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Density/Flow reconstruction via heterogeneous sources and Optimal Sensor Placement in road networks

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ABSTRACT

This paper addresses the two problems of flow and density reconstruction in Road Transportation Networks with heterogeneous information sources and cost effective sensor placement. Following a standard modeling approach, the network is partitioned in cells, whose vehicle densities change dynamically in time according to first order conservation laws. The first problem is to estimate flow and the density of vehicles using as sources of information standard fixed sensors, precise but expensive, and Floating Car Data, less precise due to low penetration rates, but already available on most of main roads. A data fusion algorithm is proposed to merge the two sources of information to estimate the network state. The second problem is to place sensors by trading off between cost and performance. A relaxation of the problem, based on the concept of Virtual Variances, is proposed and solved using convex optimization tools. The efficiency of the designed strategies is shown on a regular grid and in the real world scenario of Rocade Sud in Grenoble, France, a ring road 10.5 km long.

1. Introduction

The last decades have witnessed a considerable increase of traffic volumes, especially due to urbanisation in big metropolis, which was not matched by a comparable extension of road infrastructures. As a consequence, crucial freeways, highways and arterial roads have been steered to a state of near saturation, and experience on daily basis periods of congested traffic (Papageorgiou et al., 2007). In turn, congestion causes increased travel times and stop-and-go phenomena, leading to decreased safety, economical losses, and environmental and psychological hazards in terms of pollution and road rage (Bilbao-Ubillos, 2008). Increasing road capacity by extending road infrastructures, such as construction of new arterial roads, has been the standard way to cope with congestion problems, but it is infeasible when existing roads lie on built-in areas. Intelligent Transportation Systems (ITSs), on the contrary, are expected to provide robust techniques for real-time monitoring, prediction and actuation of traffic networks, and to better integrate with road and rail public transportation, by leveraging recent technological and theoretical advancements in distributed computation and communication.

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The present paper investigates the two interconnected problems of sensor network design and estimation in traffic networks. As illustrated in Fig. 1, we propose three procedures to address the problems of Optimal Sensor Placement, and of Traffic Reconstruction, via the two modules of Fundamental Diagram calibration and Density and Flow Estimation.

Standard devices to obtain information on the state of the network are fixed sensors such as induction loops and magnetometers. Placed over a section of road, they provide rich information on the vehicles that cross such a section over a pre-fixed period of time: (1) their number, or flow, (2) their average speed, and (3) their average density, or more precisely their occupancy (see Section 2). Current technology allows for very precise measurements, with relative errors of measured quantities against ground truth often being below 1–2%. However, deployment and maintenance of a sensing network requires considerable investment and manpower, and consequently sensing networks are usually designed to be as sparse as possible. In this paper we formulate and provide a solution to the Optimal Sensor Placement problem, that is, positioning sensors on the cells of the network given partial information on the system and in such a way to trade off between performance and cost. To this aim, we assume that traffic managers know the splitting ratios of the network, namely, the turning percentages at each road intersection, an information that can be obtained via standard surveys using optical count or radar sensors.

Optimal Sensor Placement is a ubiquitous problem that has received a high degree of attention in several communities due to its importance for network design. In Transportation Systems, it is of interest both in the dual-problem of best placement of hubs for cost-efficient transportation of goods and people (Shahabi and Unnikrishnan, 2014) and Origin–Destination coverage (Ehlert et al., 2006; Hu and Liou, 2014; Antoniou et al., 2016). In these works, and differently from the present paper, the problem is cast as a mixed integer problem which corresponds to determining the minimal set of locations from which the flows on the whole network can be determined, and sensor measurements are assumed to be perfect. Finally, recent contributions focused on Origin–Destination flows and travel time estimation from an information theoretical point of view and under several possible cost functions (Zhou and List, 2010; Xing et al., 2013), and on probabilistic approaches to the sensor placement problem that take into account sensors failures and other random events Fei et al. (2013) and Danczyk et al. (2016).

Once the sensing network has been designed an implemented, flow and density measurements are available. Sensors are not, however, the only source of information that we exploit. In fact, the recent spread of wireless devices allows sensing and communication capabilities unforeseeable up to few years ago. Limiting the attention to traffic applications, vehicles equipped with positioning devices (such as GPS) and able to communicate with an ITS monitoring system can act as a probes in the traffic and provide Floating Car Data (FCD), namely, information on the vehicles' positions and speeds. The collected data can be used to estimate the speed in the network, thus offering a second source of information. Due to privacy reasons, single vehicles traces are usually not directly used, but rather aggregated as average speed of vehicles in segments of road. Advanced methodologies ensure fine spatial partitions of the network, with segments as short as 250 m (INRIX, 2014). Compared to fixed sensors, a service based on this technology can only make use of information coming from her customers, which are a fraction of the total vehicles on the road (the *penetration rate* of the system). This implies that speed measurements are less precise and flow measurement are unavailable. On the other side, since it exploits existing communication systems it is relatively inexpensive and, more important, already covers all major traffic networks.

Fixed sensor measurements and Floating Car Data provide rich information that we employ to address the problem of estimating road usage in terms of density and flow of vehicles in a traffic network. The latter are commonly considered a good representation of the state of the system, providing more information than average speed alone. In particular, they are of crucial importance for (1) forecasting travel time and traffic evolution, along with historical data; (2) informing in real-time drivers about the state of the network through navigation systems; (3) providing public authorities with statistical data to monitor the state of the network and predict dangerous scenarios; (4) computing and actuating control actions through traffic lights, ramp metering and speed limits, or, in the future, lane change and semi-autonomous routing and navigation (Papageorgiou et al., 2003, 1991; Pisarski and Canudas de Wit, 2012; Como et al., 2013).

Traffic models for analysis and control synthesis date back to the first half of the 20th century. The most celebrated macroscopic model is the PDE based Lighthill-Whitham and Richards (LWR) model (Lighthill and Whitham, 1955), which, based on fluid kinematics, is able to reproduce crucial phenomena such as traffic shock waves. Discretization of the LWR-PDE is not straightforward but stable numerical schemes have been proposed, the most well known being the Cell Transmission Model (CTM) (Daganzo, 1994, 1995). Huge efforts have been put in the last 15 years to calibrate the CTM (Muñoz et al., 2006) and to unveil its system-theoretical properties (Morbidi et al., 2014). Fusion of flow, density and speed

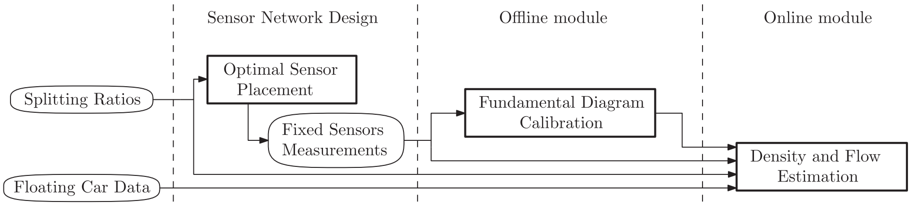

Fig. 1. Flowchart of the paper's contributions: Optimal Sensor Placement for sensor network design, Offline Fundamental Diagram Calibration, and Online Density Estimation. Curvy blocks represent information provided to the three procedures.