UTILITY-BASED KALMAN FILTERING FOR REAL-TIME ESTIMATION OF DAILY DEMAND FLOWS.

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BACKGROUND

Simulation of traffic conditions requires accurate knowledge of the travel demand. In a dynamic context, this entails estimating time-dependent demand matrices, which are a discretised representation of the dynamic origin-destination (OD) flows. This problem, referred to as Dynamic OD demand Estimation (DODE) in literature, seeks for the best possible approximation of OD flows that minimises the error between simulated and available traffic data (Cascetta, Inaudi, and Marquis 1993). Traditionally, this procedure can be applied off-line (medium-long term planning) (Cascetta, Inaudi, and Marquis 1993) or on-line (real-time traffic prediction) (Antoniou, Ben-Akiva, and Koutsopoulos 2007). In the first case, a historical database, which represents the average traffic conditions over multiple days, is adopted to test the capabilities of the simulation model in replicating congestion phenomena. However, since the dynamics of traffic systems are complex and depend on ill-predictable phenomena, daily demand patterns can substantially differ from the average ones (Zhou and Mahmassani 2007). On-line approaches focus indeed on this last aspect, hence have the goal of calibrating the model for a specific day, based on real-time data.

Recently, Cantelmo et al. (2018) introduced a Utility-Based framework for the off-line OD estimation problem. In the proposed methodology, the traffic simulator includes a departure time choice model that, by exploiting utility-based cost functions, explicitly accounts for activity scheduling and behaviour (Adnan 2010; Cantelmo and Viti 2016). Analytical properties of the model show that, as the model can include information on activity locations and duration, the localism of the problem strongly decreases, and a reasonable initial matrix can be generated even from a poor initial guess. This research aims at extending this methodology to the online case, exploiting information such as activity scheduling and duration to create demand matrices that are more consistent across the day and capture the day-to-day evolution of the demand.

Extending the model to the on-line case is far from trivial, as the following limitations should be stressed, which characterise the off-line model:

1) The model properly captures the systematic component of the mobility demand (morning/evening commute, daily shopping), but it has a hard time in considering random and structural demand fluctuations (i.e. those related to partially predictable events such as severe weather conditions).
2) We need 24h of simulation in order to fully exploit information, such as the activity duration.
3) We should map activity location or explicitly model tours of activities in order to consider activity duration. This way, consistency will be guaranteed not only on a temporal but also on a spatial scale.

In this research, we address the three aforementioned problems by formulating the on-line DODE problem as a state-space model. Specifically, we include activity scheduling, location and duration within the well-established Kalman Filtering (KF) online demand estimation approach, in order to achieve a more reliable estimation while keeping the computational time low. Hence, the proposed formulation is expected to bring two main contributions with respect to the state of the art: first, we create a model that is more robust and consistent over the day, as the activity-based demand structure is included within the estimation framework. Secondly, the framework can be applied for studying the day-to-day evolution of the demand, hence capturing activities' evolution over time.

METHODOLOGY: UTILITY-BASED KALMAN FILTER

The on-line DODE problem can be formulated as a state-space model, which is composed of two types of equations:

1) The *transition equation*, which describes the evolution of the system over time;
2) The *measurement equation*, which maps the available traffic data to the state vector – i.e. the set of variables that is sufficient to uniquely describe the evolution of the system.

The standard Kalman Filter (KF) algorithm is a powerful tool for solving this type of problems, but it is limited to linear systems. Consequently, since dynamic transport systems are nonlinear by nature, enhanced KF estimators (such as the Extended-KF and the Unscented-KF) are usually deployed in real-world applications. While most of the state-of-the-art online DODE models assume a nonlinear relation between OD flows and traffic data, a common approach to represent the transition equation is to use an autoregressive process, meaning that the state vector during a single time interval collapses to a simple linear regression model. However, nonlinear functions are more realistic in capturing the evolution of the demand over time, as the travel demand is characterized by different interacting mobility patterns. The main idea behind this study is that homogeneous classes of users (classified e.g. by common activity patterns) might be representable through a small set of carefully selected parameters. Simply stated, it is possible to model users travelling from a certain origin to a certain destination for a certain purpose through a small number of parameters, such as the preferred expected departure time and its variance (Figure 1).

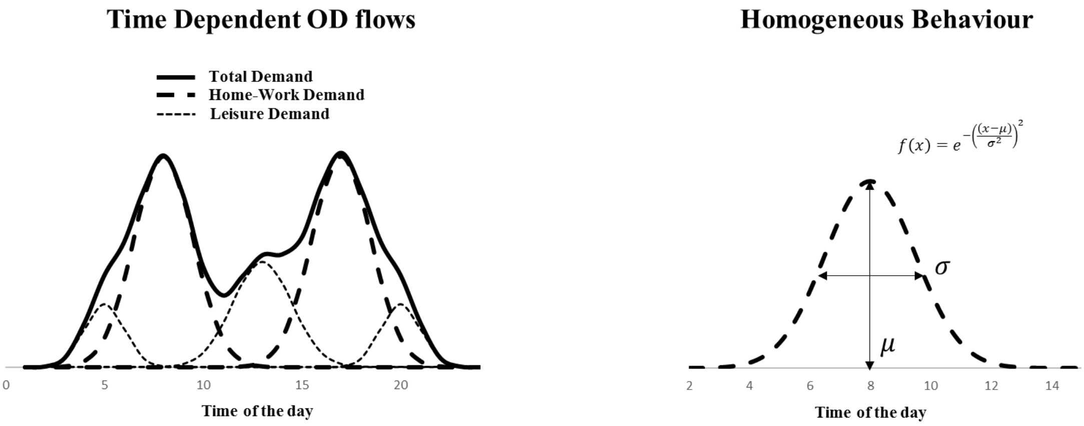

Fig. 1: Mobility Demand as a convolution of different activities;

