A global tool for environmental assessment of roads – Application to transport for road building

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1. INTRODUCTION

Roads are the main transport infrastructures of industrialised countries. Because of increasing traffic demands, roads generate more and more environmental impacts i.e. raw materials consumption, air pollution, noise. Most of industrialised countries have therefore introduced regulations imposing environmental evaluations before any new construction. Nevertheless, decisions concerning roads, and infrastructures constructions in general, are still mainly based on mechanical and economical criteria. Furthermore, technical choices (materials, geometry…) are delegated to competent technical services, in which tools based on mechanical analysis are operated.

The Sustainable Development Team of Laboratoire Central des Ponts et Chaussées (LCPC) works to elaborate an environmental tool, which enables a global analysis of roads, including initial construction and maintenance, all along road service life. Besides, the aim of this work is precisely to provide available informations, allowing to bring environmental assessment with into initial decision making, without forgetting technical road parameters. The Life Cycle Analysis (LCA) standard framework (ISO 14040-43, 1997-2000), is well adapted to consider simultaneously technological and environmental parameters during the life cycle of manufactured products. This methodology has thus been applied on the environmental assessment of one material of a specific road case (Ventura *et al*, 2004). However, this particular study showed the limit of the standard method in its application to road infrastructures (Ventura *et al*, 2003). Hence, a dedicated tool has been developed. The Elementary Road Modulus (ERM) uses an environmental model which derives from the LCA methodology. But on the contrary of the LCA functional unit concept, the ERM is elaborated to be fully modular in order to be easily adapted to various case studies. ERM modelling performs an inventory of input/output flows, focusing on pavement service life (construction and maintenance during exploitation). The next step of modelling is called Global Road Modulus (GRM). This second step consists in selecting existing (or developing new) impacts indicators, that takes territory aspects into account.

The link between ERM and GRM modelling is based on an intermediate phase, which consists in calculating inputs/outputs inventory for subsystems involving territory dependent parameters. Among concerned subsystems, transport is highly linked to the road location. Hence, accounting for transport requires to work on a given case study belonging to French network in order to use realistic calculations distances as input parameters instead of fixed mean distances as input parameters like it was previously done for ERM modelling (Hoang *et al*, 2005). The full inventory calculations model developed for every subsystem cannot be detailed in this paper and will be part of the phD report of T. Hoang that will be published in 2005. This paper only focuses on the model developed for transports inventory calculations. It carefully examines the choice of the case study to highlight distance influence. It first details Road Modulus tool principles and thus describes the case study particularities. Results such as energy and natural resources consumptions, as well as a selection of airborne emissions (CO_2, NOx, and SO_2), are then presented.

2. ERM TOOL PRINCIPLES AND DESCRIPTION

The ERM part of the tool is based on road specifications (structure design and maintenance description) over a given range of years, for an initially defined traffic prevision, and a chosen level of service. Road specifications leads to an elementary road section of 1 km which enable the calculation of masses of required materials. Materials masses are implemented in an environmental system which includes materials production processes and provides environmental flows as outputs.The presently investigated system is described in Figure 1.

The system must *a minima* include materials production processes that are directly involved into roads construction and maintenance: (i) quarry for natural aggregates, (ii) mixing plants for asphalt or cement concretes, (iii) steel plant in case of using reinforced concrete. Processes involved to provide the mixing plants : bitumen and aggregates for the asphalt concrete, cement and aggregates for the cement concrete are also included to the system. Transports of natural raw materials (clay and limestone, crude oil, recycled steel (62% according to (Barthelemy *et al*, 2001)) and iron ore) providing cement plant, refinery and steel plant, are included in the system. But their production processes is not included. Neither are included processes involving in electrical power sources are not included in the system.

