FROM ENVIRONMENTAL CONSTRAINTS TO NETWORK-WIDE ENVIRONMENT–FRIENDLY TRAFFIC PATTERNS: INVERTING THE PLANNING APPROACH FOR SUSTAINABILITY

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1. INTRODUCTION

The environment, especially in urban areas, is deteriorating at an alarming rate. Traffic emissions, especially nitrogen oxides (NOx), carbon monoxide (CO), and particulate matters (PM), are contributing to this process in a significant way. According to European Union statistics from 2006, transport contributes to 39% of total NOx emissions, 36% of total CO emissions, 18% of total non-methane volatile organic compounds (NMVOC) emissions and 18% of $PM_{2.5}$ in the 27 member states of the European Union (Eurostat Database, 2009). The sharp increase in the number of vehicles, both in developed and developing countries (European Commission, 2009; NBSC, 2007), 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.

Much work has already been done to reduce the impact of traffic to the environment. At the technological level, research is focused both on the improvement of engine efficiency to reduce the production of emissions as well as on the further elimination of emissions in the post-treatment process that takes place in the exhaust system of vehicles (Lenz et al.,1999; Schaefer et al., 1995). At the policy level, different measures and incentives are implemented to encourage people to choose environment-friendly vehicles, and to drive more efficiently (Silva et al., 2009; Flamm, 2009; Fischer, 2008). At the traffic level, the issues of improving driving patterns and discouraging the unnecessary use of vehicles are very important (Hansen et al., 1995; Beevers, 2005). In fact, the three different levels are not completely separate. The final traffic emissions are a result of a complex interaction at all three levels. There is a need for a tool that can evaluate the traffic emissions caused by different technologies as well as the effect of policy actions and the effect of different options in network management.

Traffic operations and emission levels can be adequately described by separate traffic and emission models, but integrating the results of these models can be difficult. The usual process is to first run a conventional traffic model for a whole area and to use the output of the traffic model as the input to the emission model. Depending on the output of the emission model we might choose to adjust our traffic management strategy and start a new run of traffic model and emission model in sequence. In this paper we will describe a methodology to integrate the traffic model and emission model that obviates this iterative process. The methodology suggested in this paper uses in fact an inversion of the usual process: environmental constraints directly influence the input parameters to the traffic model. The procedure works at the link level. It adjusts the traffic load of links with high emissions in order to design environment-friendly traffic patterns. These patterns are the basic for traffic management strategies. (Immers, 1991).

The flow and speed on each road link is traditionally determined and governed by the so-called fundamental diagram of traffic flow (Greenshield, 1934), which represents the basis of most dynamic traffic models and also of the one used in this study. The key process in our approach and the main contribution of this research is to adjust this diagram on the basis of environmental constraints. Using this adjusted diagram in a conventional traffic assignment program leads to flow patterns that meet environmental standards for a whole area at once.

The paper is composed as follows: In section 2, a short review is given of existing research carried out on the integration of traffic models and emission models. It also discusses the limitations of the different approaches. Section 3 describes the approach used in this paper. We explain the construction of an adjusted fundamental diagram that meets environmental constraints and we also define the traffic and emission models that can be used for this construction. In section 4 the results of a case study using the network of the city of Leuven in Belgium, together with a sensitivity analysis, will be presented and analyzed. Section 5, finally, contains the conclusions and recommendations.

2. THE INTEGRATION OF TRAFFIC MODELS AND EMISSION MODELS

Traffic models reflect and simulate traffic situations in networks or of single vehicle-driver units. They can be classified into three categories. Macroscopic models, such as TransCAD (Caliper Corporation, 2006), INDY (Bliemer et al.,2004) and many others, describe both traffic flow propagation and trips on an aggregate level, and traffic is assumed to be a fluid-like continuum. Mesoscopic models, such as CONTRAM (Taylor, 2003), move individual (packets of) vehicles according to macroscopic traffic flow relations. Vehicle movements are governed on an aggregate level, while trip-maker decisions such as route choice are made individually. Microscopic models, such as PARAMICS (Quadstone , 2000) and VISSIM (PTV, 2005) are more detailed and describe traffic flow on the level of individual vehicles. Trip-maker decisions such as route choice are represented on the individual level as well.

Emission models contain mathematical or physical relations between traffic emissions and their influencing factors. COPERT and MOBILE are pioneer emission models (Zachariadis, T. et al., 1999; U.S. EPA, 2003), developed respectively by the European Environment Agency and the United States Environmental Protection Agency (The U.S. EPA converted MOBILE to MOVES in December 2009). Their approaches are similar. They both use statistical regression from dynamometer measurement results, considering many parameters such as mileage, technology standards, deterioration, speed, temperature, I/M data (Inspection/Maintenance) and fuel quality. However, these models simplify the driving pattern, an important factor influencing emissions. Only few parameters, such as average speed and road types, can be adopted as adjustment factors for different driving patterns to convert between laboratory standards and road practice. Variables related to speed, such as acceleration, which considerably influence emissions (El-Shawarby et.al., 2005), are disregarded. In spite of their shortcomings, but because of their modest data requirements, average speed-based models are widely used nowadays, especially for macroscopic estimations for national or urban areas (Smit et, al. 2007).

More detailed traffic parameters were used in later emission models. The University of California developed the IVE model (Lents et. al. 2004), which applies VSP (Vehicle Specific Power) and Engine Stress as important traffic parameters. VSP is a function of speed, acceleration and grade and its physical significance is the ratio of vehicle instance power and mass. CMEM is a physical model (Boriboonsomsin, 2008), which considers both engine load and the physical and chemical creation principles of pollutants. The data demands however are high. No less than 47 parameters have to be supplied. For this reason the model is mainly used as a microscopic model focusing on the link or road section level.

