THE ARTEMIS EUROPEAN TOOLS FOR ESTIMATING THE POLLUTANT EMISSIONS FROM ROAD TRANSPORT AND THEIR APPLICATION IN SWEDEN AND FRANCE

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ABSTRACT

The international engagements as well as the impact studies require accurate and agreed methods for assessing the pollutant emissions from the road transports. This ARTEMIS project - with 40 European research laboratories and a budget of about 9 M€ was initiated for the setting-up and improvement of the European inventorying tools for application at different spatial and temporal scales and which should enable objectives comparisons and evaluations.

These tools rely on consequent experimental works and integrate most of the European related knowledge. They concern all transports modes in Europe, their pollutant emissions and fuel consumption, their characteristics of use. The ARTEMIS project resulted in many important scientific results and in a unique state of the art on the topic in Europe. We recapitulate the main lines of the project and its results: emission measurements, principles of the modelling, street-scale approach based on the definition of traffic situations, and the resulting tools.

The tools application requires detailed and reliable data describing the traffic (vehicle fleets and activity, driving conditions, etc.). We highlight this aspect through the ARTEMIS application in Sweden, first country to implement the tools for emissions reporting, and through a road network based approach envisaged in Lille for impact studies at a city level.

Keywords: *Pollutant emission, transport, model, fleet model, road network.*

1. INTRODUCTION

In many contexts, an accurate estimation of the pollutant emission from the transport is needed: monitoring of the international commitments for the air pollution and greenhouse gases, impact studies for road projects, transport policies, regulation or technologies assessment, input data for the physic-chemical models, etc. The European Commission decided thus to support a large research project - ARTEMIS, with 40 European laboratories and budget of about 9 M€ over 5 years -, to set-up and improve the European methods for estimating and inventorying the pollutant emissions from the transports. It concerned all transports modes in Europe. The linked COST346 action (Emissions from the heavy duty vehicles) enabled a significant effort for these vehicles and an enlargement of the partnership (50 participants from 17 countries). Besides the tools, which are today available, the ARTEMIS project resulted in many scientific results and in a unique state of the art on the topic in Europe.

2. MAIN RESULTS FROM THE ARTEMIS PROJECT

Amongst the main results, we can note:

- The elaboration of real-world test procedures (ARTEMIS driving cycles for the passenger cars, - see Figure 1, André, 2004 -, test conditions for the heavy duty vehicles, etc.) and a systematic analysis of the methodological aspects that lead to uncertainty in the emission estimation (vehicle sampling, test conditions, fuel, etc.). The test procedures were applied in ARTEMIS, but also in national programmes, which enlarged considerably the emission database. These experimental and methodological works result also in significant progress and recommendation regarding the test procedure for emissions measurements.
- A high number of duty vehicles, 2-wheelers and recent cars were tested with a particular focus on the non-regulated pollutants - badly known up to now -, the cold start and evaporative emission, the contribution of the auxiliaries and air conditioning.
- Coherent modelling approaches at different scales (from regional to street) and their integration in modular tools, which enable the estimation of the vehicle fleets and their emissions, and constitute a powerful plate-form for emission estimation exercises.
- The collection of national and European statistics and the elaboration of realistic assumptions regarding the traffic characteristics (vehicle fleet, driving conditions, etc.).
- Heavy experimentations in three European tunnels to validate the works by comparing simulations and real-world pollutant concentrations.

The non-road transports (air, rail, maritime) were also dealt with in ARTEMIS, through consequent campaigns of measurements and the development of specific tools. Thus there are fully renewed and improved tools, which result from the ARTEMIS research project. A huge number of technical reports recapitulate the numerous scientific results (Boulter et al., 2007).