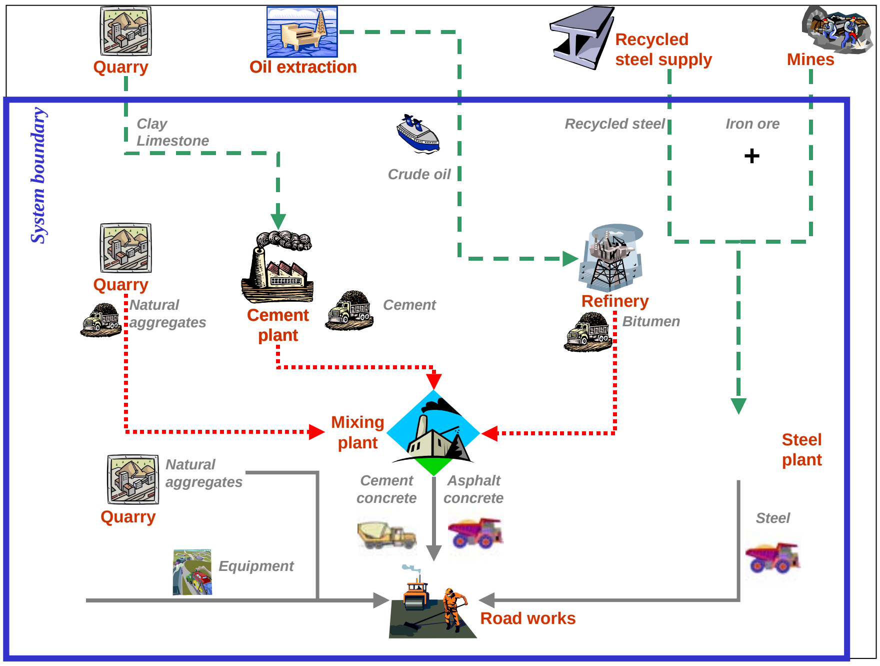


Figure 1 : ERM general system

Legend :

▭ *System boundary*

→ *Level 1 : direct link to roadworks*

⇢ *Level 2 : secondary link to roadworks*

⇢ *Level ≥ 2*

3. PRESENTATION OF THE HIGHWAY CASE STUDY

3.1. Highway location, structure and maintenance

An existing highway – the A71- was chosen for tool testing for the following reasons as follows. (i) the northern part of this highway is located in the center of France between Orléans and Bourges as shown in Figure 2, which is representative of a “central French case” in terms of raw imported materials transports; (ii) the structure of A71 pavement is composed of both asphalt and cement concretes, which are the two main kinds of materials and techniques used for road building in France. This so-called “mixed” structure (Laurent, 2004) allows to analyze a representative panel of classically involved raw materials; (iii) the highway structure is designed to support a heavy traffic (initially 750 heavy vehicles/day/lane) which is close to the theoretical case used to develop the Road Modulus model (Hoang *et al*, 2005).

