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Large scale simulation of CO_2 emissions caused by urban car traffic: An agent-based network approach

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ABSTRACT

CO_2 emissions caused by private motorized traffic for the city of Graz, a typical European inland city with about 320 000 citizens, are investigated. The main methodology is a newly developed agent-based model that incorporates empirical data about the mobility behavior of the citizens in order to calculate the traveled routes, the resulting traffic and subsequent emissions. To assess the impact of different policies on CO_2 emissions, different scenarios are simulated and their results are compared to a base line scenario. The model features a local and temporal resolution, effects like congestion and stop-and-go traffic as well as commuters to and from other regions. In addition to the evaluation of certain policies (like a focus on electric cars, telecommuting or an improvement of the road infrastructure), a method is provided, that makes it possible to compare many diverse scenarios, featuring technological changes, societal changes or changes in the road network, all within the same framework. The findings suggest that one of the most promising strategies to decrease urban CO_2 emissions is to focus on the use of electric cars, especially if it is combined with offering alternatives to private car traffic and incentives for telecommuting. Banning the use of old cars only yields a significant result if a large amount of cars is affected, which would make such a policy difficult to implement. Expanding the road network has no significant positive effect and may even encourage using cars, therefore leading to even more CO_2 emissions. Due to its flexible structure the presented model can be used to evaluate policies beyond what is presented in this study. It can easily be adapted to other conditions and geographical regions.

1. Introduction

The role of cities in the mitigation of climate change and the adaption to its effects is of high importance for various reasons. First of all, more than 50% of the world population lives in cities (UN DESA, 2014). Additionally, cities are responsible for more than 75% of the global energy consumption (Gouldson et al., 2016) and the global greenhouse gas (GHG) emissions (Change, 2015). However, cities do not only cause the majority of the GHG emissions (Mi et al., 2015), they are also highly affected by their consequences like climate change (Geng et al., 2014). On the other hand, cities are also in the unique position to tackle the challenges of climate change. They have the means to find and implement various policies that could help in the mitigation of climate change (Rosenzweig et al., 2010). The International Energy Agency (IEA) estimates that urban energy use is responsible for about 76% of all global emissions (IEA, 2009). A significant portion of urban energy use is caused by traffic. Especially here, the public sector has ample opportunities to influence the behavior of the citizens with various policies. A good public transport system, certain incentives for the use of electric cars, or the strict regulation of cars that emit too much CO_2, can have a huge impact on the GHG emissions of the city.

The problem with such policies is that it is difficult to assess their impact, since one would need a complex, yet large-scale model to predict all effects that a change in the traffic system or a change in mobility behavior could have. There are various approaches to tackle this challenge (see section 2 for details on them), but currently there is no method that is fast enough to evaluate a satisfyingly large number of variations of parameters of a policy scenario, while being flexible enough to consider technological, social, and juridical changes within the same framework. In order to fill this research gap, this study introduces a novel way of traffic simulation that is agent-based, yet all of the interaction between the agents is considered on the base of a network approach, which

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drastically speeds up simulation time. The presented method is then applied to the city of Graz, an Austrian City with a population of about 320 000 people, serving as a typical example of a city of this size, with a simple structure (no multiple city centers, no huge industrial clusters, consistent population density within each district).

This manuscript is organized as follows: Section 2 gives a short introduction to state-of-the-art approaches to traffic modeling, listing advantages and disadvantages and detailing differences to the presented method. Section 3 gives further details of the model. Results of various scenarios are presented in section 4. Section 5 concludes with policy recommendations as well as this study's contribution to the advancement of the state-of-the-art.

2. Methodology

There are many different ways to simulate traffic and all approaches have unique advantages and disadvantages. Many traffic simulations are constructed bottom-up, i.e. they start from the behavior of single vehicles and aggregate to obtain macro-scale results. Maybe the most famous model, based on Cellular Automata, is the Nagel-Schreckenberg model (Nagel and Schreckenberg, 1992). It starts out from very simple rules and is able to predict complex phenomena like the emergence of traffic jams. Beyond that, there are more complex, agent-based models that can also include pedestrian movement in the form of the Social Force Model (Helbing and Molnar, 1995), and a more complicated car following model (Wiedemann and Reiter, 1992). Most prominent are the commercially available PTV VISSIM (Vissim, 2008) and the open-source projects MatSIM (Balmer et al., 2009) or SUMO (Krajzewicz et al., 2002). For a more detailed review on traffic simulations, see (Kotusevski and Hawick, 2009). Traffic models are of course primarily developed to predict and analyze traffic flow, but they can be augmented by emission models, like for example the Comprehensive Modal Emission Model (Barth et al., 2000), to gain accurate predictions on traffic emissions (Wang and Fu, 2010). The main methods to simulate traffic-caused emissions are bottom-up approaches (mostly agent-based and on the micro-scale) that can also produce good results in an urban environment (Hülsmann et al., 2011). However, these models have their focus on accurately depicting the travel time of each vehicle, which is computationally very expensive and not necessarily required for investigating CO_2 emissions.