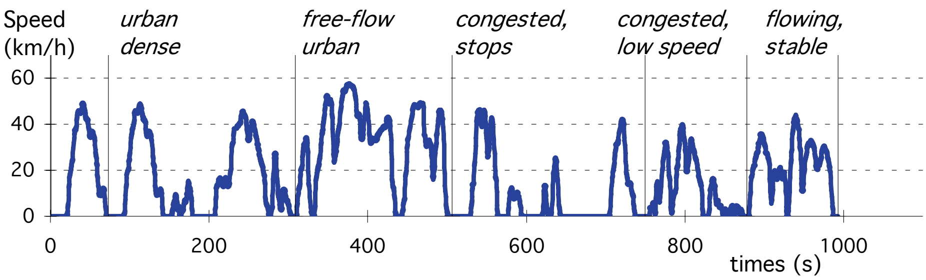

Figure 1: The Artemis urban driving cycle for passenger cars

3. THE ARTEMIS TOOLS

3.1. Fields of application

The ARTEMIS tools were designed for three main applications: (i) classical emission inventories (at regional or national scale, per month or year), (ii) scenario calculation for assessing the impacts of alternative measures (time series over years), (iii) inputs for air quality models for assessing local and temporal impacts on the environment. The model was then designed to enable calculation at an aggregated level and at a street level. The daily calculation can be declined on a hourly basis or aggregated by year, over the 1980-2030 period.

3.2. Concepts and structures

The tools manage most of the pollutants: regulated (CO, HC, NOx, PM, Pb, SO2) as well as the fuel consumption and non-regulated pollutants (CO2, methane, ammonia, benzene, toluene, xylene, polycyclic aromatic hydrocarbons, PM in size and number, 1.3-butadiene, acetaldehyde, acrolein, benzopyrene, ethylbenzene, formaldehyde, hexane). These last components are however missing for certain vehicle categories. Hot, cold start and evaporative emissions are managed for the most relevant vehicles concepts (up to EURO4) through actual emissions measurements, while assumptions are proposed for the future vehicles. The user can also make its own assumptions for future technologies.

The calculation relies on a detailed classification of the vehicles into families (light-duty vehicles, motorcycles, heavy duty vehicles), categories (cars, light commercial vehicles, buses, and coaches, heavy goods vehicles) and sub-categories (rigid-, articulated and truck and trailers). Vehicles categories are broken down into segments by technology and size (i.e. petrol, diesel by engine size, hybrids, CNG, E85 for cars, trucks by vehicle weight and configuration, midi-, standard- and articulated-buses and coaches, fuelled with diesel, CNG or ethanol, moped and motorcycles by engine size and technology - 2- and 4 strokes). These segments are themselves combined with the emissions concepts (pre-Euro, Euro1 to 5 plus several other cases).

3.3. Emissions data and modelling

A large number of recent vehicles and engines have been tested within the framework of the project and combined with existing emissions data and national campaign of measurements. In all 102 engine maps and 27 transient tests were performed with Euro0 to 3 engines for the heavy vehicles, which enabled the building-up of averaged emissions up to the Euro5. The PHEM model (Rexeis et al., 2005, Figure 2) was then designed for simulating accurately the detailed operation as and the resulting emissions and consumption from all types of lorries and buses for various traffic situations, gradient and vehicle load, while taking into account of the transient operation, fuel quality and cold start.

