SIMULATION OF EXHAUST GAS POLLUTION WITHIN AN EVENT-DRIVEN MULTIMODAL DYNAMIC TRAFFIC MODEL

E. CORNELIS
FUNDP (University of Namur)
Transportation Research Group (TRG)
rue de Bruxelles, 61, 5000 NAMUR, BELGIUM

B. MASQUILIER
FUNDP (University of Namur)
Transportation Research Group (TRG)
rue de Bruxelles, 61, 5000 NAMUR, BELGIUM

PH. TOINT
FUNDP (University of Namur)
Transportation Research Group (TRG)
rue de Bruxelles, 61, 5000 NAMUR, BELGIUM

Abstract

We discuss the combination of an event-driven multimodal dynamic traffic model (PACSIM) with models for the estimation of pollution caused by exhaust gasses in a urban environment. Then nature of the PACSIM model and the reasons for considering it in the framework of pollution assessment are first discussed. We then consider the particular pollutant emission models used and discuss their scope and parameters, as well as the availability of the latter within PACSIM. We conclude the paper by illustrating the use of the combined traffic/pollution model in the context of a speed enforcement policy within selected urban neighbourhood zones.

INTRODUCTION

Public awareness for the environment is often thought to be a major development of the last decade, and the quality of life in cities is part of these emerging and widely spread concerns. Among the drawbacks of urban life, one often mentions the level of pollution, mostly resulting from the ever growing traffic. It is therefore natural for the public decision makers to consider strategies that aim at reducing this pollution as much as possible, and, as a consequence, to search for tools for the assessment of the effects of these strategies. The literature on this topic is vast: see Krupnick *et al.* (1997) for a recent survey, and the references therein.

If an analysis of the pollution caused by traffic is possible on the basis of field measurements of certain pollutants such as CO, NO_x or heavy metals, this technique cannot be applied for assessing the effects of policies not yet implemented. One therefore needs modelling tools whose purpose is to predict global and local pollution levels depending on scenarii associated with specific political decisions. In what follows, we focus on gas pollution caused by urban vehicles (cars and busses), a major source of urban environment deterioration.

Several aspects of a "pollution reduction scenario" are of interest. The first is its dependence on the behaviour of car (and other vehicles) users when faced with evolving conditions of traffic, these conditions being themselves influenced by strategies to alter the modal choice in order to favor public transports, or with advanced driver information systems, or with road pricing, whenever these policies may be applied. The second is the temporal evolution of the pollution level, both globally and at the scale of specific city areas, depending on various factors such as weather conditions, occurrence of traffic incidents and the general congestion at peak hours.

At this point, it soon becomes clear that modelling tools with the capacity to estimate all these parameters must rely on a relatively detailed description of the traffic itself, combined with the use of similarly detailed emissions models for urban vehicles. In particular, it is important to be able to distinguish among the different types of these vehicles, and among the different pollutants. Moreover, if one is interested in dynamic and behavioural prospective, the traffic description must itself be sensitive to those parameters. In other words, we need to build pollution evaluation tools on detailed, dynamic and behaviourally sensitive traffic models.

The purpose of this paper is to describe how such a combination of detailed pollution analysis and traffic model of the type discussed above can be made effective. It is organized as follows. Section 2 outlines the main features of PACSIM, the urban traffic model considered here, while Section 3 discusses the techniques used to assess pollutant emissions by urban vehicles and their relevant characteristics. An example of application of the combined traffic-pollution models is described in Section 4. Finally, conclusions are presented in Section 5.

THE TRAFFIC MODEL

We have stated above the necessity to consider a dynamic and behaviourally sensitive model of traffic which is sufficiently detailed to represent the different traffic situations (congestion, queues or free flow) for which distinct pollution characteristics are known. We have, in this paper, chosen to use the PACSIM model produced by the authors' transportation research group. PACSIM was originally initiated with the support of the DRIVE I European program (IMAURO project) and developed further with the support of the impulse program (Services of the Belgian Prime Minister). The purpose of this note is not to describe this model again (see Dehoux and Toint (1991), Toint (1994), Cornélis and Toint (1998) or Cornélis (1997) for further details), but we still need to outline its main features in order to clarify how pollution models can be built on it.