Emission inventories may be viewed on different spatial scales, depending on the purpose of the analysis and the applied traffic models and emission models. Figure 1 shows the different spatial scales.

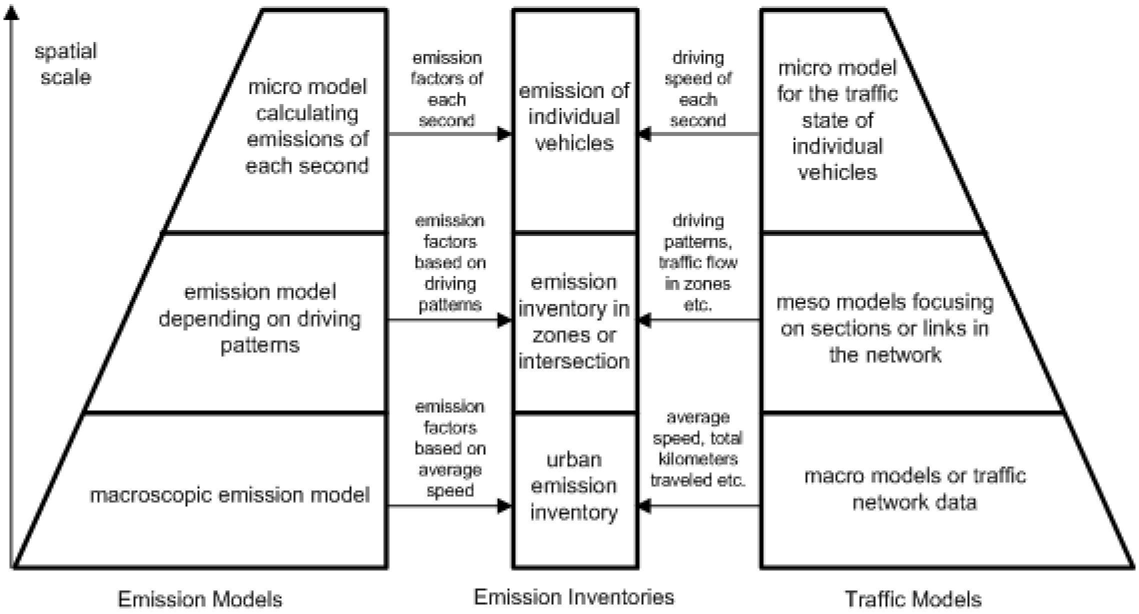

Figure 1. Different scales of traffic models and emission models

Macroscopic traffic models combined with macroscopic emission models can be used to study larger areas (Wang et al, 2009; TMLeuven, 2007). We can also combine microscopic traffic models with microscopic emission models as was done by (Boriboonsomsin, 2008) and (Noland et al, 2006). Sometimes microscopic traffic models are used together with macroscopic emission models for studies that focus on microscopic or mesoscopic areas (Mensink et al, 2008, Nesamani et al, 2006. Cook et al, 2006). The choice of the traffic model determines the accuracy of the integration with the emission model. Macroscopic traffic models generally do not allow detailed analysis of emission concentrations, for instance at hot spots like intersections. Microscopic traffic models are certainly more detailed and can also account for microscopic changes in the traffic pattern and in the driving cycles, like changes in speed variations, stop-and-go dynamics, etc. However, their reliability strongly depends on the calibration of their driving behavioral parameters, which are often left in default factory settings in practice. This very often yields unrealistic results in terms of estimated emissions, and generally forces the traffic planners to extrapolate the results to the macroscopic level (Viti et al. 2008).

The traditional research method in an environmental study usually involves following the cycle: Policy ⇒ Traffic ⇒ Emission ⇒ Concentration ⇒ Health Impact ⇒ Economics ⇒ Policy. Many models are available for the evaluation phase between two consecutive steps and necessary parameters are not difficult to define for a given step. As can be seen in the cycle above, the output of a traffic model is one important part of the emission model input. Emission inventories are the results from the integration of traffic models and emission models. These emission inventories are compared to the environmental constraints and are analyzed in the later steps of the cycle.

However, there are some drawbacks to using the traditional cycle mentioned above. Firstly, the analysis cycle is too long, causing higher uncertainty in the calculations and it prolongs the analysis time. Secondly, some necessary data are rather difficult to acquire for certain types of research and error in calibration propagates and magnifies when moving along the cycle. Thirdly, the direction of the evaluation steps is one-way, 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 detailed sections depending on different scales of models. They can hardly specify the important sections influencing the whole network if the scale is macroscopic, or the influence of the road section to the whole network if the scale is microscopic.

As mentioned in the introduction, this paper introduces a methodology that, in a sense, reverses the traditional cycle by going from environmental constraints to network requirements. In contrast to previous research this approach uses the environmental constraints as part of the input for a macroscopic traffic model. In this way the environmental constraints can adjust the traffic state in a direct way.

3. PROPOSED METHODOLOGY TO INTEGRATE TRAFFIC MODELS AND EMISSION MODELS

In this section of the paper we first explain the basic idea of our approach. This is followed by a discussion of the specific traffic and emission models that we have selected to illustrate our proposed methodology.

3.1 Basic approach

3.1.1 The traffic model

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 by the formula $v = q / k$, thus only two of the three variables are independent. A behavioural relationship between two of the remaining independent variables is assumed to exist. Greenshields (Greenshields, 1934) first proposed a linear relationship between traffic speed v and density k, that was based on a rather limited range of measurements. The linear speed-density relation converts into a parabolic relation between density and traffic flow. Later researchers improved the findings of Greenshields. Nowadays, for a single link, the fundamental diagram of traffic flow as it is called, relating traffic density to traffic flow, is often approximated by a triangular diagram.