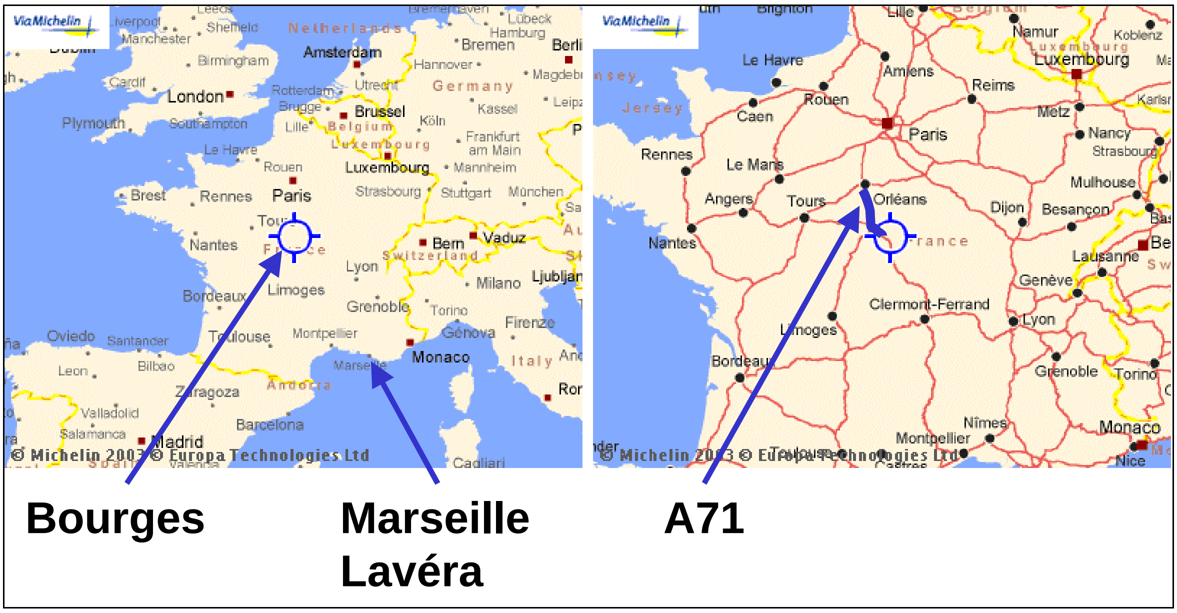
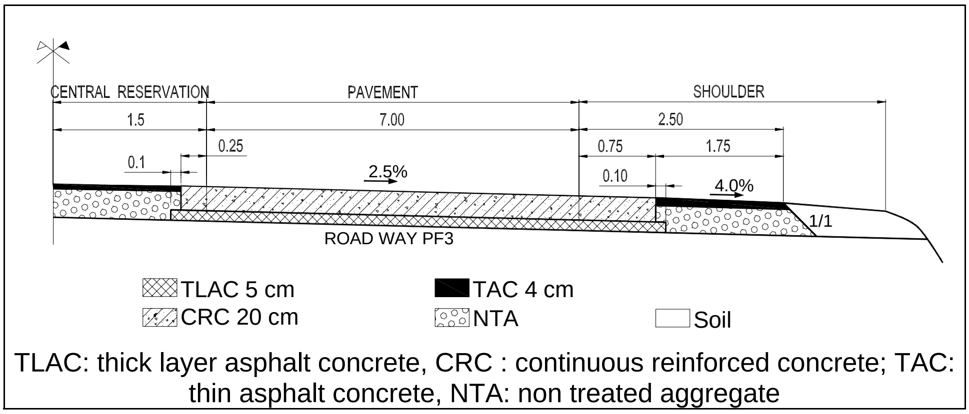


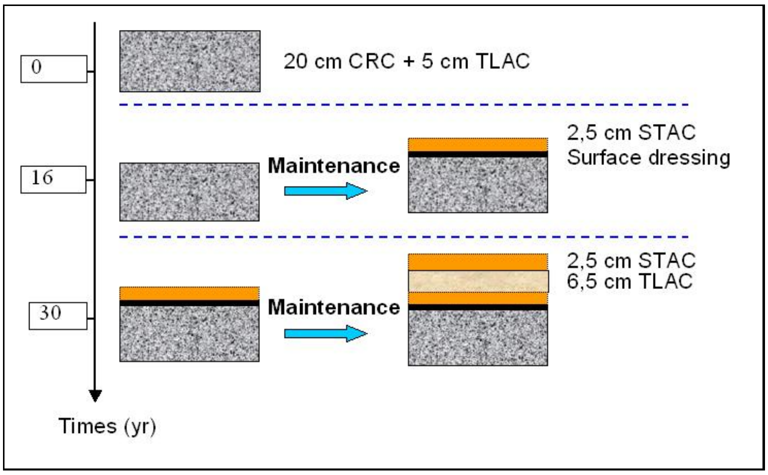
Figure 2 : A71 location



TLAC: thick layer asphalt concrete, CRC : continuous reinforced concrete; TAC: thin asphalt concrete, NTA: non treated aggregate

Figure 3 : Cross-section of the A71 motorway pavement.

A71 is a French double 2 lanes motorway which was built in 1986. The half cross section structure of this motorway is shown in Figure 3. The considered length is 50 km. Only a half section is taken into account because the other sense has a different structure design. The A71 maintenance road works on have been done twice according to (Laurent, 2004) since its construction as shown in Figure 4 (the year 0 corresponds to initial construction). After 16 years, the upper



Continuous Reinforced Concrete (CRC) layer has been covered by a surface

Figure 4 : A71 maintenance operations

dressing and a 2.5 cm Super Thin Asphalt Concrete (STAC). After 30 years the wearing course has been reinforced by a 6.5 cm Thick Layer Asphalt Concrete (TLAC) and 2.5 cm STAC. The different materials compoundings used for the different layers are presented in Table 1. Cement CEM II/A32.5 was assumed to be constituted of 80% clinker, and 20% additives, and clinker was assumed to be 20% of clay and 80% of limestone (Baron and Sauterey, 1982).

