AN APPROACH TO DESIGNING ENVIRONMENT-FRIENDLY NETWORKS

Integrating environmental constraints in the fundamental diagram

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ABSTRACT

In this paper, the integration of traffic fundamental diagram and environmental constraints is presented. Differently from more conventional design and management approaches, by which the solutions are identified by looking first at the simulated traffic patterns and later they are tested through emission analysis, the proposed approach takes the environmental constraints into account already in the traffic simulation process, leading to environment-friendly design solutions. This approach has been developed and applied in a case study with chosen traffic and emission models. The results show that emission rates get much closer to the emission constraints while keeping an acceptable travel delay by this approach, and the calculation time is much less than the conventional optimization approach.

KEYWORDS

Traffic environment, traffic emission, network management and design

INTRODUCTION

The environment, especially in urban areas, is deteriorating at an alarming rate. Traffic emissions are contributing to this process in a significant way. The sharp increase in the number of vehicles, both in developed and developing countries is forcing authorities to face and solve the problem of traffic emissions. Taking environmental impacts into account is therefore becoming increasingly important when considering urban traffic management strategies. Thus, environmental constraints become essential to achieve a sustainable network. However, environmental impacts are not considered in the design phase, but they traditionally are considered in the evaluation of the different solution scenarios, making the decision process rather complicated. The traditional method in an environmental study usually involves the following cycle: Policy → Traffic simulation → Emission → Concentration →

Health Impact → Economics → Policy. According to this cycle, the output of the traffic model is an important part of the emission model input, and as a consequence emission inventories are the results from the integration of traffic models and emission models. These emission inventories are compared to the environmental constraints and further analyzed in the later steps of the cycle. However, there are drawbacks in adopting the traditional cycle. First, the analysis cycle is too long, causing higher uncertainty in the calculations and prolonging the analysis time. Second, some necessary data are rather difficult to be acquired and calibration errors propagate and magnify when moving along the cycle. Third, the direction of the evaluation steps is not reversible, meaning that a later step cannot influence or control a former step directly. A former step can only be adjusted after a whole cycle is finished. Finally, analyses usually only focus on the whole network or individual sections depending on different scale of models. They can hardly specify the impact of important sections to the whole network if the scale is macroscopic, or the influence of the road section to the whole network if the scale is microscopic. This paper introduces a methodology that, in essence, allows the reversion between the traffic step and emission step in the traditional cycle. Compared to previous researches, the new approach considers the environmental constraints as a part of the input for a macroscopic traffic model. By doing so, the environmental constraints can influence the traffic state in a direct way.

METHODOLOGY

In a macroscopic traffic model, traffic on a road link is characterized by three macroscopic variables: flow q, density k and average speed v. The three variables are related in stationary conditions by the traffic fundamental relationship v=q/k (Prigogine and Herman, 1971), thus only two of the three variables are independent. From this formula, a behavioral relationship, called traffic fundamental diagram, between two of the remaining independent variables is assumed to exist. Using this relationship traffic dynamics are modeled and evaluated. For an overview we refer to e.g. Hoogendoorn and Bovy (2001).

In an emission model, for each pollutant p, a formula is used to calculate emissions. On the level of one single road link, this formula can be written in a rather general way as:

$$Emission_p = q_i \times EF_p(v_i, T, Fleet, ..) = k_i \times v_i \times EF_p(v_i, T, Fleet, ..) \tag{1}$$

Here, q_i, v_i, k_i are respectively the traffic flow, average speed and density on link i, EF_p , whose unit is g/km • hour, is the emission factor for pollutant p. This factor can be a complex function of different parameters, for example, environmental temperature T and vehicle fleet composition, etc. We can rearrange equation (1) so that it gives the maximum density on a link that in turn respects all emission constraints:

$$k_{i,Max}(v_i) = \frac{1}{v_i} \min_{for\ all\ p} \left[k^p_{i,Max(v_i)} \right] = \frac{1}{v_i} \min_{for\ all\ p} \left[\frac{Emission\ Constraints\ of\ p}{EF_p(v_i, T, Fleet, ..)} \right] \tag{2}$$

In this formula $k_{i,Max}(v_i)$ is the maximal allowed density at a certain speed v_i, that avoids the emissions exceeding the maximal allowed levels. $k_i(v_i)$ is not allowed to exceed $k_{i,Max}(v_i)$. In our approach we develop a method to compare and adjust $k_{i,Max}(v_i)$ and $k_i(v_i)$ during the traffic simulation process instead of doing this after the simulation has completed. The process essentially leads to drawing up a revised fundamental diagram as illustrated in Figure 1. In this figure the density-speed and flow-speed versions of the fundamental diagram are given. In the density-speed diagram, the emission constraints line represents the maximal allowed density at a certain speed or the maximal speed at a certain density. Only traffic states to the left of the emission constraints line satisfy the emission constraints. As can be seen in the diagram traffic, state A is beyond the emission constraints line. The main idea of our approach is to force point A to move to the emission constraints line.