The triangular diagram is used because of its advantages in dynamic traffic modelling (Newell, 1993).

The fundamental diagrams can be expressed in a mathematical form. For example, the equation corresponding to Greenshields diagram is:

$$q(v) = v \cdot k_{jam} \cdot \left(1 - \frac{v}{v_f}\right) \tag{1}$$

In this equation k_{jam} and v_f correspond respectively to the jam density and free flow speed on a road link.

3.1.2 Emissions

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 as:

$$Emission_p = q_i \times EF_p(v_i, T, Fleet, ..) = k_i \times v_i \times EF_p(v_i, T, Fleet, ..) \tag{2}$$

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*. It is a complex function of different parameters, for example, environmental temperature *T* and vehicle fleet etc.

The emission formula can be used after a traffic simulation to calculate the pollutant concentrations in order to check whether the traffic conditions satisfy the emission constraints for each pollutant.

We can rearrange equation (2) so that it gives the maximum density on a link that respects all emission constraints:

$$k_{i,Max}(v_i) = \frac{1}{v_i} \min_{for\ all\ p} \left[k^{p}_{i,Max(v_i)} \right] = \frac{1}{v_i} \min_{for\ all\ p} \left[\frac{\text{Emission Constraints of } p}{EF_p(v_i, T, Fleet, ..)} \right] \tag{3}$$

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.

3.1.3 Integration of Traffic and Emissions

The process essentially leads to drawing up a revised fundamental diagram as illustrated in Figure 2.

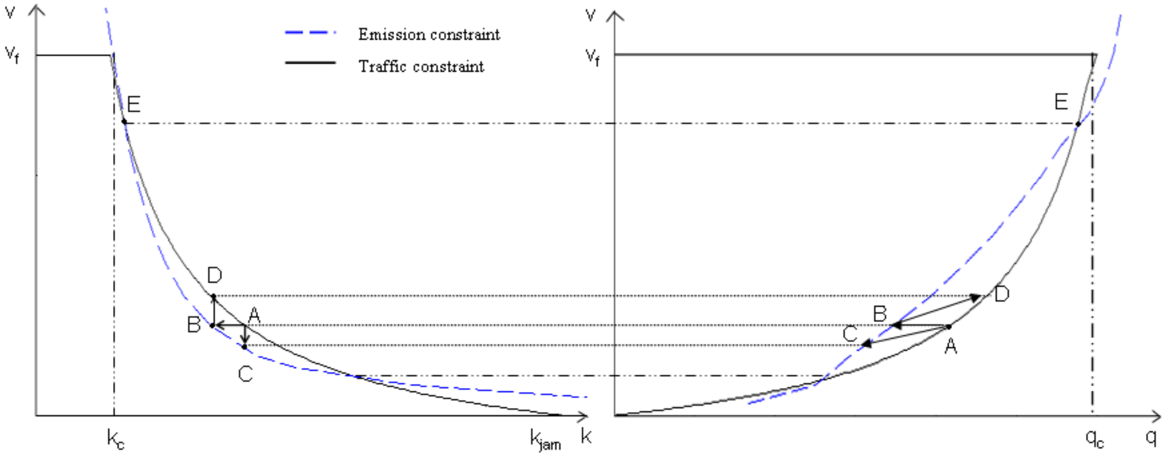

Figure 2. Emission constraints to triangular fundamental diagram

In Figure 2 the density-speed and flow-speed versions of the triangular density-flow 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 consists 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 (3) to limit the inflow of the link in order to ensure that the density satisfies the maximal allowed density (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 revert 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. That considerably reduces the ability of receiving flow from incoming links, thus may cause congestion and queue in incoming links. As a result, the total capacity of network decreases intensely if we force state A move to state E.

Some remarks are in order. Firstly, the new emission-traffic diagram will also influence route choice. Traffic flow in links where emission constraints are exceeded will switch to other links which have higher travel time but lower emission. Secondly, modifying driving behaviour in order to attain the desired traffic pattern is an essential part of the proposed methodology. There are several ways in which this change in driving pattern could be achieved. 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 (Daganzo, 2008). All of these issues, i.e changes in route choice, ways to modify driving behaviour and using our approach at the zone level, are the subject of ongoing research and will not be addressed in this paper.

3.2 Selection of the traffic model: Link Transmission Model

Most traffic models can be adopted for our approach, but there are still some requirements. A first requirement for the traffic model is that it should be possible to adjust traffic flows at any moment during the simulation. Secondly, the traffic state at any moment should be known, because the emission factors are directly dependent on this traffic state. Finally, it should be easy to update the traffic model during the simulation. All these requirements are best met by using a dynamic traffic model instead of a static one. We selected the Link Transmission Model (LTM) (Yperman, 2007) as a traffic model in our research.

LTM is a macroscopic dynamic network loading model that combines high realism in the representation of queue propagation and dissipation with computational efficiency. It is consistent with simplified first order kinematic wave theory. This theory assumes a functional relation between traffic flow and density, captured in the triangular shaped fundamental diagram. As abstraction is made of the multi-commodity framework of LTM (where each commodity corresponds to a specific pre-defined route), traffic is represented by the total cumulative number of vehicles $N(x, t)$ at the upstream end and the downstream end of each link. Traffic flow, density, average speed, free flow speed, link capacity can be acquired in each time slice by post-calculation and looking into input data. The LTM algorithm can be divided into three steps, executed for every time interval Δt. The first step consists of the processing of a link model. For each node, the sending flows at the downstream end of all incoming links and the receiving flow at the upstream end of all outgoing links are calculated. The sending flow $S_{ij}(t)$ at time t is defined as the maximum amount of vehicles per time unit that could leave incoming link i and enter outgoing link j during time interval [t-Δt, t], assuming an infinite capacity for link j. The receiving flow $R_j(t)$ of outgoing link j at time t is defined as the maximum amount of vehicles per time unit that could enter link j during time interval [t-Δt, t], assuming an infinite demand.