Mixed materials	Compounding (for 1 m^3 of mixture)		Mixing plant type	Ref.
	Materials	Mass (kg)		
CRC (for CRC layers)	Sand 0/5	800	Cement concrete mixing plant	(LCPC-SETRA 1997)
	Coarse aggregates 5/10 (Ryolithe)	440		
	Coarse aggregates 10/20 (hard limestone)	585		
	Plasticizer	1.65		
	Air entraining agent	0.06		
	Cement CEM II/A32.5	325		
	Water.	145		
	Steel	53.67		
STAC	Bitumen	144	Continuous asphalt mixing plant	(SETRA-LCPC, 1994)
	Aggregate	2,410		
Surface dressing	Bitumen	1.60 kg/m^2	-	
	Aggregates	280 kg/m^2		
TLAC	Bitumen	134	Continuous asphalt mixing plant	
	Aggregates	2,437		
TAC	Bitumen	129	Continuous asphalt mixing plant	
	Aggregates	2,450		

Table 1 : materials compounding

3.2. Transport hypotheses

3.2.1 Hypotheses on the supplying of the materials

Table 2 shows the transport parameters of these materials. Local resources (natural aggregates, recycled steel, clay, limestone) as well as mixing plants and cement works were assumed to be located in Bourges, at a 25 km average distance from roadworks. Bitumen was assumed to come by truck from the Lavéra refinery near Marseille (France). Distances of transports performed by trucks in France were obtained from (Michelin, 2004) mostly by motorways. Iron ore was assumed to come from Krivorozhsky to Odessa by truck, then by freighter from Odessa to Marseille, and again by truck from Marseille to Bourges steel plant. Crude oil transport hypotheses was taken from (Eurobitume, 1999) that is 30% of crude oil coming from Venezuela, and 70% from the Middle East.

Depending upon the transport mode, go and return journey is to be considered. The methodology for inventory calculations is precisely described in section 3.

Type	Material Mass (tons/year)			Journey		Distances (km)				Single / return
							Truck			
	0	16	30	Departure	Arrival	Ship	Highway	Rural	Total	
Equipment	-	-	-	Bourges (France)	A 71 Roadworks (France)	0	25	0	25	Return
Asphalt concrete	60,712	30,641	92,328			0	25	0	25	Return
Cement concrete	183,737	-	-			0	25	0	25	Return
Steel	4,293	-	-			0	25	0	25	Return
Cement	26,000	-	-			0	25	0	25	Return
Natural aggregates	294,567	50,679	87,399			0	25	0	25	Return
Bitumen	3,265	5,292	13,154	Lavéra (France)	Bourges (France)	0	649	12	661	Return
Crude oil	6,530	10,585	26,309	Middle East	Lavéra (France)	11,920	0	0	0	Return
	1,632	2,646	6,577	Venezuela	Lavéra (France)	9,520	0	0	0	Return
Iron ore	2,590	-	-	Krivorozhsky via Odessa (Ukraine)	Bourges via Marseille (France)	3,400	649	307	956	Single
Recycled steel	4,225	-	-	Bourges (France)	Bourges (France)	0	25	0	25	Return
Clay	25,792	-	-			0	0	0	0	Return
Limestone	6,448	-	-			0	0	0	0	Return

Table 2 : Parameters of materials transport

3.2.2 Hypotheses about the carriers and vehicle typology

In order to simplify calculations, each material was assumed to be transported by the same type of transporting unit (carriers or vehicles), during the whole road service life, although it was probably not the case from the highway construction in 1986 until nowadays. Properties of the transporting ships chosen for iron ore and crude oil transports are given in Table 3.