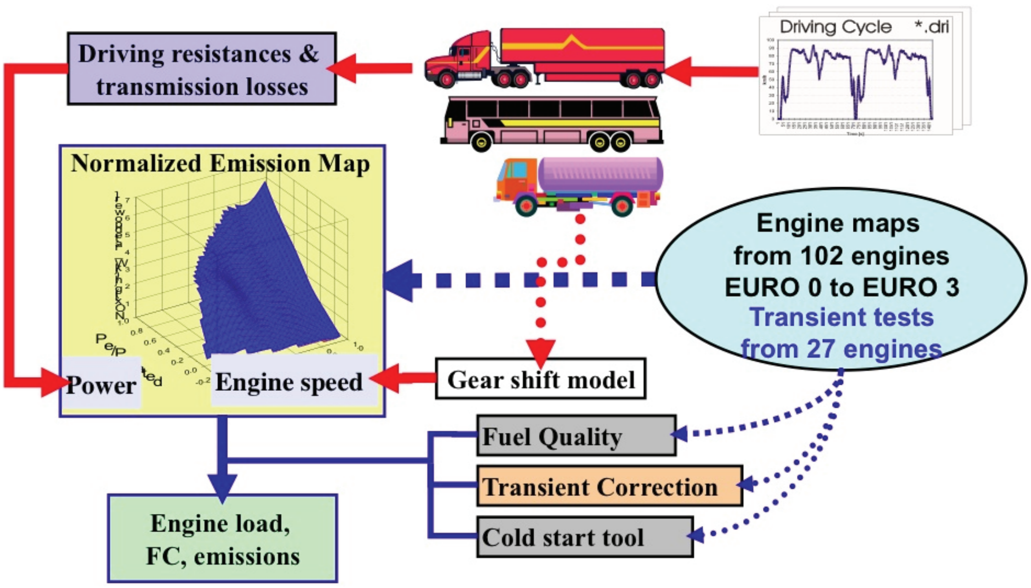

Figure 2: Schematic picture of the model PHEM for computing emissions and fuel consumption from the heavy duty vehicles

Also, 115 motorized 2-wheelers were tested over representative test cycles and enabled the development of emissions functions as regards speed for both mopeds and motorcycles. Similarly, tests were conducted on light duty vehicles with dedicated driving cycles to elaborate emissions functions as regards their speed and the vehicle load.

To measure accurately the non-regulated pollutants, -insufficiently known up to now -, the cold start effect and the detailed influence of the driving patterns, 130 recent cars were heavily tested. To derive the hot emission factors, the previous data was combined with about 2700 other vehicles, representing in all more than 28,000 tests measured using hundreds of test cycles. This heterogeneous dataset required thus an harmonization as regards the driving cycle. An approach was developed in that aim, which consists in the building-up of a typology of test patterns to aggregate similar test cycles The real-world driving cycles were thus described through the 2-dimensional time distribution of the instant speed and acceleration, and an automatic clustering enabled the classification of the cycles according to their kinematic similarity, defining thus a typology into 15 test patterns. For each of these test patterns, it was then possible to derive reference emissions, by computing the corresponding driving cycles and emissions figures.

Considering any real-world speed curve, we can thus compute its speed x acceleration distribution, process that distribution through the Correspondence Analysis, and measure thus the distance between the speed curve and each of the 15 previous test patterns. We compute thus the corresponding emissions by linear combination of the reference emissions of the closest test patterns (Figure 3). This process was also used to derive coherent emissions versus speed functions. In parallel, sophisticated models were proposed to compute the cold start (incl. the trip length and usage aspects) and the auxiliaries effects (in particular the air conditioning, based on technical, climatic and behavioral aspects).