The vehicle movements

Even if it can be used to model inter-urban situations, PACSIM is typically a model for the assignment of traffic in urban areas. As a result, it focusses on simulating the movement of vehicles (private and public) along the streets of an urban network, and, most importantly, across its junctions. For this simulation to be realistic, several elements of the urban network must be taken into account. The first is that traffic flow speed along streets (far from junctions) does depend on vehicle density. The second is that not all movements are allowed at a typical junction: for instance, left-turns may be forbidden by the design of the junction or by appropriate signposting. Furthermore, junctions are controlled by traffic lights or by priority rules. The detailed description of these (including light phases and synchronisation) must therefore be correctly and completely represented in the model. When traffic density increases, the junctions' and streets' capacities may be exceeded, in which case queues of vehicle build up, with the well-known spill-back effect that a queue at a junction might block another neighbouring one. We will not expand further on these characteristics. But we observe that specific elements of the vehicles' movements are available from the simulation, including the amount of time a particular vehicle spends in a queue, the time elapsed since it departed from its origin, the distance it has already travelled and its current speed. Furthermore, the type of the vehicles is also known.

Dynamics and transient effects

For the control or analysis of pollution scenarii centered on transient phenomena (such as the occurrence of traffic incidents), dynamic transportation models seem unavoidable. This is also true if the temporal evolution of pollution levels is of interest. The passing of time is modelled, in PACSIM, using the notion of event-driven modelling. At variance with models like DYNAMIT (Antoniou *et al.*, 1997), METROPOLIS (de Palma and Marchal, 1996) or DYNASMART (Jayakrishnan *et al.*, 1994) that use time-slices of predetermined length (for which the movements of vehicles and users in the network are successively computed and accounted for in suitable network statistics), PACSIM views time as the succession of a number of events. These events are of two distinct natures. The first type of event is associated with true physical event happening in the transportation network itself, as occurrence of congestion or bad weather conditions, traffic light changes, arrival of cars at intersections, up- and downloading of passengers at public transport, road works or traffic accidents. The second type of event is associated to the transfer of traffic information: detectors actuation and information transmission across the communication network. These two types of events are then scheduled within PACSIM, according to parametrized priority rules.

In this framework, each movement in the network, once initiated, is assigned its own completion time, at which further action might be necessary. For instance, the arrival of a vehicle at a signalised intersection typically means that this vehicle queues up to the next green phase (with the typical pollution characteristics of a queuing vehicle). Observe that not every event generates pollution, but that their successive occurrences is the fabric of our traffic description.

Behavioural sensitivity

Two particular aspects of aggregate users' behaviour have a direct impact on pollution estimates: the mode choice and route (between the origin and destination of a particular trip) decisions, and all combinations of them. These decisions can be broadly split into two phases (see Ben-Akiva *et al.* (1992)), both driven by behavioural theory: the user knowledge is asserted first, followed by some choice between the decisions that are possible in the restricted context of this knowledge. The behavioural mechanism that drives PACSIM is organised along two complementary stages, corresponding to these two phases. We briefly describe them in the case of route choice.

The network as perceived by the driver is first defined according to the following steps.

- A "perceived network" is built, that contains a detailed view of the links and nodes in the surroundings of anchor points, with the level of detail fading away with distance. These anchor points represent parts of the network that are well known to the user (see Golledge and Stimson (1987)). At present, the origin and destination of the trip are typically chosen as anchor points.
- Behavioural rules (see Bovy and Stern (1990)) applicable to the driver then modify this restricted network, according to the trip characteristics and the information it has accumulated in past events. Links can, for example, be removed from the network because they do not belong to the driver's knowledge of the area; they can also be added or reversed as a consequence of dynamic traffic management decisions (as tidal flows) which are communicated to the users via driver information systems.