Similarly, each activity can be modelled through a (nonlinear-in-parameters) utility function. By combining these functions through a Logit-type approach, a more realistic distribution of the departure time choice probability can be obtained. The main challenge becomes thus to identify the activity-based demand segments to be considered within the transition equation. We consider two alternative methodologies to achieve said goal: if a historical OD matrix is not available, the Utility-Based OD Estimation (UB-DODE) framework proposed in Cantelmo et al. (2018), which jointly estimates activity-based OD flows and the parameters of the utility function, can be used to estimate the systematic component of the demand off-line (Figure 2). Alternatively, if an historical OD matrix is already available, a Markov Chain Monte Carlo model can be used to approximate these distributions. (Scheffer, Cantelmo, and Viti 2017).

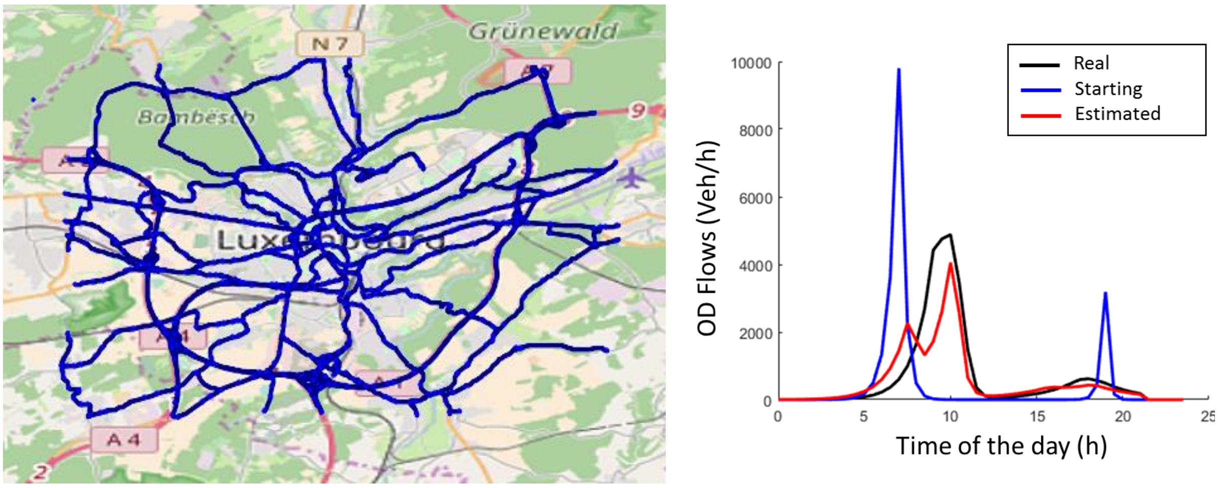

Fig. 2: Example of the demand function for the Network of Luxembourg City (Synthetic Experiment);

The Kalman filtering approach assumes that at each step we have two Gaussian distributions: one representing the expected state of the system, and one modelling the probability of reproducing the data Then, the model determines the most likely value of the demand by considering the combination of these two distributions. It appears then that different assumptions on each of them will strongly influence the overall quality of the estimated matrix.

The proposed model leverages on this specific property in order to improve the on-line DODE. Since the *Transition Equation* captures the systematic component (or average behaviour) of the demand, we can use the realistic demand function derived from the *Utility-Based* approach previously discussed to account for activity preferences within the transition equation. Then, the error term and the covariance matrix allow us to capture the non-systematic behaviour of the demand by exploiting the mathematical properties of the KF model, which assumes that the estimated variables are random and Gaussian distributed. More specifically, this formulation brings two contributions: first, the *transition equation* keeps track of the activity preferences. Second, we directly update some of the parameters of the departure time choice model, which allows us to consider spatial *and* temporal variation of the demand.

In this research, we will assess if the proposed methodology is capable of jointly estimating the systematic and not-systematic component of the mobility demand. Specifically, two situations will be investigated: if the parameter the departure time choice model are assumed to be constant over the estimation period, then the model is expected to provide reliable estimations over a short period of time. However, if these parameters are also included in the estimation process, the model can be applied to estimate the day-to-day evolution of the demand i.e. how activity preferences evolve over time. This work will specifically analyses properties of reliability, convergence and robustness for the proposed approach. Then, experiments on synthetic networks will show the advantage of the proposed approach in a fully controlled and predictable environment, as the effect of the new specified variables on the covariance matrix is a key factor to be evaluated.

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