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On the computation of the energy-optimal route dependent on the traffic load in Ingolstadt

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ABSTRACT

In this paper, we evaluate energy-optimal paths in the road network of Ingolstadt. The energy consumptions associated with the segments of the road network are derived from the measurements of the traffic load based on vehicle probe data, using a mesoscopic traffic model and a physical vehicle consumption model. The resulting description of the network is time-dependent, thereby reproducing the variations in time of the traffic load in Ingolstadt. The results suggest that the average energy consumption associated with energy-optimal paths is approximately 10% lower than the average energy consumption associated with fast paths. Moreover, we find that energy-optimal paths differ from fast paths in more than 90% of the considered test cases and that the density of junctions has a strong impact on the average energy consumptions. Although the time dependency of the network description leads to an increase in the computation time of optimal paths, the query times of one of the evaluated methods are promising for practical applications.

1. Introduction

Up to now, many citizens are skeptical towards electric vehicles because of their small cruising range and high battery cost (Meyer, 2008). Indeed, the battery is the most expensive component of hybrid and electric vehicles, since it must meet the high demands on energy capacity and power demand in road traffic (Meyer, 2009). As the energy capacity is proportional to the cruising range, a conflict of objectives results between the cost and the cruising range of the vehicle.

One possibility to alleviate this problem is the computation of energy-optimal routes. It is thereby not only possible to predict, but also to optimize the cruising range. Since the energy consumption associated with a road segment in the road network depends on the traffic load (Kesting and Treiber, 2008; Greenwood et al., 2007) and the existence of queues with energetically unfavorable acceleration, there results a need for precise traffic data and a corresponding energy consumption model which allow the attribution of each road segment with an energy consumption for each traffic load, as well as routing algorithms which efficiently solve the resulting optimal path problem.

The purpose of this paper is the presentation of an approach which is suitable for solving the above problem in real-time applications, such as vehicle navigation systems or centralized traffic optimization. To this end, we derive a mesoscopic traffic model which is suitable for incorporating variations of the traffic density and average speed in urban traffic, which is applicable as input to a physical (i.e., power and load based) energy consumption model, and which is simple enough to be used in real-time applications (i.e., which depends on a small number of easily measurable input variables and which can be applied with little computational effort). This model can be seen as a first approach to the development of

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instantaneous power and load based energy consumption model (which might also easily be adapted to the calculation of emissions) for microscopic applications and of a traffic simulation model for macroscopic applications (Corsmeier et al., 2005). We further present and evaluate algorithms which are capable of computing energy-efficient routes in time-dependent networks within the constraints given by real-time applications. We then exemplarily apply this approach to traffic data which has been collected in the German city of Ingolstadt.

A common means for describing the traffic load on a road segment is the measurement of average speeds throughout the day. Measuring methods include, e.g., inductive loop sensors and floating car data (Schäfer, 2005; Zhang et al., 2009). Using the average speeds derived from floating car data in the German city of Ingolstadt (Dittrich et al., 2009) and a recently published model of urban traffic flow (Helbing, 2009), we obtain a time- (resp., load-)dependent description of the road network of Ingolstadt. The description of the network also takes acceleration at intersections into account, as the derived speed distribution for road segments shows a high relative frequency of small speeds and the transition between zero speed and free flow speed is also modeled (see peak at $v = 0$ in Fig. 4(a) and in Fig. 5). These distributions are derived from a model of urban traffic which is based on a consideration of the existence, length and quality (growing, shrinking or in saturation) of queues at intersections (Helbing, 2009).

In the following, we will not only describe in which manner the energy consumption can be derived from the traffic measurements, but we will also use two recently published algorithms (Kluge et al., 2011) to compute energy optimal routes for a representative number of location-destination pairs.

The remainder of this paper is organized as follows: We describe the collection of the traffic data in Section 2 and present the energy consumption model and the traffic model in Section 3. We formally introduce the resulting time-dependent network in Section 4 and review two solution methods for the time-dependent optimal path problem in Section 5. We then describe the experimental setup and the computational results in Section 6. Finally, we conclude the discussion of energy-optimal paths in Section 7.

2. Data collection

The speed values which form the basis for the evaluation of our algorithm are derived from taxi floating car data according to the traffic state estimation method presented in Dittrich et al. (2009). The taxi data is gathered from a taxi fleet in Ingolstadt. Taxis are driving along the same streets as other car drivers. There is no explicit lane for taxi drivers. Therefore we assume that the derived speed values correspond to the traffic in general within the inaccuracy given by the sample size, neglecting possible different driving behavior.

First the received position is matched to the nearest road segment. With the subsequent position the most probable route through the network is calculated. The speed is calculated from the length of the route and the needed time to pass it. If this results in a higher speed value than the allowed speed, the calculated speed is set to the speed limit (cf. Fig. 3).

The arithmetic mean of all so derived speed values on a road segment is computed for time intervals of 15 min. The aggregation interval is set to 15 min as the macroscopic traffic state does not change every minute, but smoothly over a longer time interval. In addition the taxi fleet of Ingolstadt has a limited number of around 100 vehicles sending their positions every 30 s. Therefore, using the available floating car data, a traffic state estimation with smaller aggregation interval is not feasible. The estimated speed is updated every five minutes to take account of smooth changes within traffic state (see Fig. 1).

The traffic state is therefore defined by a speed value for each link of the road network calculated as arithmetic mean of all speed values from floating car data of the past 15 min. The aggregation results in 288 update times within one day, i.e., at times $t_k = k \cdot 5$ min, $k = 0, \ldots, 287$. The speed values are verified by the taxi dispatch center as the streets on their map change their colors corresponding to the currently estimated speed. These calculated speeds have been stored in a data base for the duration of about one year.

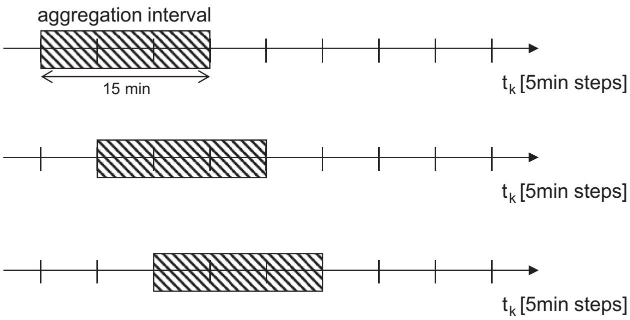

Fig. 1. Time aggregation and update interval employed here.