Once the driver's knowledge of the network is established, further behavioural rules are applied to determine the route structure as a sequence of subroutes. These subroutes are finally computed and assigned to the vehicle. PACSIM actually uses time dependent randomized shortest path computation in the modified network for this very last step (in a spirit close to that of stochastic assignment, as described Daganzo and Sheffi (1977) and Sheffi (1985) for example).

The inherent behavioural route choice of PACSIM imply that a mechanism is provided for the drivers to memorize some past informations for later use. However, routing information cannot be based on this information only, as has been already observed: in particular, a user would not be able to start his or her route in the network because he or she is just, at this stage, beginning to accumulate information. Some degree of anticipation based on experience is thus necessary. PACSIM provides a mechanism (called the background network) to build up such long term dynamic experience of the network, which can be judged admissible in a limited sense (see Dehoux and Toint (1991)). This provides the requested anticipation of traffic effects in the route planning decision process, at the condition that the knowledge of the anticipated effects can be acquired with experience.

We mentioned above that certain behavioural rules are applicable to drivers. The set of all these rules constitutes a behavioural theory of route planning, which is used as input parameter by PACSIM. These rules are specified in a formal language that has been specifically designed for the purpose, and which is described elsewhere (see Mc Arthur (1991)). We note that rules expressed in this language cover variations in behaviour potentially influenced by a wide range of parameters as availability, quality, accuracy and timing of user's information, location in the network, trip purpose, transportation mode, time of the day, weather conditions...

The impact of traffic information and management systems

As one of the main goals of drivers information or management systems is to reduce congestion, one may therefore anticipate that these techniques also impact the level of pollution, both locally and at the scale of the city (see Delsey (1997) for instance). The fact that PACSIM provides support and modelling of advanced information systems thus allows the quantitative evaluation of these pollution levels, and the distinction, within this evaluation, of the specific effects corresponding to different types of information systems. In particular, the evolution of pollution levels over time may depend on the particular technology used to transfer traffic information to drivers, as it has consequences on the timing and location of possible re-routing decisions, and thus on global length of trips. For instance, it may be of interest to distinguish the results of using variable message signs or radio broadcasting systems for incident warning.

Multimodal aspects

A solution to the traffic congestion observed in urban area can not only be found with changes in the infrastructure. Alternatives to the car must be found if a certain level of mobility is to be maintained. This question is of primary interest in policies for sustainable mobility, in which pollution also plays an important role. It is thus useful to combine, in a single tool, the analysis of modal shift and of its result in terms of exhaust gas pollution.

The potential impact of public transport usage on congestion and pollution is multiform. The simplest analysis considers the effect of a modal shift from cars to busses, say, and then deduces the combined effect of the reduction of emissions by cars and of the emissions of public transport vehicles. A more sophisticated approach consists in analyzing the effects of park and ride policies on atmospheric quality. Note that such policies may or may not involve driver information systems, which indicates that the combination of all these techniques must be evaluated as a whole. Observe also that the interaction of private cars and public surface transportation vehicles such as busses induces potential effects on pollution, since the latter class of vehicles also contributes to the build-up of congestion. Again, building a pollution estimator on PACSIM provides all of these simulation possibilities.

POLLUTANT EMISSION ESTIMATIONS

We base our estimations of atmospheric pollution by exhaust gasses on two main sources, the CORINAIR models (Eggleston *et al.*, 1991), and the analysis of Joumard and co-workers (Joumard *et al.*, 1990, and Joumard *et al.*, 1995). Taken together, these emission models consider the combined effect of the following parameters.