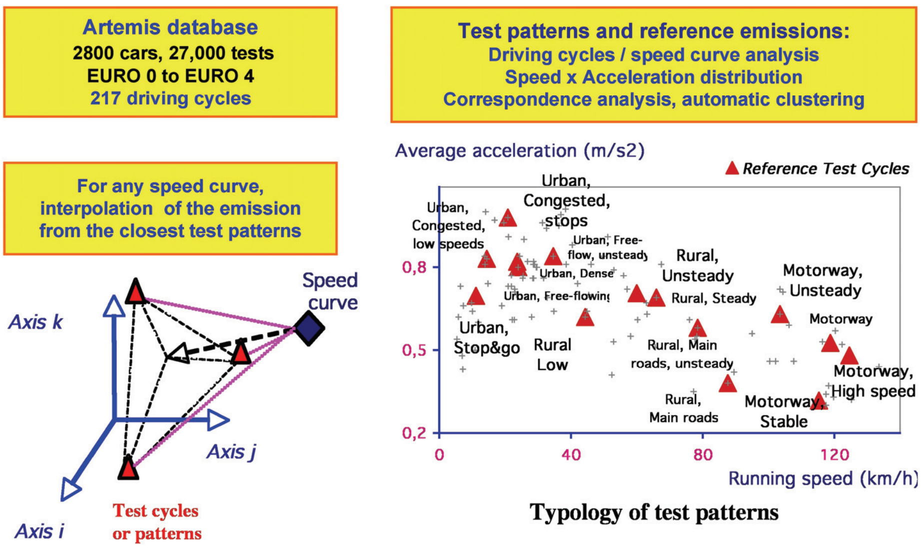

Figure 3: Schematic modelling of the passenger car emissions and fuel consumption

3.4. Traffic situation approach

The estimation of the emissions at a street level implied the definition of "traffic situations". A user- and practices- oriented "traffic situations scheme" was derived from the analysis of existing road classifications. It distinguishes urban and rural areas, the road network functions and hierarchical organization, and declines motorway / road and their most common characteristics and speed limits in Europe (Table 1, André et al, 2006). The traffic condition is then described in (i) free-flow traffic (speed at 85-100% of the free speed), (ii) heavy traffic (constraint speed at 65-85% of the free speed), (iii) unsteady saturated traffic (variable speed with possible stops, 30 to 60% of the free speed) and (iv) stop-and-go (speed around 10 km/h).

We defined thus several hundreds of traffic situations as combination of road configurations, speed limits, and traffic conditions. For the different vehicle categories, the computation of the emission for each of these traffic situations relies on representative speed curves (recorded in real-world conditions within several European research projects) and on the previously described modeling approaches (Figure 4).

Table 1: Urban and rural roads typology

	Main function	*Characteristics*	*Speed limit (km/h)*
Urban	National and regional network - Through-traffic	5a - Motorway	80 - 130
		5b – Non-motorway	70 - 100
	Agglomeration primary network - Primary distributor	4a - Motorway (ring, etc.)	60 - 110
		4b - Non-motorway	50 – 90
	Districts distributor	3 - Road	50 - 80
	Local distributor- Inner exchange, local traffic	2 - Road	50 – 60
	Access road - Local traffic.	1 - Road, side road, etc.	30 - 50
Rural	National and regional network - Through and distribution traffic	5 - Motorway	80 - 150
		4 - Trunk road	60 - 110
	Distributor	3 - Road	50 - 100
	Local distributor - Inner exchange, local traffic	2 - Road	50 - 80
	Access road - Local traffic	1 - Road, side road, etc.	30 - 50

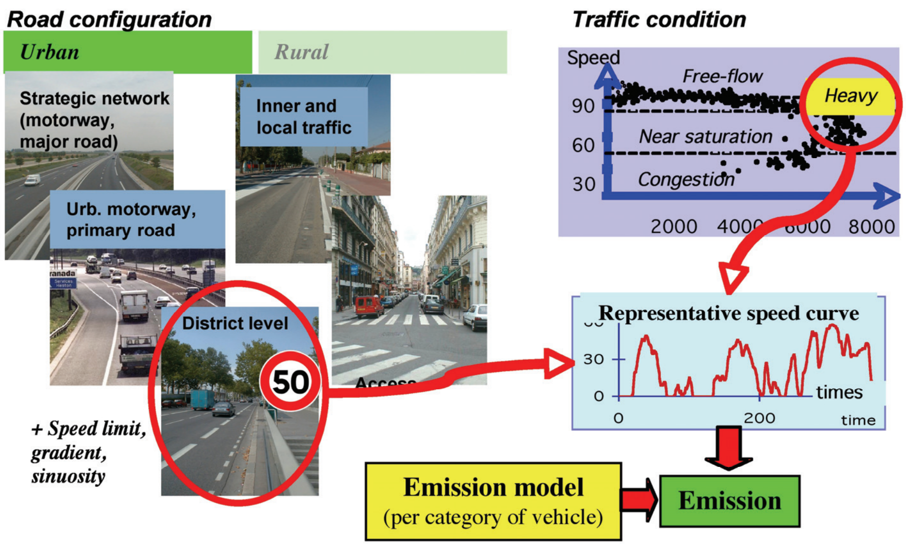

Figure 4: Schematic picture of the traffic situation approach

3.5. Operational aspects

The ARTEMIS tools consist mainly in (Figure 5):

