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Anticipating emission-sensitive traffic management strategies for dynamic delivery routing

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ABSTRACT

Traffic pollution is an increasing challenge for cities. Emissions such as nitrogen dioxides pose a major health threat to the city's inhabitants. These emissions often accumulate to critical levels in local areas of the city. To react to these critical emission levels, cities start implementing dynamic traffic management systems (TMS). These systems dynamically redirect traffic flows away from critical areas. These measures impact the travel speeds within the city. This is of particular importance for parcel delivery companies. These companies deliver goods to customers in the city. To avoid long delivery times and higher costs, companies already adapt their routing with respect to changing traffic conditions. Still, a communication with the TMS may allow anticipatory planning to avoid potentially critical areas in the city. In this paper, we show how communication between TMS and delivery companies results in benefits for both parties. To exploit the provided information, we develop a dynamic routing policy anticipating potential future measures of the TMS. We analyze our algorithm in a comprehensive case study for the TMS of the city of Braunschweig, Germany, a city often used as reference for a typical European city layout. We show that for the delivery company, integrating the TMS' information in their routing algorithms reduces the driving times significantly. For the TMS, providing the information results in less traffic in the polluted areas.

1. Introduction

The demand for city transportation, individual and freight, is increasing through continuous growing e-commerce and urbanization. This general increase in transportation has led to substantial challenges for both urban municipalities and logistic service providers. Both parties operate within the urban traffic environment and an information exchange suggests itself. However, a communication has not been established yet. In this research, we analyze how the exchange of information, more specific, the provision of traffic control information from the urban municipalities to the service providers leads to benefits for both parties' objectives.

Urban municipalities need to enable effective and efficient transportation. Still, they also need to provide a livable environment for the citizens without pollutions (Zhou et al., 2015). As an example, an EU regulation limits the yearly average air pollution in cities to 40 $\mu g/m^3$ of NO_2 (EU, 2015). To enforce these regulations, many German cities like Braunschweig or Potsdam install *emission-sensitive online traffic management systems* (TMS) to dynamically control traffic flows based on current and expected emission levels (Diegmann et al., 2010). The city's TMS constantly monitors the pollution levels in hot-spot areas, where the emissions tend to be

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critical (Boltze and Kohoutek, 2010; Celikkaya et al., 2016). If the emission levels exceed a threshold, the TMS changes the *traffic strategy* (Han et al., 2015). These changes reduce and/or increase traffic capacity in certain areas of the city by adapting traffic light programs and speed controls. In essence, access to polluted areas is limited while traffic around and out of the hot-spots areas is accelerated by coordinately changing the traffic light intervals in the affected area. These traffic strategies are dynamically changed during the day with respect to emission levels. Furthermore, the emissions are subject to stochastic elements like weather conditions and congestion. In many cases, reliable predictions of future emission levels are possible only for a limited time horizon.

Major producer of urban emissions is the freight transport sector, especially Courier, Express and Parcel companies (CEPs). According to the US Environmental Protection Agency, CEPs account for about 20% of the CO_2 emissions of all mobile sources, and for about 50% of the NO_x and nearly 40% of the PM_x emissions (Inventory, 2005). Recently, CEPs initiate eco-friendly programs (DHL, 2016; UPS, 2016). Nevertheless, in practice, CEPs often ignore emissions in their transport activities due to the high cost-pressure keeping in mind that last-mile delivery is responsible for more than 50% of the overall delivery costs (Bernau et al., 2016). Hence, CEPs optimize and update their delivery routes with respect to delivery costs (Ehmke et al., submitted for publication). One of the main costs factors are the drivers' working times. Because TMS decisions impact the travel times within the city, these costs indirectly depend also on emissions. More specific, a traffic strategy may change an individual shortest path and/or the travel time between two customers. Each traffic strategy induces an individual travel time matrix and a change in the traffic strategy may render a current routing plan inefficient. Furthermore, a mere reaction to new information may be insufficient. Anticipation of potential future changes is necessary. There are two measures to avoid inefficient planning by anticipation. The TMS can communicate the next planned decisions to the service provider and the provider can estimate potential future decisions based on current information by means of predictive analytics. The derived information needs then to be integrated in the planning algorithm.

In this research, we present dynamic routing policies for CEPs anticipating potential traffic strategy changes. We focus on a CEP-routing problem where the TMS provides information about the current and the near-future traffic strategy. The problem under consideration can be defined as *dynamic vehicle routing problem with stochastic changes of travel time matrices* (DVRPMC). A fleet of vehicles delivers goods to a set of customers. A set of travel time matrices is given, each representing a traffic strategy. Initially, the goods are assigned to the vehicles. While the vehicles are on the road, the traffic strategy and, therefore, the travel time matrix changes based on stochastic emission developments. At any point of time, the dispatcher has access to the current and near-future traffic strategy as well as the current emission levels. Based on this information, the dispatcher can dynamically adapt the planned routes for each vehicle of the fleet. The objective is to minimize the expected travel times for delivery.

In the according Markov decision process model of the DVRPMC, we experience curses of dimensionality in all capacities. The number of states is vast because of the exponential increase with respect to the number of customers. The information space models the potential emission changes and is therefore continuous. Finally, the action space is large since it incorporates routing decisions. To account for the large state and information space, in every decision point, we apply a heuristic policy sampling emissions and evaluating current decisions with potential future developments. To account for the large action space, our policy identifies *critical* areas in the matrix with potentially long travel times. We incorporate these areas in the travel time matrix in such as way that we can solve the resulting model with state of the art routing software for delivery planning. The solution determines the current routing plan and the next customer to visit.

We evaluate our method for a case study for the City of Braunschweig, Germany. Braunschweig represents the layout of a "standard" medium-sized city and is therefore often used as reference city in mobility research (DLR, 2017). We draw on historical emission observations and test the policy for instance settings varying in the number of vehicles and the TMS's impact. We compare our policy with static routing and dynamic routing on current information. Our analysis provides two main managerial implications:

1. Our anticipatory dynamic routing method reduces travel times for the CEP on average by 6.8% and up to 16.0%. The reduction is particularly high if the number of deliveries per vehicle is large and the impact of the TMS's decisions is high.
2. A cooperation between city's TMS and CEP leads to an average reduction of CEP-traffic in polluted areas by 54.6%. The co-operation is therefore highly beneficial for both parties.

Our contributions are as follows. This paper is the first quantifying and analyzing how a cooperation of traffic management and CEP lead to benefits for both. With the DVRPMC, we provide a new and relevant dynamic routing problem reflecting emissions and TMS in the decision making. We further provide a comprehensive Markov decision process model enabling the depiction of stochastic *correlated* travel times, a feature generally neglected in the literature. Our work is similar to the recent suggestion by Gendreau et al. (2016) to draw on a "set of suitable designed scenarios" for different travel time patterns.[1] Our presented solution method is able to incorporate correlation and significantly improves solutions with respect to the objectives of CEP and TMS.

This paper is outlined as follows. We present TMS in Section 2. In Section 3, we model the DVRPMC as a Markov decision process. We present our policy and the benchmark heuristics in Section 4. In Section 5, we compare the policies for a case study of the City of Braunschweig. The paper concludes with a summary and an outlook in Section 6.

2. Traffic management

In this section, we describe how the TMS changes their strategies and how a strategy changes the travel times within the city. The

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[1] For a comprehensive literature review, we refer to Appendix A.1.