There are many methods of forcing point A to the emission constraint curve. For example, we could reduce only the traffic speed to arrive at state C or we could reduce the density but

retain the same speed to arrive at state B. Another method may consist of reducing the link capacity to the environmental capacity. This implies a shift of the fundamental diagram to the left. In this paper, we apply Equation (2) to limit the inflow of the link in order to ensure that the density satisfies the maximum allowed density (i.e. moving from state A to state B). Note that we cannot achieve state B by only reducing the density but we also need to maintain the speed at the same level. Otherwise, according to the fundamental diagram, the traffic state will move to traffic state D which does not satisfy the emission constraint. Reducing (only) the density again when at point D will eventually bring us to traffic state E where the maximal allowed density is too low, i.e. leading to a negative policy in terms of traffic efficiency. This would in fact considerably reduce the ability of receiving flow from incoming links, thus may cause congestion and queue in upstream links. As a result, the total capacity of the network would decrease significantly if we force state A to move to state E.
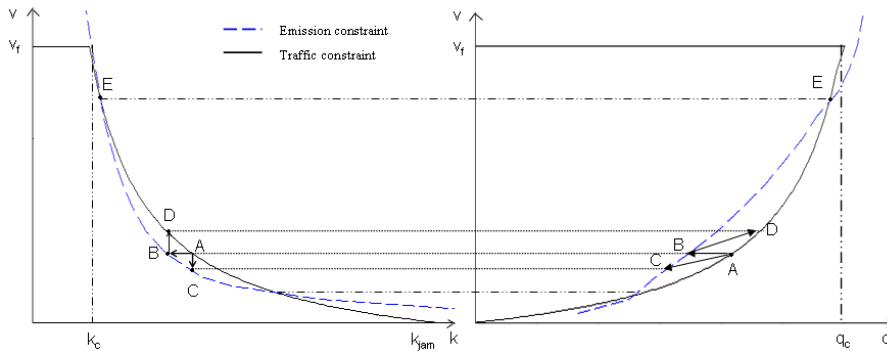

Figure 1: Emission constraints in relation with the triangular fundamental diagram

Some remarks need to be mentioned. First, the new emission-traffic diagram will inevitably also influence route choice. Traffic flows in links where emission constraints are exceeded will switch to other links which have higher travel time but lower emission. Second, modify driving behavior in order to attain the desired traffic pattern is an essential part of the proposed methodology and needs further attention in further research. There are several ways in which this change in driving pattern could be achieved. For instance, one could consider implementing a tolling scheme, another way would be to adjust signal settings to limit the number of vehicles entering specific links or one could possibly implement infrastructural changes to traffic links and intersections. And, finally, our approach could be used not only at the link level but also at the zone level using a macroscopic fundamental diagram for urban traffic and adopting access control to areas and sub-networks (Daganzo, 2008).

CASE STUDY

In order to test the model, a simplified network together with an origin-destination (OD) table reflecting three morning peak hours for the city of Leuven in Belgium was used. A new module was added to the Link Transmission model (Yperman, 2007) in order to meet the new fundamental diagram with the emission constraints. COPERT4 (Zachariadis et al., 1999) is the emission model adopted in this study. A stochastic dynamic route choice model is adopted, with the help of route generation from the program INDY (Bliemer et al., 2004). Emission constraints refer to European Air Quality Concentration Standards, and were adjusted to short time limitations. We refer to Xin et al. (2010) for more detailed information on the input data. The result of the case study shows that the total travel time increases (15.9% increase), since the capacity of the network decreases by introducing the emission constraints. Total emissions have risen (CO: 17.0%, NO_2: 19.2% and PM_{10} 19.0%) because of the increase in total travel time. However, the number of hours and the road length times the hours that emissions exceeded the standards has decreased sharply while emission rates remained approximately the same. The total number of hours that the emissions exceeded the

constraints decreased from 1165 hours to 502 hours from NO_2, and from 1181 hours to 596 hours from PM10 respectively. Constraints are still violated after importing emission constraints into the traffic simulation, and the main reason is that the density cannot be decreased to less than the maximal allowed density in heavily congested links. The sensitivity analysis suggests that stricter constraints (for example, set the maximum allowed excess emission 20% lower than the standards constraints) can result to 110% total travel time and only 35% excess emission hours to the standard emission. However, we should notice the absolute number of total travel time increase is very large. The sensitive analysis also indicated that the main roads in Leuven network are the most influenced links. Because we take the emission constraints into the fundamental diagram, and no optimization is used in this approach. The calculation time only increases 6.5% compared to the calculation without emission constraint. Although the optimization can tend to a better balance between total travel time lost and emission benefits, the much less calculation time is one benefit of the approach. Instead of a simple logit-based route choice model which is used in this case study, an improved route choice model is supposed to tend a better result and much less calculation time.

CONCLUSIONS

The major contribution of this study is the idea of integration of the fundamental diagram of traffic model and emission constraints. By applying this approach, the environmental constraints can directly suggest how traffic patterns should be at a network level to meet the emission levels. This approach can be used in traffic simulation, design and management studies as well as in real-time traffic control. The method is not dependent on specific traffic or emission models and can be applied at different spatial scales. In future works, the appraisal of the different methods that can be used will be identified and further refined. The approach will involve dispersion models which can reflect the step from emission rates to concentration levels in the traditional research cycle.

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