The next steps incorporate the processing of a node model. For each node, the flows $q_{ij}(t)$ (veh/h) that are transferred from every incoming link *i* to every outgoing link *j* are determined. The last step is an update step: for each node, the cumulative vehicle numbers at the downstream ends X_i^L of the incoming links i and at the upstream ends X_i^0 of the outgoing links *j*, are updated. We refer to Yperman (2006) and Tampère (2009) for more detailed information on the Link transmission Model.

In order to implement the proposed methodology, we insert an emission module between the link model and the node model. After processing the link model for a certain time slice, the traffic variables of the link during the time slice can be estimated. Using these traffic variables, we calculate the emission factors, by means of an emission model. These emission factors are used to determine $k_{i,Max}(v_i)$, as shown in Equation (3). If the traffic density of the link is larger than $k_{i,Max}(v_i)$, the process returns to the beginning of the time interval, and recalculates the receiving flow $R_j(t)$ in order to satisfy the maximal allowed density. If the recalculated $R_j(t)$ is negative, then $R_j(t)$ is set equal to zero, because it means that the emissions have already been exceeded and that no vehicle is allowed to enter. The process is illustrated in Figure 3.

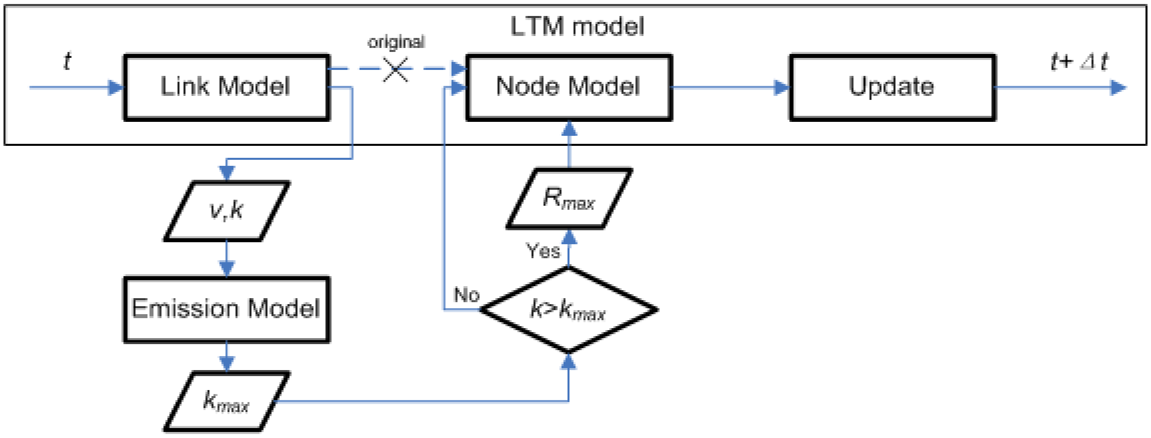

Figure 3. Emission Constrains Process for LTM model

3.3 Selection of the emission model: COPERT4

The most important issue to be considered in the selection of an emission model is the spatial scale. Since all simulations are done at link level in the network, the emission model should also calculate the emissions at the link level. Seen from this viewpoint, it would appear that both microscopic and macroscopic models would be the suitable types of model. However, the more detailed the model is, the more detailed are the required input data. Unfortunately, LTM is not able to calculate the detailed speed variables necessary for a microscopic emission model, and thus we selected a macroscopic / mesoscopic emission model for our investigations. We developed a maximal capacity function, similar to Equation (3), based on the emission factors as calculated by COPERT4. As explained earlier, COPERT is a macroscopic model financed by the European Environment Agency. The latest version is COPERT 4. The input traffic parameters of COPERT 4 include average speed and road type. If we assume traffic composition in the urban network to be constant and not changing according to flow and road type, the average emission factors can be expressed as a function of average speed. Figure 4 shows this function for the city of Leuven, Belgium.

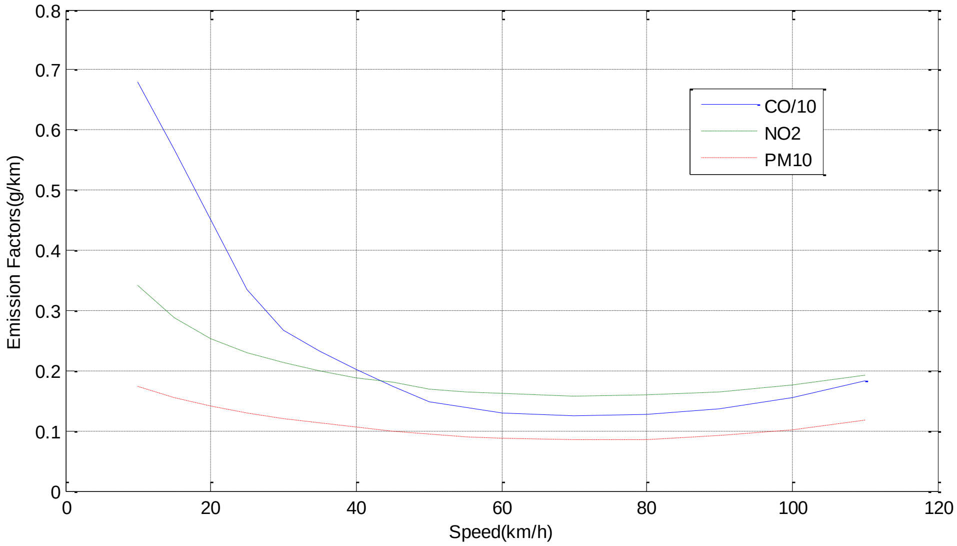

Figure 4. Emission factor functions with speed for the city of Leuven

Noise emission also plays an important part in the environmental impact of urban traffic, thus noise should also be considered in network management. In our study we adopted a simple noise model originating from a Dutch Legal Standard, depicted in equation (4):