Ship	ship size (tons)	Engines energy (kW)	Average speed (km/h)	Length (m)	Breadth (m)	Design draught (m)	Unitary values			
							Energy (MJ/km)	CO_2 (g/kg ind. fuel)	NOx (g/kg ind. fuel)	SO_2 (g/kg ind. fuel)
Source	(MAN B&W, 1999), (MAN B&W, 2004)							(Toniello, 2001) and (Energetics, 1998)		
Iron ore carrier	10,000	2,920	25	117	19.3	8.6	901.9	3,250	32.92	57.69
Crude oil tanker	165,000	16,800	27.8	274	50	15.6	4,669.9	3,250	32.92	57.69

Table 3 : parameters of transporting ships

Oil tankers were chosen taking into account their geometrical parameters in order to be authorised to cross the Suez Canal : the cross-sectional area of the ship (breadth x draught) below the waterline must be less than about 820 m^2 (MAN B&W, 2004). Iron ore ship was chosen a small ship size, as a function of the total iron ore mass to transport.

For road transports, different types of vehicles may be used : truck mixers, tank-lorries, exit lorries and articulated lorries. Furthermore, each vehicle has a particular useful load and engine, and unitary consumption and emissions should therefore be case specific. To simplify calculations, in this paper, all lorries are considered equivalent to the articulated lorry Gilbert SBE 233 with a 27 tons useful load (F.N.T.P, 2000). The corresponding energy consumption is taken from CERTU, 1997 for two types of engines running-in : rural and highway. Airborne emissions are taken from by (EMEP/CORINAIR, 2001) in g/kg diesel.

4. CALCULATION METHODOLOGY OF CONSUMPTIONS AND EMISSIONS

For each journey, the total consumptions/emissions that can be attributed to one material transport, is expressed as follows :

$$E_{total} = (1+\alpha).\sum_{i=1}^{N} E_i \qquad \textit{(eq. 1)}$$

where $\mathbf{E_{total}}$ *is the total consumption/emission in MJ or tons for one journey and one material,* $\boldsymbol{\alpha}$ *is the return journey coefficient,* $\mathbf{E_i}$ *is the consumption/emission in MJ/tons of the transporting unit i (truck or ship), and* **N** *is the number of transporting units.*

The value of α depends on the further use of the transporting unit after the material deposit :

- if the transporting unit makes an empty return journey, the emissions (consumption) of the return journey are included in the system, because they are a consequence of the initial journey. In that case $\alpha = 0.8$ because an empty transporting unit is assumed to consume/emit 80% of a full transporting unit consumption/emission (Eurobitume, 1999);
- if the transporting unit comes back or goes further with a new cargo then consumptions/emissions of that journey are not included in the system because they are not a part of it. In that case : $\alpha = 0$.

For each journey, the number N of transporting units is calculated from (eq. 2):

$$N = E\left(\frac{m_{total}}{L_u}\right) + 1 \qquad \textit{(eq. 2)}$$

where $\mathbf{m_{total}}$ *is the total mass of material that is transported on one journey (tons),* $\mathbf{L_u}$ *is the useful load of the transporting unit (tons).*

The emissions (consumption) of the transporting unit i, is calculated below :

$$E_i = e_u.\ell.\frac{m_i}{L_u} \quad \textit{for ships (MJ or tons)} \qquad \textit{(eq. 3)}$$

$$E_i = e_u.\ell \quad \textit{for trucks (MJ or tons)} \qquad \textit{(eq. 4)}$$

where $\mathbf{E_i}$ *is the consumption/emission in MJ or tons of the transporting unit i (truck or ship);* $\mathbf{e_u}$ *is the unitary consumption/emission in MJ/km or tons/km of the transporting unit i,* ℓ *is the distance of the considered journey (km),* $\mathbf{m_i}$ *is the mass of material that is transported by the transporting unit i (tons).*

Ships are assumed to always make the journey with a full load, although the required mass of material for the system is generally lower. Therefore consumptions/emissions allocated to the system depends on the mass ratio as written in (eq. 3).

Trucks are assumed to transport the exact required mass of material. Therefore, (eq. 4) does not include a mass ratio : a partially loaded truck is assumed to produce equivalent consumption/emission of a full load one.

5. RESULTS AND DISCUSSION

Results of the A71 case study are presented in Figure 5 for (a) energy consumption, (b) CO2 , (c) SO2 and (d) NOx emissions. Comments are presented below for each graph.