On the other end of the spectrum, and especially relevant for emission estimation, there are top-down models. For example a statistical emission model, that requires very little input, but is sufficiently complicated to produce reasonable results was developed (Cappiello et al., 2002). In general, top-down models can have many advantages, for example they do not rely on detailed origin-destination surveys and are numerically relatively cheap (Tuia et al., 2007). However, they lack the microscopic detail that bottom-up approaches offer. Top-down approaches are computationally cheaper, but often lack the flexibility that is needed to run diverse scenarios, since they heavily rely on statistical data that cannot be adapted easily for all interesting scenarios. Hybrid approaches, i.e. simulations that depict all road traffic in a way abstract enough to allow for fast computation, are also very promising for investigating emissions (Cetin et al., 2003).

A different approach is using a dispersion model to calculate emissions (Berkowicz et al., 2006). Dispersion models use some form of emission estimation, like the COPERT software (Ntziachristos et al., 2000) to find out what amount of emissions are generated by roads and then add a dispersion model, like the Operational Street Pollution Model (Berkowicz, 2000) in order to gain local resolution of the dispersion of these emissions. However, it should be noted that the local resolution of emissions is not very relevant, when investigating CO_2 emissions.

Even though there are currently many approaches that are suitable to simulate urban traffic emissions (see Table 1 for an overview), Grote et al. find that there is still a high demand for new ways of modeling urban traffic emissions, since currently Local Government Authorities do not necessarily have the right options to meet their requirements (Grote et al., 2016). Additionally, each state-of-the-art method has certain disadvantages that make it difficult to evaluate all policies and scenarios of interest within the same framework. Therefore, a novel model is needed to fulfill the following requirements:

- to be fast enough to be computed for many different scenarios often enough to make reliable predictions,
- to include accurate information about used cars and their emissions,
- to depict increased emissions due to congestion and stop-and-go traffic without the need for statistical data about road congestion,
- to require no exact origin-destination data, yet to produce realistic path origins and destinations,
- to include the road infrastructure, and
- to consider additional trip information, like for example the purpose of a trip (e.g. working trip, shopping trip, etc.)

The main advantages of the proposed model, compared to current state-of-the-art traffic emission models, are the following:

- its 1:1 scale, i.e. each citizen is represented in the model,
- its fast computation time (a 24-h scenario can be calculated in roughly 3 h using a single processor core, i.e. significantly faster than real-time)
- that it does not depend on origin-destination data, but is based on input parameters that are easy to modify to correspond to various scenarios
- that it is flexible enough to evaluate various scenarios regarding juridical, social, or technological changes
- that it can adapt to various possible future developments, like population growth or urban sprawl

A comparison between a traditional and the presented approach is given in Fig. 1. Note the difference in input data, which makes the model better suited to support decision-makers. Additionally, it is fast and flexible enough to evaluate many different scenarios within the same framework. It is possible to investigate social changes (e.g. changing the mobility behavior of the agents), technical changes (e.g. changing the emission rates of cars), juridical changes (e.g. banning old cars within the city) or changes in the road infrastructure, and therefore compare fundamentally different policies and their impact on CO_2 emissions within the same model.

3. The model

The purpose of this model is to calculate the emissions caused by urban car traffic. This is achieved in several steps. First the road network is generated, as detailed in section 3.1. Then the simulated agents use this network to make realistic trips. For this, origin-destination data is required, which is generated as detailed in section 3.2. In order to obtain realistic road usage, commuters with residences outside the city limits were included as well, using entry points generated from statistical information (Statistik Austria, 2011). Note, that the actual update order of the agents is of no relevance, since all interactions between agents are included later on, when all the trips have been determined. With precise