$$L_{\max} = 10\log_{10}\left[\frac{q\cdot\left(p_l \times 10^{Y_l} + p_m \times 10^{Y_m} + p_z \times 10^{Y_z}\right)}{d}\right] \tag{4}$$

where:

$L_{\max}$ = the maximal allowed noise level in dB(A)
q = traffic flow (veh/hour)
Y = noise emission parameter
Y_l = $5.12 + 0.021u_l - \log_{10} u_l$
Y_m = $6.84 + 0.009u_m - \log_{10} u_m$
Y_z = $7.62 + 0.003u_z - \log_{10} u_z$
u_l, u_m, u_z = average speed km/hr

p_l , p_m , p_z = fraction of vehicles
d = distance of facade to road axis in meters
meaning of the suffixes: l = passenger cars, m = medium-heavy traffic, z = heavy traffic

If we assume the speeds *v* of different vehicle types to be the same, than we can rearrange Equation 6 to calculate the maximal allowed density for noise. This results in Equation (5) comparable to Equation (3).

$$k_{noise,\max} = \frac{1}{v}\left(\frac{d}{{}_{l}\times 10^{Y_l} + p_m \times 10^{Y_m} + p_z \times 10^{Y_z}} \right) \cdot 10^{L_{\max}/10} \qquad (5)$$

4. CASE STUDY

In order to test the model, a simplified network together with an origin-destination (OD) table for the city of Leuven in Belgium were used. The network contains 61 nodes, comprising 25 centroids and 236 one-way links. (See Figure 5).

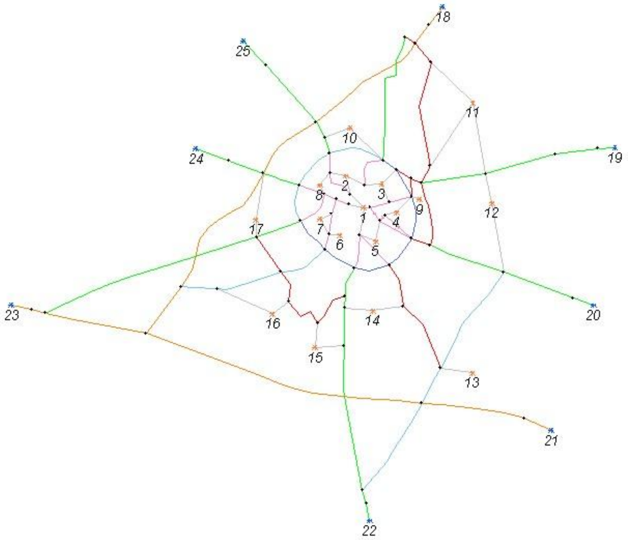

Figure 5. The network of Leuven

4.1 Input data

Four groups of input data can be distinguished in this case study. First we have the link parameters, including capacity, free flow speed and jam density. They are based on the assumption of a triangular shaped fundamental diagram and have different values for different link types. Next to the link parameters we have the Origin-Destination table describing a typical morning peak hour for Leuven and finally the chosen routes from the model of INDY. In our study route choice patters are fixed, we only consider density and speed variations.

The third group of input data concerns pollutant functions. Besides noise, we study the emissions of CO, NO_2 and PM_{10}. Data on traffic fleet composition, mileages, and road type shares for Belgium are obtained from COPERT Database. The speed–emission factors functions are calculated by COPERT 4 with a speed bound from 10 km/h to 110 km/h because COPERT 4 adjusted the speed dependency factors to that bound. For speeds that are not in this bound, we use the boundary values. Figure 4 shows the emission factors functions. Noise is calculated by Equation (5).

The last group of input data involves the environmental constraints. For the emission constraints we adopted the regression results for different road types and concentrations from the dispersal model Caline4 (CDT, 1989). The pollutant concentrations refer to European Air Quality concentration standards, and were adjusted to brief period limitations. We should mention that using the assumptions from COPERT for one part of the model and the assumptions from Caline4 for another part may result in some loss of integrity of the calculation results. In this example we think this is acceptable, but in practical applications it is advised to use a consistent suite of models. Four scenarios containing different series of constraints are studied. Scenario I has no emission constraints at all. Scenario II has constraints on the emissions of CO, NO_2 and PM_{10}. In Scenario III we assume only a constraint on the emission of noise and finally Scenario IV has constraints on chemical as well as on noise emissions. The emission and noise constraints for local streets are shown in Table 1.

Table 1. Emission constraints

		Scenario I	Scenario II	Scenario III	Scenario IV
constraints	CO	-	30 000g/km.h	-	30 000g/km.h
	NO_2	-	240g/km.h	-	240g/km.h
	PM_{10}	-	120g/km.h	-	120g/km.h
	Noise	-	-	70dB(A)	70dB(A)

- = no constraint

4.2 Results

Table 2 shows the results of the simulation. It is not surprising that the total travel time typically increases going from Scenario I to IV, since the capacity of the network decreases if we decrease the allowed density. Although total emissions have slightly risen because of the increase in total travel time, the number of hours and the number of length×hours that emissions exceeded the standards has decreased sharply while emission rates remained approximately the same. The constraints are still exceeded in Scenario IV. There are two reasons: on the one hand, the density cannot be decreased to less than the maximal allowed density in heavily congested links; on the other hand, in practice, the traffic follows the fundamental diagram, which means that when the density decreases the speed is not constant but will increase. In our approach, we assume that speed remains constant when we adjust the density. But in the simulations, speed increases due to reduced density. So the actually attained state is point D in Figure 2, instead of point B.