- An **emission data set** includes all the emission data and functions needed for the computation of the different emissions (hot, cold start, fuel evaporation, etc.)
- A **fleet model** enables the calculation of the detailed fleet composition in number of vehicles (static fleet) as well as in vehicle x kilometres (traffic volume). This results from the setting-up of a *fleet scenario*, which combines a yearly detailed description of the fleet stock and the age distribution of the vehicles, and/or the yearly registrations of new vehicles and their survival probabilities. A *traffic activity scenario* combines then the fleet composition and the annual mileage assumptions, per detailed vehicle categories and segments, and per driving area (urban, rural, motorway). This scenario considers also the distribution of the traffic activity/mileage according to the traffic situations (i.e. road types and traffic conditions) and specifies the climatic and usage conditions (temperature, trips, starts, parking conditions, traffic distribution) and their temporal variations (hourly, daily, yearly) for the computation of the cold start, fuel evaporation and air conditioning related emissions. Finally the *emissions concepts scenario* specifies the years and share of introduction of the different emissions concepts (Euro1 to 5, etc.). These 3 scenarios determine fully a *traffic scenario*, i.e. a fleet composition, activity and distribution according to the traffic situations, by vehicles segments and emissions concepts.
- An **emission factor processor** enables the computation of all the relevant emissions factors (hot, cold, evaporative) corresponding to a given fleet or traffic scenario, with an aggregation at any level (from the detailed sub-segments to the entire fleet).
- A **traffic data set module** combines a traffic scenario with an application (definition of road links for a use with traffic models, areas, time periods, etc.) in a ready-to-use dataset.
- The **emission computation module** derives the total emissions for a given case study (traffic data set) according to the user specifications (pollutants, years, vehicles) and enables detailed results and their analysis.

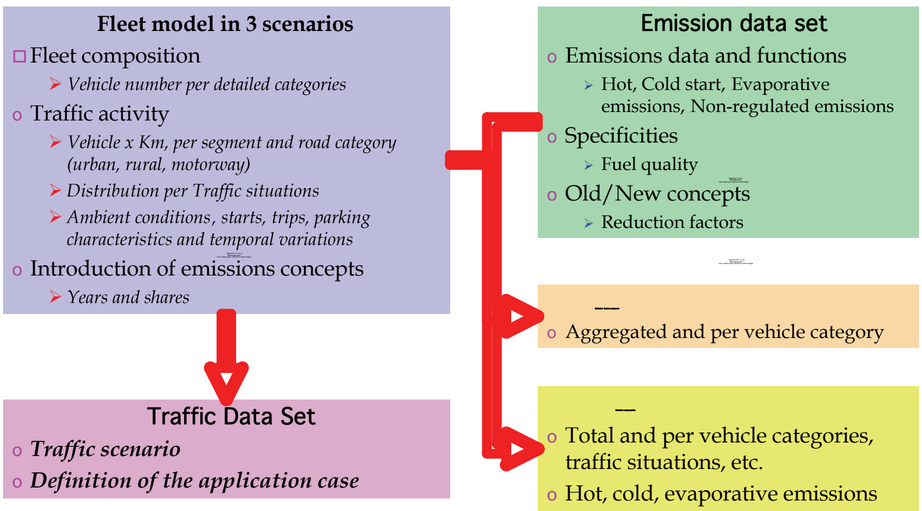

Figure 5: Schematic structure of the ARTEMIS tools

All the relevant data and distributions as well as the resulting scenarios are stored and managed in a Datapool, with the possibility to copy, rename, export / import to MS Excel or similar tools. A large range of cross-tables and analysis requests enables detailed analyses and validation of the results, which are also stored in the User Database (MS Access). A library is proposed to archive / import / export data and scenarios between countries or application cases. Basically it contains default data and a full dataset allowing an easier introduction to the tools.

