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ENERGY CONSUMPTION AND EMISSIONS FROM THE ROAD TRANSPORT IN SPAIN: A CONCEPTUAL APPROACH

Pedro José Pérez-Martínez

TRANSyT – Transport Research Centre, Technical University of Madrid, 28040 Madrid, Spain
E-mail: pjperez@caminos.upm.es

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Abstract. The interurban road transport is one of the largest sources of emissions within all the economical sectors of Spain and accounts for 30% of the total energy consumption and subsequent CO_2 emissions. Fuel consumption, mostly gasoline and diesel, has decreased by –0.7% between 2004 and 2009 despite the increase of vehicle fleet (14.7%) and related travelled performances (3.1%). The paper estimates the energy consumption and subsequent emissions of CO_2 and pollutants, CO, NO_x, PM and NMVOC, of the interurban road transport in Spain for the period 2004–2009 by the use of a conceptual procedure. This procedure makes an effort to allocate the fuel sales, liters of diesel and gasoline, across different categories of vehicles (ages and technologies) operating on the interurban Spanish roads. In order to elaborate the inventory of energy consumption and emissions, the procedure uses the emission factors from the Copert process-based model, optimized for the Spanish interurban driving conditions. According to the inventory, total CO_2 emissions have decreased from 68.0 Mt of CO_2 in 2004 to 66.9 Mt (–1.6%). This trend is due to diesel road vehicles. The CO_2 emissions of gasoline vehicles and the total emission of related pollutants followed a downward trend due to technological improvements of vehicles and decrease of gasoline consumption. The CO_2 emissions of diesel vehicles and the total emission of related pollutants followed an upward trend due to the increase of diesel consumption despite technological improvements of vehicles. Better estimates of energy consumption and emissions are possible in the future by using specific emission factors for different vehicle categories based on telemetric systems.

Keywords: efficiency, emission estimates, interurban transportation, bottom up, Spain.

1. Introduction

Interurban road transport is by far the main mode of transport both for passengers and freight in Spain, as has gain an importance in the Spanish transport system during last two decades at expenses of rail transport. The increase is due not only in the vehicle fleet, but also is due to the road network that has been developed during this period mainly with the sources from the European Community. The Spanish interurban road network has increased from 156 thousand km in 1990 to 165 thousand km including all types of road (MF 2009a). Interurban road transport has experienced higher growth in the last year's, especially since 1995, due to the new registered motor vehicles. The number of registered vehicles has increased from 15.7 million in 1990 to over 30 million in 2008 (DGT 2009), at an annual rate of 3.5% (Fig. 1). The number of vehicles per 1000 inhabitants has also increased from 394 vehicles in 1990 to 670 vehicles in 2008. In 2007, interurban road transport represented 89.5% of passengers-km and 83.9% of tons-km registering an annual growth of 4.0% in passenger performances and 3.4% in freight performances during the period 1990–2007 (Pérez-Martínez, Monzón de Cáceres 2010). The flexibility of operations, prize advantages and time reliability makes road transport the most usable choice

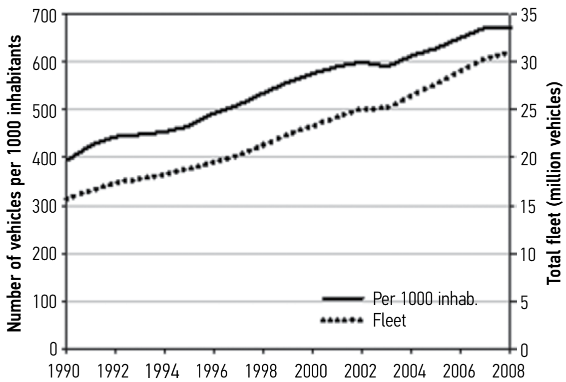

Fig. 1. Trends in vehicle fleet in Spain

among transport modes (Schipper *et al.* 1997). The growth of the Spanish economy, especially during the period 1995–2007, and associated growth of personal incomes, has generated increasing need for transportation (both passengers and freight). This economical growth has induced the increase in the ownership of private cars and the performance of transport services operating and relaying predominantly on diesel vehicles (Pérez-Martínez 2009). The diesel cars have become the most popular mode of private transport in Spain in detriment of the gasoline cars, due to lower operation costs (lower fuel prices and fuel consumption of diesel). Similarly, diesel heavy vehicles have been used for the passenger and freight transport and account for a significant share of diesel consumption in Spain (36% in 2004). In 1990, transport consumed 39.5% of total primary energy in Spain and 40.7% in 2004 (MF 2009a).