Surprisingly, no effect, even a negative effect, of the noise constraint can be observed in Table 2. But in fact, the noise constraint exerts a positive effect to the number of hours or length×hours that emission exceeds the standards. This will be explained in the sensitivity analysis section of the paper.

Table 2. Summary of result

		Scenario I	Scenario II	Scenario III	Scenario IV
Total travel time (hour)		5278	5851	5926	5995
Total Emission (kg)	CO	502.0	510.5	555.8	563.1
	NO_2	52.4	53.4	57.1	58.0
	PM_{10}	29.7	30.2	32.3	32.8
Emission rate (g/h)	CO	95.1	87.3	93.8	93.9
	NO_2	9.9	9.1	9.6	9.7
	PM_{10}	5.6	5.2	5.5	5.5
Total emission exceeding the constraints(g)*	CO	0	0	0	0
	NO_2	245.1	118.6	186.5	114.8
	PM_{10}	167.4	96.3	136.8	84.4
Number of hours that emission exceeded constraints*	CO	0	0	0	0
	NO_2	245	72	103	59
	PM_{10}	195	81	104	63
	Noise	415	292	412	370
	Any	422	305	418	386
Amount of Length×time that emission exceeded constraints (km.hour)*	CO	0	0	0	0
	NO_2	190	105	75	44
	PM_{10}	195	117	75	46
	Noise	415	384	551	540
	Any	422	389	553	547

* as compared to constraints of Scenario IV

4.3 Sensitivity analysis

By means of a sensitivity analysis we investigated the effects of the input data on the amount of chemical emissions and noise emissions for the network of Leuven.

4.3.1 Sensitivity to different pollutants.

Three pollutants besides noise are studied in this research, and they have a different weight on the flow constraints. Figure 6a and b shows the maximal allowed traffic density for the four pollutants used in the case study with the norms (constraints) of scenario II in Table 1. The line 'traffic' in the figures indicates the original traffic fundamental diagram.

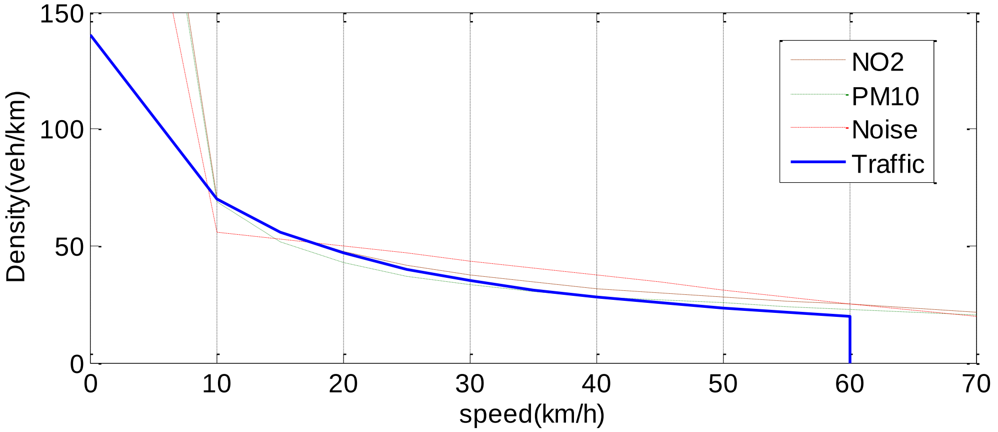

Figure 6a. maximal allowed density for different emissions (NO_2, PM_{10}, Noise)

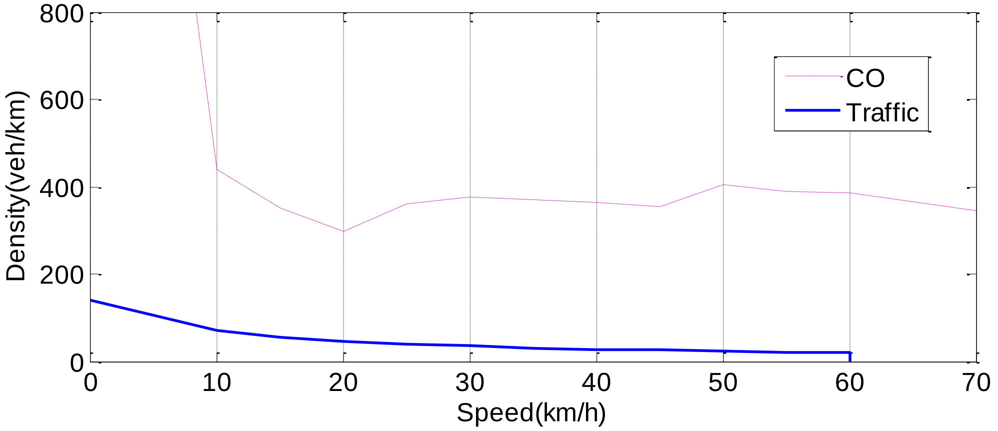

Figure 6b. maximal allowed density for different emissions (CO)

It is clear from Figure 6b that CO puts no constraint on the traffic since the maximal allowed traffic density for CO is much larger than the actual traffic density. The results for CO in Table 2 appear to support this. However, the three other pollutants may dominate the overall maximal allowed density for different speeds.