4. APPLICATIONS

Sweden was the first country to compute the road transport pollutant emissions using ARTEMIS. After a first implementation for validation (Sjödin et al. 2006), the tools were applied over the period 1980-2006 for reporting the 2005 and 2006 national emissions (SRA 2006, 2007) and for the evaluation of the urban toll system in Stockholm. They should be implemented into the Swedish planning system for road investment analysis and within the SIMAIR model (Swedish Internet Model for Air Pollution) for calculating the air quality in the vicinity of the roads.

In that aim, consequent works were conducted to constitute the input data and assumptions needed by the methodology. The Swedish vehicle fleet and their distribution according to age and emissions concepts were determined from the National Vehicle Register, which provides by detailed categories the new registrations and the destruction of the vehicles. The distinction between buses and coaches was made according to vehicle weight and allowed passenger number, and the cars engine capacity was determined through a yearly consumer survey. The motorcycle engine type (2- 4-strokes) was determined using make statistics. Truck and trailer configurations and weights were estimated by surveys while the in-use vehicle loads were estimated from the 1997 Swedish survey on domestic goods transport.

Yearly mileages and their evolution according to the vehicle age are based on the overall traffic (measured on the Swedish roads) and on the annual mileage by detailed vehicle categories recorded within the inspection & maintenance programme. Finally, trip lengths, parking times and ambient temperature related statistics - needed for cold start and evaporative emission estimation -, and their seasonal and diurnal variations were determined using instrumented cars and meteorological data. Fuel characteristics were taken from the national petroleum statistics.

The distribution of the mileage by detailed traffic situations was realised through the GIS database of the Swedish national road network and traffics (cars / lorries). For the municipal and private roads, a simulation was conducted for 4 typical regions using SAMPERS (transport demand) and EMME/2 (traffic) models. The total traffic in the cities was estimated through an empirical relation (mileage = 3976 x population).

The total traffic was then declined according to urban and rural areas (from buildings and population data) and broken down into the 33 main road configurations (road design and function and speed limit) encountered in Sweden. Yearly speed-flow curves were used to determine the traffic condition as regards the recorded traffic flow, for each road types of the main network and for the 4 representative regions and 2 big cities. However, this method does not enable the identification of the stop-and-go condition. A detailed analysis of the hourly traffic flows was thus conducted to that aim.

This led to the identification of 85 main traffic situations in Sweden (out of the 276 proposed by the tools), of which 40 in urban areas. The 10 most commons (5 urban, 5 rural) represented 80% of the total mileage. It revealed also the low occurrence of the stop-and-go (0.05%), while free-flow driving represented 94%, heavy traffic 3% and congested 2% of the mileage.

Based on the above data and assumptions, the calculation of the Swedish national emissions gave a certain coherency with the simulations using the previous tools. The gaps (NOx higher by 19% in 2004 and CO_2 by 6%) were analysed, agreed and attributed to more reliable emissions data in ARTEMIS, while a good agreement was also found with the national fuel deliveries (confirming the fuel consumption and CO2 emission estimated by ARTEMIS) and with on-road emissions measurements. Figures 6 and 7 highlight the evolution of the Swedish emissions over the period 1980-2020 as predicted by the ARTEMIS tools (Hammarström et al. 2006).