In 2004, final energy consumption of the transport sector was slightly more than 38 million tons oil equivalent (toe). Besides being the economic sector with major final energy consumption, transport is the sector with major consumption of fossil fuels (55.2%, 2004). In absolute terms, green house gas (GHG) emissions from transport during the period 1990–2009 have grown 70% (MMA 2010). At an annual growth rate of 2.8%, emissions are expected to double over 25 years (Pérez *et al.* 2010). Emission growth is due mainly to road passengers and road freight transport. The road passenger traffic demands have increased from $2.07 \cdot 10^{11}$ passenger-km in 1990 to $4.09 \cdot 10^{11}$ passenger-km in 2009. Similarly, the road freight traffic performances have increased from $1.99 \cdot 10^{11}$ ton-km in 1990 to $2.94 \cdot 10^{11}$ ton-km in 2009. Only road transport is responsible of 75% of total sector emissions (MF 2009a). The interurban road transport has experienced an average annual growth rate of 2.5% in freight and 5.1% passenger traffic performances during the last 20 years (which is expected in the future to stagnate or even to decrease due to the declining economic growth in Spain) which consequent increase in emissions of green house gases.

In the Kyoto protocol, the European Union undertook to reduce GHG emissions in its area by 8% over 1990 levels between 2008 and 2012. Current trends in transport demand and associated GHG emissions in Spain, expressed as relative indicators, show higher growth rates than the Gross Domestic Product (GDP) and the Spanish population (Fig. 2). The significant increase in GHG emissions for the transport sector in Spain cannot be explained simply by demographic growth, nor even by economic growth (Tolón-Becerra *et al.* 2010), both of which have grown at a lower rates. Therefore, mobility of persons and goods is increasing at a faster rate than in our European neighbors (Pérez-Martínez *et al.* 2010). Growth of passenger transport is also observed to be greater than freight transport, whereas the trend in Europe is the opposite.

The energy consumption pattern in Spain is characterized by mainly two things. Firstly, diesel consumption has gradually increased its share over the total energy

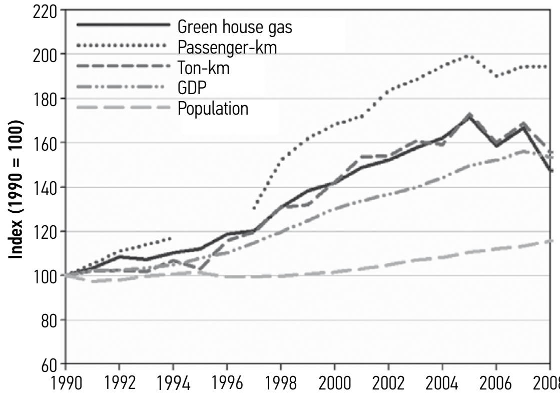

Fig. 2. Relative evolution, according to the figures of 1990, for Spanish transport GHG emissions, passenger and freight performances, GDP and population from 1990 to 2008. Base 100 = year 1990 (Pérez-Martínez *et al.* 2010)

consumption in the road transport at around 79%. It is higher, compare to gasoline consumption, due to the increased in performances of freight and passenger transport using diesel vehicles. Secondly, gasoline (mainly cars) has primarily used for private passenger transportation. The energy intensity per capita of road transport has gone from 0.46 toes per inhabitant in 1990 to 0.71 in 2007 (an increase of 54%) (Pérez-Martínez, Monzón de Cáceres 2010). Similarly, the energy intensity per unit of gross domestic product (GDP) of road transport (at constant 1995 prices) has gone from 0.045 ton per million Euros in 1990 to 0.052 in 2007 (15% growth). However, the maximum elasticity of GHG in relation to GDP was reached, and this implies that future increases in GDP will entail more minor changes in emissions (Pérez-Martínez, Monzón 2007).