4.3.2 Sensitivity to the level of the emission norms

Figure 7 and Figure 8 show the maximal allowed density of NO_2 and noise at different emission standards. In Figure 7, the allowed traffic density curve for NO_2 at a norm of 360g/km remains above the traffic density curve. That means NO_2 puts no constraints to traffic if we allow such high levels of NO_2 emissions. There is only little influence to traffic when the NO_2 constraint is at 240g/km, while the influence to traffic increases sharply if we limit the NO_2 emissions to 120g/km. We find similar results for noise and PM_{10}.

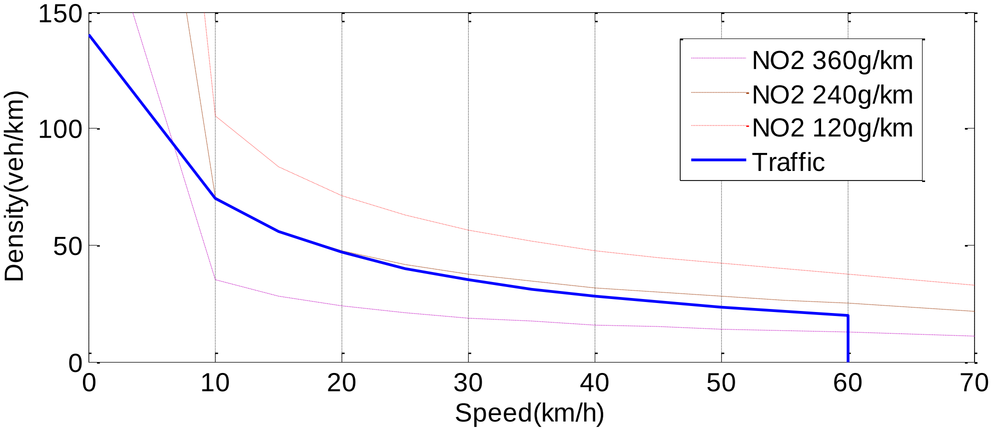

Figure 7. Maximal allowed density at different NO_2 norms

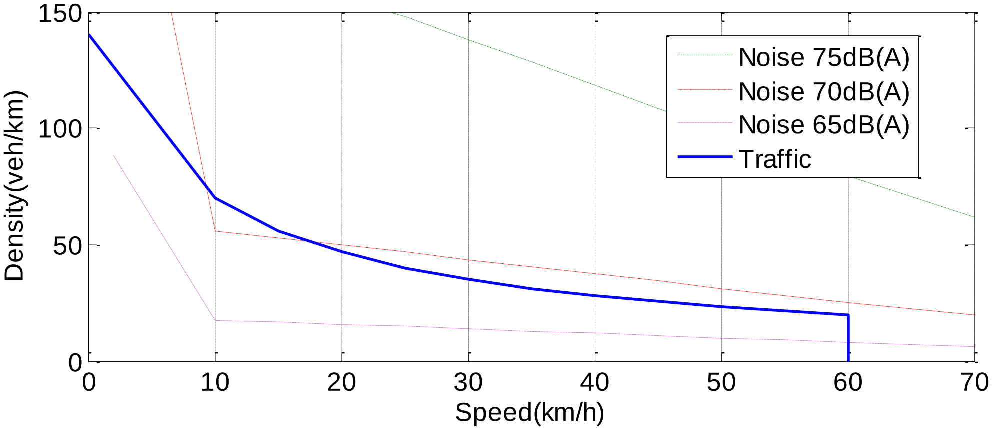

Figure 8. Maximal allowed density at different noise norms

Table 2 showed a negative effect for noise. Figure 9 depicts the distribution of the noise-level for different noise norms. The distribution of the noise-level is concentrated in a small zone around the constraint level. Introduction of noise constraints will attract the noise distribution from both sides to the centre of the constraints. The noise levels exceeding the constraints are mainly caused by the increase of speed. Generally, noise constraints limit the excess of noise to a small zone near the constraint. Although the amount of length x time that noise levels exceeded the constraint without a noise constraint being in effect is less than that with a noise constraint in effect, the latter one performed better. On the other hand, the total travel time increases sharply after the noise constraint curve crosses the traffic density curve, as shown in Figure 10.