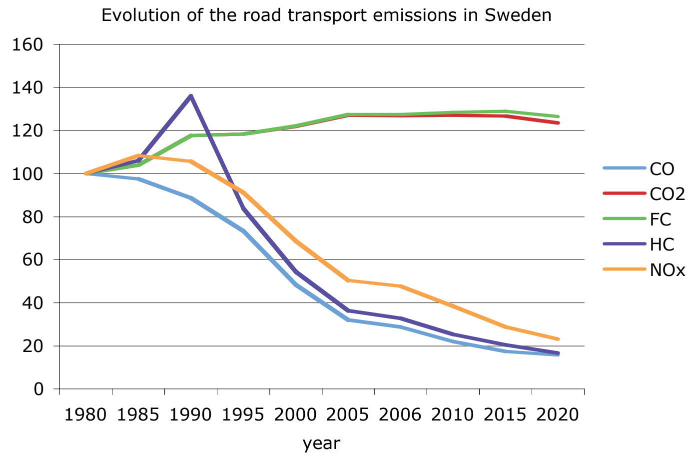

Figure 6: Evolution of the Swedish road transport emissions (by Artemis, basis 100 in 1980)

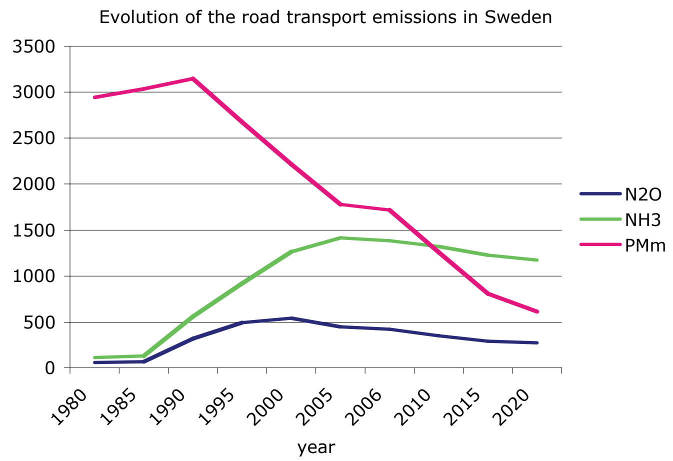

Figure 7: Absolute emissions for non-regulated pollutants from the Swedish road transport

The ARTEMIS methodology is currently implemented for the analysis of the emissions from the road network of the urban area of Lille, north of France. In that aim, the road network is described into 6,300 geographically referenced links, i.e. 2,300 km of roads and most of the roads (national and urban motorways and major roads, city distributors, etc.) but not the access roads. The local traffic is then considered through artificial “injection” links (Figure 8).

The first aim of the study should be a calculation with Artemis and comparison with CopCETE (derived from COPERT3) for the assessment of the Mobility Plan of the City (PDU). That concerns the year 1998 and the working days only. Two applications are envisaged in that aim: (i) a macroscopic case using rough traffic data (average speeds, daily traffics, assumed to be free-flow) to determine the difference between the 2 methods and the improvement brought by ARTEMIS at this level, and (ii) a microscopic application, with detailed traffic data, over a limited area of the agglomeration for which such detailed data can be available.

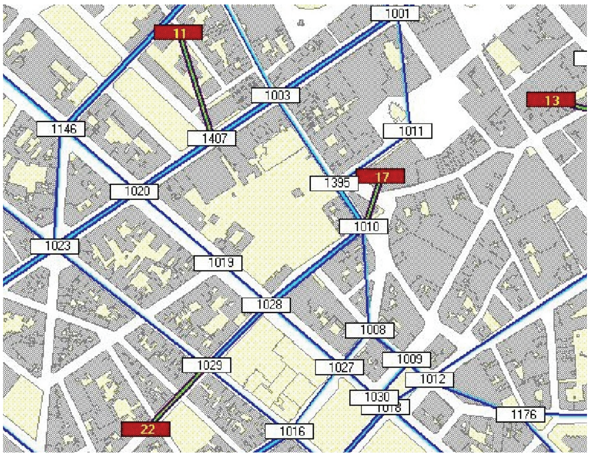

Figure 8: View of a part of the Lille road network with injection links for the local traffic

The traffic data are computed from the EMME/2 model and from the hourly distribution of the traffic flows (annual statistics) and adjusted by road counting to cover only the working day. The bus traffic should be made available by the bus operator, and the 2-wheelers traffic should be derived from a mobility survey. Each link of the road network is described by its road type and capacity, origin and destination, length, number and speed of cars and of lorries, a rate of cold engine operation (cold start emission). The speed-flow curves and capacity should enable the determination of the traffic condition.