- The first parameter is obviously the pollutant itself. We include formulae for carbon monoxide (CO), nitrogen oxides (NO_x), nitrous oxide (N_2O), carbon dioxide (CO_2), sulphur dioxide (SO_2), heavy metals and non-methane volatile organic components (NMVOC). This list is not exhaustive, but covers most of the main pollutants and is of interest in the framework of global warming forecasts, see Nicolas (1997).
- Vehicles are separated in a number of categories. We have focussed on those that are present in Belgium, namely ECE 15/00-01, ECE 15/02, ECE 15/03, ECE 15/04, 91/441/EEC for

gasoline vehicles, to which we added classes for diesel and LPG vehicles. We refer the reader to Eggleston *et al.* (1991) for a detailed description of these categories.

- Cubic capacity of engines is also important. In the above categories we still have to distinguish cases where the cubic capacity is below 1.4 liters, between 1.4 and 2 liters or superior to 2 liters, as far as gasoline vehicles are concerned, or below or above 2 liters for diesel engines.
- Finally, the current state of the vehicle at the instant of emission is crucial. We distinguish the following possible states.
    - ◊ The vehicle can be stopped with engine running (for instance at a traffic light or stuck in congestion). We then compute the emission of pollutants in grams per hour.
    - ◊ The vehicle can be moving at a speed above 10km/h. In this case, our knowledge of emission levels is quite reliable and complete.
    - ◊ The vehicle can be moving at a speed below 10km/h, in which case we only know emissions very approximately (in grams per kilometer).

  In all cases, we still need to distinguish between hot and cold engines, as their emission patterns are different (cold engines pollute more). We have used the convention that the engine of a vehicle starting a trip within the simulation network is assumed to be cold, while it is assumed to be hot if the origin of its trip is outside the city network. Furthermore, the engine warms up if it started cold, and is considered to be hot after a certain time or distance travelled. These times and distances depend on the pollutant and vehicle class. See Joumard *et al.* (1995) for further details.

As an example, we mention the formula of NO_x emissions for 91/441/EEC class gasoline vehicles of cubic capacity below 1.4 liters. The emission level is then given (in g/km) by

$$0.4880 - 0.0055 * (\text{vehicle speed in km/h}) + 0.00006 * (\text{vehicle speed in km/h})^2$$

if the engine is hot, that is if either more than 5.7 km have been travelled or if the engine was started more than 22.3 minutes before emission, or it must be multiplied by the factor

$$1.3 - 0.013 * (\text{ambient temperature})$$

otherwise, that is when the engine is considered cold. Note that the emissions of heavy metals can be deduced from gasoline consumption, which requires the use of consumption models.

The emission formulae are used in PACSIM in the following way. At each event of the simulation corresponding to a vehicle movement, the characteristics of the vehicle (speed, temperature of the engine, type, ...) are looked up and the corresponding emission of pollutant is calculated and accumulated in a counter associated with the pollutant considered and with the link on which the vehicle moves. The pollution corresponding to the period where the vehicle was (possibly) stopped before its movement is also computed and accumulated in the counter associated with the link on which it was stopped. These counters are output at specified times of the simulation (timeslices) and reset to zero. In this manner, the total of pollutant emission is available for each timeslice, each pollutant and each link. Further aggregation by zones or at the city level is obviously possible from this disaggregated data. Observe that this procedure requires the maintenance, within PACSIM, of the complete set of vehicles parameters, which is in general not available from standard traffic simulation packages.

Once the pollution levels have been computed, it is also possible to visualise their relative value on a map of the city within a GIS.

A CASE STUDY: SLOW TRAFFIC ENFORCEMENT IN NEIGHBOURHOOD AREAS

We now consider an application of the pollution evaluation tool described above to the case of a strategy to enforce slow speed for vehicles in specific city areas. The city in question is Namur, and the areas selected for slow traffic enforcement cover the inner city centre, except for the most important traffic links. The network features around 300 nodes and 800 links. The simulation period covers the morning peak hour (from 7h45 to 8h45) during which an overall traffic of approximately 25000 vehicles is simulated. The traffic demand corresponds to an ordinary week day. The ambient temperature was chosen constant for the complete simulation period and equal to 17.8 degrees (a day in August).