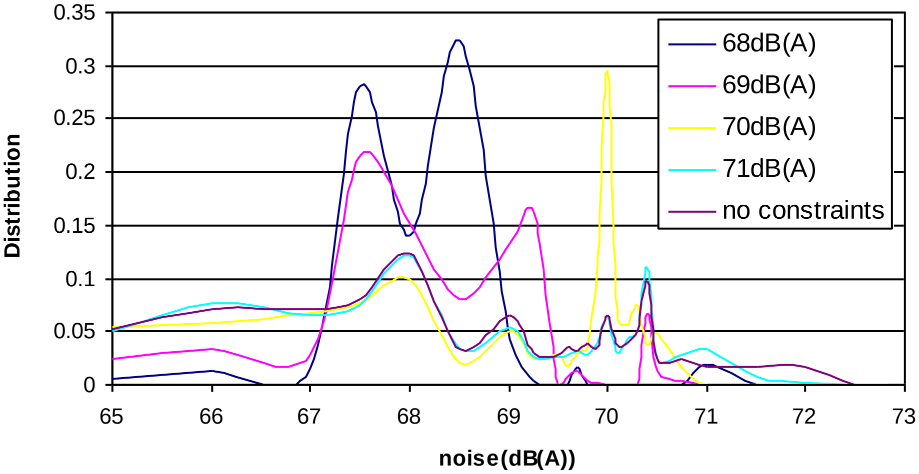

Figure 9. Noise distribution at different noise constraints

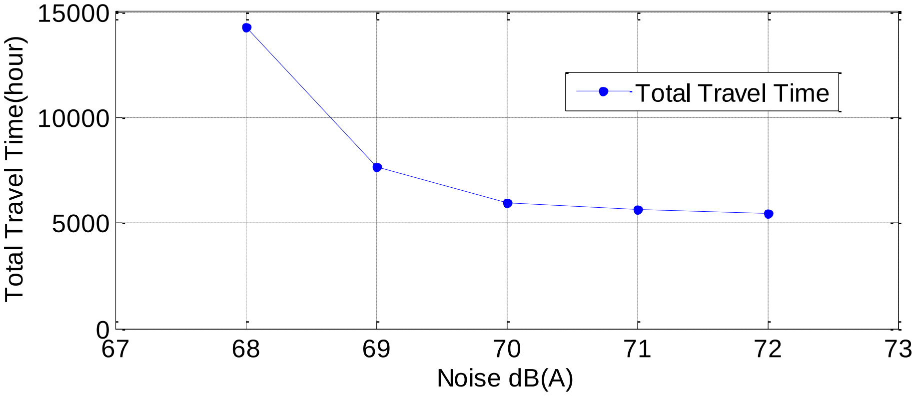

Figure 10. Total travel time at different noise constraints

4.3.3 Sensitivity to emission factors

Equation (3) demonstrates that the maximal allowed traffic density is proportional to the ratio of emission constraint to emission factor at a given speed, meaning that the sensitivity to emission factors is the inverse of the sensitivity to emission norms. Besides the influence of emission factors we need to investigate the dependency on speed. The maximal allowed traffic densities caused by constraints on NO_2 emissions corrected for speed are shown in Figure 9. The speed correction factors are relative to an average urban speed of 25km/h.

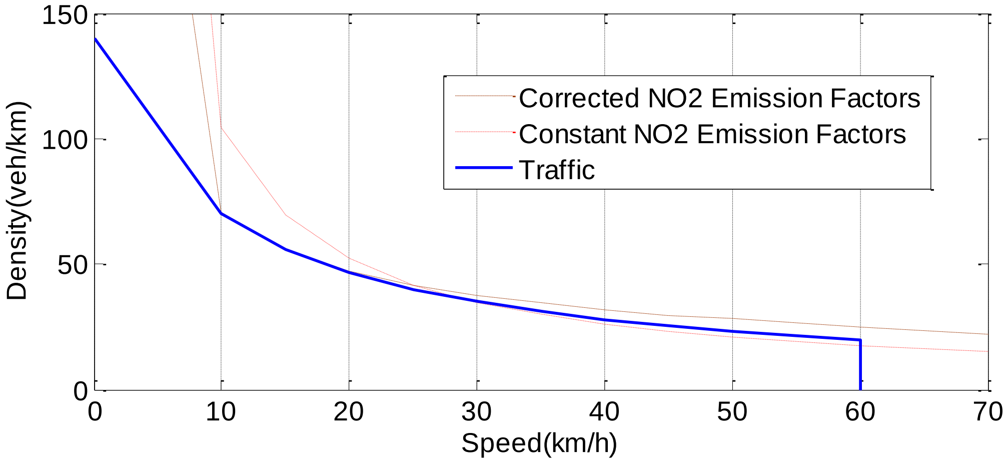

Figure 11. maximal allowed density of NO_2 with or without speed correction factors

As shown in Figure 11, emission factors without speed correction may overestimate the maximal allowed traffic density in low speed zones but underestimate it in high speed zones.

Other important results of the sensitivity analysis are:

- Road type: increasing the capacity, free flow speed and jam density of the network all increases the impact of the constraints.
- Traffic demand: The impact of constraints increases with an increasing traffic demand. However, the impact starts to decrease when the traffic demand becomes too high. Then the traffic becomes the main constraint in heavily congested conditions.

5. CONCLUSIONS AND RECOMMENDATIONS

The major contribution of this study is the idea of adjustment of the fundamental diagram of traffic flow on the basis of emission constraints and by doing so inverting the traditional research cycle used in an environmental study. By applying this approach, environmental constraints have a direct influence on the traffic patterns for a whole area. This approach can be used in traffic simulation studies as well as in real-time traffic control. The latter application however was not dealt with in this paper. The method is not dependent on specific traffic or emission models and can be applied at different spatial scales.

A significant problem is an appraisal of the different methods that can be used to make the traffic behave according to the modified fundamental diagram. Travel time increases if we want to adhere to environmental constraints, meaning that an optimal balance must be found between increasing travel time and decreasing emissions. Different traffic measures will influence traffic patterns in a different way, and these differences should be clearly identified.

In our case study, we did not consider a change in route choice. In practice, route choices are bound to change if we influence traffic densities, speeds and consequentially travel times. Taking the changes in route choices behaviour into consideration could be possibly result in a better use of network capacity. In future work, we intend to develop a traffic model integrating route choice behaviour.

Emission constraints become important when the emission constraint line crosses the traffic constraint line. An inversion approach from concentrations to emissions (between dispersal models and emission models) needs to be developed in order to determine precise emission constraints. This is a complex issue because dispersal models are space-dependent. This means, for example, that the emissions of crossing or parallel links have a combined effect on pollutant concentrations.

6. ACKNOWLEDGEMENTS

First of all, I would like to thank Jim Stada for his comments on the paper and English writing. I am also grateful to the project European Database of Vehicle Stock for the Calculation and Forecast of Pollutant and Greenhouse Gases Emissions with TREMOVE and COPERT funded by the European Commission DG Environment for their traffic data of Belgium.

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