In a first phase, the affectation of each link to a given traffic situation was undertaken, which demonstrated the difficulty, due to a lack of coherency between the existing geographical and road network related data and the proposed concepts (urban definition and road categories). A sensitivity study was thus conducted to quantify the relative error induced by the urban / rural affectation (with similar road categories) or by similar road configurations. The results demonstrated that emissions recorded on urban and rural motorways with speed limit at 130 km/h significantly differed (importance to discriminate correctly between urban and rural in that case) while in several cases urban, rural and even different road configurations with the same speed limit recorded similar emissions (low importance of the affectation). The previous cases could justify a simplification of the traffic situation scheme (similarity of cases) or rather a flexibility of its usage, as it could be better to preserve the scheme if this one is satisfying from a user or traffic related point of view.

5. CONCLUSIONS

The ARTEMIS tools are the result of a large European co-operation around the pollutant emissions and energy consumption of the transports. They represent a significant research effort and include a large number of new measurements for most vehicles categories, recent technologies and the non-regulated pollutants. The tools propose harmonized methods and approaches at different scales in particular for local estimation.

Their application was demonstrated in the case of Sweden for which the input data were collected using a large range of existing traffic and transport statistics.

Such tools constitute a real work plate-form for assessing various projects and contexts. Their application to other contexts and case studies - French cases, European research projects, application in emerging countries - will contribute to enrich the experiences, to envisage improvements, and to extend thus their field of application.

6. REFERENCES

André, M. (2004). The ARTEMIS European driving cycles for measuring car pollutant emissions. Sc. of the Tot. Envir., n°334-335, p. 73-84, 2004.

Boulter, P., McCrae, I., Joumard, R., André, M., Keller, M., Sturm, P., Hausberger S., et. Ali. (2007). ARTEMIS: Assessment and reliability of transport emission models and inventory systems – Final Report, Deliverable 15. Commission Européenne. Crowthorne, UK: TRL, TRL Report UPR/IE/044/07, 333 p.

Rexeis, M., Hausberger, S., Riemersma, I., Tartakovsky, L., Zvirin, Y., Cornelis, E. (2005). Heavy Duty vehicle Emissions - Final COST346/ARTEMIS Report. Inst. for Int. Comb. Engines and Thermodynamics; TU Graz, 2005

André, M., Fantozzi, C., Adra, N. (2006). Development of an approach for estimating the pollutant emissions from road transport at a street level. Commission Européenne. Bron, France: INRETS, LTE0628, 149 p.

Sjödin, A, Ekström, M., Hammarström, U., Yahya, M.R., Ericsson, E., Larrson, H., Almén, J., Sandström, C., Johansson, H. (2006). Implementation and evaluation of the ARTEMIS road model for Sweden's international reporting obligations on air emissions. Int. coll. of Transport and Environment, Reims, 2006.

SRA (2006). 2005 - The road transport sector - Sectoral report. Swedish Road Administration, Borlänge, Sweden. 68p.

SRA (2007). 2006 - The road transport sector - Sectoral report. Swedish Road Administration, Borlänge, Sweden. 72p.

Hammarström, U., Yahya, M.R., Björketun, U. (2006). Emissionsberäkningar till VV:s års- och sektorsredovisning 2006. VTI Draft Report, Linköping, Sweden. In Swedish. 59p.

Gadrat, M. (2008): Test et application du modèle Artemis à l'agglomération Lilloise - Phase 1: description des situations de trafic. Cete Nord-Picardie, to be published.