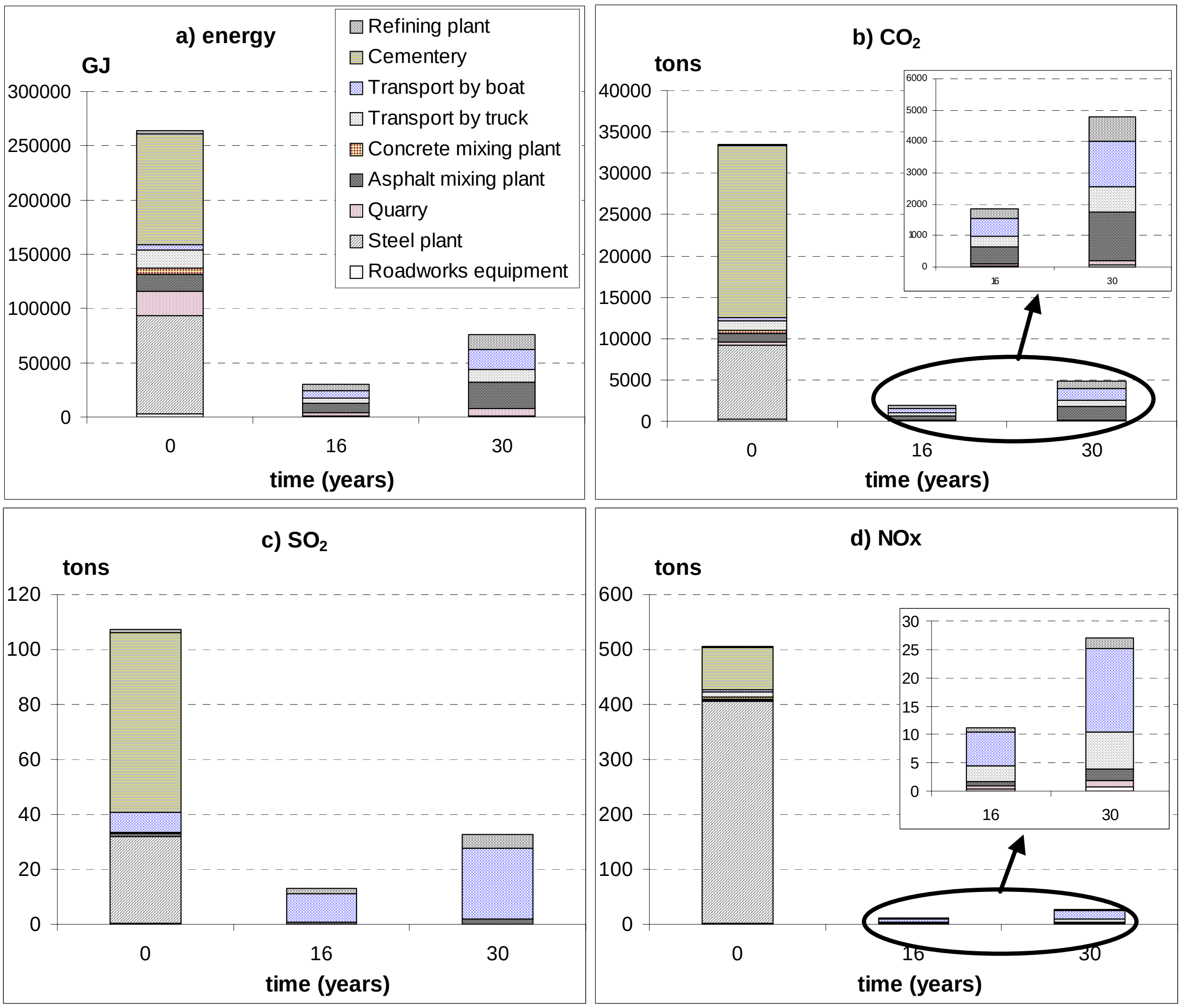


Figure 5 : inventory results of A71 construction and maintenance

Energy consumption : Only fuel energy has been considered in that study, i.e. the part of primary energy entering the system which is consumed. Materials feedstock energy, i.e. the one which could be released by incineration, was not considered in this study.