In order to measure the impact of the chosen policy, we simulate two scenarii, the first corresponding to a situation where the speed enforcement measures are not applied and the second where the speed reduction is enforced (corresponding to a speed limit which is half of the actual speed limit). We illustrate the results of these simulations by considering first a set of two links within the zones where speed reduction is enforced (in scenario 2), which we call "inner 1" and "inner 2", and three links on the periphery of the city center, called "bank", "bridge 1" and "bridge 2". The CO_2 pollution levels (in grams) computed for these five links and the two scenarii are given in Table 1 for four timeslices of 15 minutes each. A null pollution level must be interpreted as resulting from no traffic on this link during the timeslice.

Table 1: Evolution of CO_2 pollution levels (grams)

		7:45-8:00	8:00-8:15	8:15-8:30	8:30-8:45
Inner 1	*Scenario 1*	5455	4159	874	644
	Scenario 2	8436	5990	1930	1678
	Difference	54 %	44 %	120 %	160 %
Inner 2	*Scenario 1*	12112	24873	21637	3322
	Scenario 2	2092	1068	891	137
	Difference	- 82 %	- 95 %	- 95 %	- 95 %
Bank	*Scenario 1*	30799	17587	12603	10063
	Scenario 2	50581	40199	11949	14674
	Difference	64 %	128 %	- 5 %	45 %
Bridge 1	*Scenario 1*	36071	32045	6363	1769
	Scenario 2	38786	35899	7677	2551
	Difference	7 %	12 %	20 %	44 %
Bridge 2	*Scenario 1*	61324	50479	8616	3706
	Scenario 2	56703	90701	45826	3717
	Difference	- 7 %	21 %	431 %	0 %
City total	*Scenario 1*	11043173	9407192	3333135	2093112
	Scenario 2	11293929	9452040	3321036	1964252
	Difference	2 %	0 %	- 0 %	- 6 %

A first observation is that the total CO_2 pollution levels at the scale of the city does not significantly vary between scenarii 1 and 2. However significant differences appear when considering links in particular.

On link Inner 1, the pollutant emissions strongly increase. This situation can be explained by the fact that, due to the speed reduction enforcement, the average speed of the vehicles decreases and, as consequence, the pollution increases (according to the formulae used for the considered pollutant). It must also be noticed that the traffic flows remain high in the scenario 2 because this link is an important penetration axe.

On the opposite, the pollution is really decreased on link Inner 2. This is correlated with a reduction of the traffic; in scenario 2, the routing process avoids this local link where the speed reduction is enforced.

The situation on the link Bank is more complex. Two phenomena seems mixed there : an increase of the traffic but also, in some time slices, a higher average speed. The conjunction of these factors leads to a generally increasing pollution but with decreasing emissions during a timeslice.

On the bridge 1, the pollutant emissions are slightly increased corresponding to a small increase in the traffic flow. On the bridge 2, the large difference (431 %) observed between 8.15 a.m. and 8.30 a.m. is due to a noticeable decrease of the average speed of vehicles (from 47 km/h to 12 km/h) resulting from congestion.

CONCLUSIONS

We have shown that is is possible to combine a dynamic event-driven traffic model like PACSIM with pollutant emission analysis in order to obtain a detailed assessment of pollution levels resulting from a variety of possible scenarii. In particular, we have indicated that the combined model is capable of estimating the impact of policies involving traffic management or driver information measures, the first of these possibilities being illustrated by a small case study.

The analysis of our example also suggests that the effects of traffic management policies may be rather complex in terms of pollution levels, and that it may be important to consider these effects in details at the network level to fully understand the tradeoffs between improved traffic conditions and lower pollution.

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