is then very important to derive accurate travel time estimations (Dion et al., 2004; Skabardonis and Geroliminis, 2005; Liu et al., 2009; Nagati, 2009; Viti and Van Zuylen, 2010; Zheng and Van Zuylen, 2011; Wu and Liu, 2011; Qi et al., 2013; Hans et al., 2014). These data are fully available for traffic managers but have to be processed to derive accurate travel time estimation. Behavioral assumptions about traffic dynamics are necessary. The most common traffic flow model is the seminal Kinematic Wave (KW) model (Lighthill and Whitham, 1955; Richards, 1956), often combined with a triangular Fundamental Diagram FD (Chiabaut and Leclercq, 2011). This model properly reproduces global traffic behavior, especially in urban networks where traffic dynamics are dominated by traffic signals (Papageorgiou, 1998; Leclercq, 2005).

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To estimate travel times, a first approach is to compute the KW solution on the whole arterial for a given situation defined by upstream and downstream boundary conditions in flow. A simple way is to directly compute vehicle trajectories according to Newell's model (Newell, 2002). Many other methods can also be applied. Numerical solutions based on a time–space discretization (Godunov, 1959; Daganzo, 1994) or on exact schemes (Mazaré et al., 2011) can be applied. Other works use the very convenient and popular concept of cumulative count curves to compute the solution at each intersection rather than on the whole arterial (Qian et al., 2012; Hans et al., 2014). The main difficulty with these last methods is the detection of spillbacks. They correspond to downstream queue that prevents vehicles from the current link from going further. Neglecting spillbacks may lead to considerable errors in travel time estimation (Knoop et al., 2006). Lots of works focus on this specific problem (Wu and Liu, 2011; Geroliminis and Skabardonis, 2011; Qian et al., 2012; Qi et al., 2013).

Most studies only focus on free-flow conditions (Viti and Van Zuylen, 2010; Zheng and Van Zuylen, 2011; Hans et al., 2014). Some consider oversaturated conditions due to an inflow higher than the arterial capacity (Skabardonis and Geroliminis, 2005; Skabardonis and Geroliminis, 2008; Nagati, 2009; Wu and Liu, 2011; Hofleitner et al., 2012). Congestion can also appear when downstream outflow is restricted (Leclercq et al., 2014). A global approach able to efficiently compute travel times for all traffic conditions is still needed.

Recently, Daganzo (2005a,b) introduced the concept of Variational Theory (VT). It has been widely used to analytically estimate the Macroscopic Fundamental Diagram (MFD) for arterials (Daganzo and Geroliminis, 2008; Geroliminis and Boyaci, 2012; Leclercq and Geroliminis, 2013; Leclercq et al., 2014). The MFD is an elegant and attractive tool to describe all the possible homogeneous traffic states on the arterial. It also provides the harmonic mean speed of vehicles depending on the flow. Moreover, Leclercq and Geroliminis (2013) pointed out that the MFD properly accounts for spillbacks and capacity reductions. Unfortunately, it only provides mean travel times. This paper resorts on extended VT to estimate the dynamic evolution of travel times corresponding to the KW solutions. The derivation of travel time distribution is then straightforward.

The paper is organized as follows. Section 2 provides background elements about VT, MFD and travel times. A particular attention is paid to the accurate estimation of the capacity of an arterial. Section 3 presents two travel time estimation methods based on VT that correspond to two different scales for traffic representation: macroscopic (MFD) and mesoscopic. At the mesoscopic scale, the method provides the exact solution of the KW model at upstream and downstream boundaries while accounting for all internal interactions. Section 4 compares both methods on several case studies (periodic and non-periodic arterials) and provides analytical upper bounds for the differences. Finally, Section 5 proposes a brief discussion.

2. Background for MFD and travel time estimation

2.1. Sufficient variational graph

Consider here an urban arterial composed of $M+1$ successive links with P lanes, separated by M traffic signals. The length of the link m (between signals $m-1$ and m) is l_m [m] . We denote $x_m = \sum_{i\leqslant m} l_i$ the position of the signal m and $L = \sum l_m$ the total arterial length. The settings of signal m are: red r_m [s], green g_m [s], cycle $c_m = r_m + g_m$ [s], and offset o_m [s] from a common reference. The arterial is modeled as a single-pipe and thus the lane changing phenomenon is not considered. For the sake of simplicity, we do not consider turning movements.

Traffic dynamics are defined by the KW model with a triangular FD. Its parameters are: free-flow speed u [m/s], wave speed w [m/s], jam density K [veh/m/lane]. The maximal capacity during green times is equal to $Q = PwuK/(w+u)$ [veh/s]. Daganzo and Geroliminis (2008) show that the MFD can be approximated by the following set of lines with respect to the speed V:

$$q = min_V[R(V) + kV; V \in [-w, u]] \quad (1)$$

where q [veh/h] is the mean flow and k [veh/m] the mean density on the whole arterial. $R(V)$ denotes the maximum average rate at which traffic can overtake a moving observer at average speed V. Usually a line $R(V) + kV$ is denoted a cut. The theoretical MFD is the lower bound of all the possible cuts. Cuts that are tangent to the MFD are called tight cuts.

The crucial task for MFD estimation is to compute $R(V)$ for a relevant set of speeds V. In practice, $R(V)$ is determined from moving observers who travel at the average speed V in the time–space diagram (Daganzo and Geroliminis, 2008). Along its path, an observer can take different local speeds v between $-w$ and u. The VT defines the local cost $r(v)$ [veh/s] associated to v. This relation is linear for a triangular FD. In this case, Leclercq and Geroliminis (2013) explain that only bidirectional moving observers travelling at local speeds $-w$, 0 and u are of interest. A Sufficient Variational Graph (SVG) in time and space gathers all the possible paths of these observers. The SVG provides full connectivity between points of interest (nodes) located at link ends. Original nodes correspond to the beginning and the end of all red and green phases. It is composed of four kinds of edges associated to different pairs of speed v and cost $r(v)$ (see Fig. 1a):

- Edges with speed 0 and cost $r(0) = Q$ corresponding to green phases;
- Edges with speed 0 and cost $r(0) = 0$ corresponding to red phases (Daganzo and Menendez, 2005);
- Edges with speed u with a cost $r(u) = 0$ that start at the end of red phases and stop when they reach another red phase downstream;