Energy consumption (Figure 5a) is found above 250 000 MJ for the road construction, which corresponds to one year of energy consumption for 6 252 French residential inhabitants in 1999, calculated from (Labouze, 2002).

Maintenance operations represent 8% and 21% at 16 and 30 years respectively, of the total energy consumption of A71 since initial construction. Transports contribution to energy consumption for initial construction is quite small (around 8%) compared to steel plant (34%) and cement works (38%). But total transport contribution increases for maintenance operations, and reach 40% at 16 and 30 years. This can be explained by the fact that maintenance works do not require cement concrete, and corresponding subsystems (cement works, steel and concrete mixing plants) do not intervene after initial construction. Comparing ships and truck transports, it can be seen that trucks are the main energy consumers at initial construction, but ships become primary energy consumers for maintenance operations. As a matter of fact, crude oil masses increase from 6,530 tons during initial construction to 26,309 tons during last maintenance operation (see Table 2).

CO_2 emissions (Figure 5b) are generally linked to energy consumption, as CO_2 is mainly emitted by the combustion of fossil raw materials. This can be verified for CO_2 emissions profiles during maintenance operations, which are very similar to corresponding energy profiles. Initial construction CO_2 emissions are mainly due to the cement works subsystem (62%). The cement works emits CO_2 during chemical process of clinker production (Holcim, 2004), as well as during burning processes. During initial construction, the contribution of transports to CO_2 emissions, is therefore smaller (4%) than their contribution to energy consumption. As noticed above for energy, part of transports to CO_2 emissions increases during maintenance operations : 49% at the 16th year maintenance work, and 47% at the 30th year.

SO_2 emissions (Figure 5c) during initial construction are mainly emitted by cement works (61%) and steel plant (29%). These figures are not surprising if bring close together with emissions of French manufacturing industries in 1999 : 25.2% of total SO_2 emissions were emitted by ferrous metals industries, and 28% by minerals and construction materials industries. Transports are only responsible for 7% of total SO_2 emissions during construction (Labouze, 2002). As maintenance operations do not require any intervention of cement works nor steel plant, the transports contribution is increased to 79%. Comparing transports modes, ships are the only mode of transport responsible for SO_2 emissions because they use industrial fuel, which contains sulphur whereas diesel fuel used by trucks is generally desulphurized (Energetics, 1998).

NOx emissions (Figure 5d).are mainly emitted by the steel plant (80%) and cement works (16%) during construction. More generally, ferrous metals industries and minerals and construction materials industries are responsible for respectively 30.3% and 70.2% of total NOx emissions in France in 1999 (Labouze, 2002). During maintenance operations, transports contribution reach 78% and 79% of the total NOx emissions of the 16th and 30th year respectively. Ships and trucks transports contributions rear up to 53-54% and 24-25% respectively.

6. CONCLUSIONS

The Sustainable Development Team of LCPC works on elaborating an environmental tool, dedicated to the global analysis of roads, called Road Modulus. This tool is separated in two parts : (i) Elementary Road Modulus (ERM) whose modelling performs an inventory of input/output flows, focusing on pavement service life (construction and maintenance during exploitation); and (ii) Global Road Modulus (GRM) whose modelling takes into account the whole road inside its territory using existing or specific indicators.

A previous work (Hoang *et al*, 2005) has detailed the ERM model, and further model development consisted in establishing the link between ERM and GRM. This paper has been detailing that part, focusing on transports as a territory dependent subsystem. For that purpose, the French highway A71 has been chosen (Figure 2), and different transport hypotheses have been made on supplying of materials (Table 2) and carriers (§ 3.2.2).

Results present flows of energy and a selection of airborne emissions (CO_2, SO_2 and NOx) of the studied system.

All calculated flows (Figure 5) show that transports of materials and equipments contribution is quite small during the road construction step, primarily due to the major contributions of steel plant and cement works subsystems. However, transports contribution becomes important during maintenance operations. This trend is mainly explained by the increasing quantity of necessary crude oil, transported by ships for long distances. SO_2 emissions are the most concerned, because ships engines require industrial fuel, which is a fuel with a high sulphur content.

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