Productive processes in Spain are increasing their consumption of transport, contrary to Community targets which aim to generate economic growth with lower increases in transport flows of passengers and freight (Tapio 2002; OECD 2003; EEA 2009). Therefore, a decided action to supply alternatives to motorized mobility is needed, especially regarding private car use, to reach destinations and goods that guarantee the well-being of the society (Acutt, Dodgson 1996; Schafer, Victor 1999; Rodenburg *et al.* 2002).

Emissions from the interurban road transport are directly proportional to the amount of gasoline and diesel consumption and the increase in CO_2 emissions in the past twenty years has been due both to an increase in the distance travelled by the road vehicles and in the vehicle fleet. The combination of these factors has resulted in increasing CO_2 emissions. There are methodologies and studies which estimate energy consumption and emissions from the transport sector (Lenzen 1999; Steenhof *et al.* 2006; Singh *et al.* 2008; McKinnon, Piecyk 2009). For instance, energy consumption and CO_2 emissions can be estimated based on transport data by using the methodology and the emission factors developed by the Intergovernmental Panel on Climate Change (IPCC 1995). These emissions are directly proportional to the carbon content of the fuel used in transport (expressed in kilotons of equivalent CO_2 per pega-joule, $ktCO_2$ eq./PJ). Most of the carbon is converted into CO_2 during combustion, although a part is released as carbon monoxide (CO), methane (CH_4) or hydrocarbons without methane which oxidize into CO_2 over time. Analogously, the emissions of pollutants (oxides of nitrogen NO_x, CO, non-methane volatile organic carbon NMVOC and particle matter PM), acidifying substances and ozone precursors, are proportional to the pollutant content (expressed in kilograms of pollutant per pega-joule, kg/PJ).

2. Data Sources

2.1. Activity Data and Distance Travelled

At regular time intervals, the Spanish Road Traffic Survey (SRTS) provides information with measurements of traffic flows at many locations across the Spanish road network (MF 2009b). Therefore, the level of traffic flow is disaggregated by vehicle types (heavy and light duty vehicles). Knowing the annual traffic flow at different locations and the length of the network related to the traffic flow, the SRTS provides a measure of the distance travelled by the interurban road vehicles. In 2004, the total traffic performance for the whole interurban road network (165152 km) was 241715 million vehicle-km and the annual average daily traffic (AADT) was 4010 (vehicles/day). This traffic does not include the interurban network managed by the municipalities (361192 km) which constitutes 3.5% of the total performance. The sample of vehicles monitored in the SRTS includes both Spanish and foreign-registered vehicles and constitutes a comprehensive measure of vehicle-km travelled.

In 2004, about the 13% of the total traffic performance corresponded to heavy duty vehicles (HDVs), trucks and buses (31906 million vehicle-km), and the rest 87% corresponded to light duty vehicles (LDVs), motorcycles, vans and cars (209809 million vehicle-km). Using the data from the Permanent Road Freight Transport Survey (PRFTS) of road freight operators (MF 2009c) on a ton-km basis (220816 million ton-km in 2004) and the load per vehicle (7.2 tons/vehicle), the distance travelled by trucks can be estimated (30482 million truck-km in 2004). By differences with the HDVs traffic, the distance travelled by buses was obtained (1424 million bus-km in 2004).

For the breakup of the LDVs activity data a similar procedure was followed. Using the data from the Spanish Road Traffic Survey (SRTS) and the Road Passenger Transport Observatory (RPTO) (MF 2009d) on a passenger-km basis (1844 million passenger-km in motorcycles and 330192 million passenger-km in cars) and the number of passengers per vehicle (1.5 passengers/motorcycle and 1.8 passengers/car), the distance travelled by motorcycles and cars respectively can be estimated (1229 million motorcycle-km and 186769 million car-km). By differences with the LDVs traffic data, the distance travelled by vans was obtained (21811 million van-km).

2.2. Fuel Consumption

The Spanish Government compiles the energy statistics based on the sales of gasoline and diesel fuel for road vehicles. However, the statistics do not differentiate vehicle types at the point of purchase. The division of gasoline and diesel fuel between different transport modes must be undertaken under certain assumptions and energy consumption estimates are based on the levels of activity of the transport modes consuming diesel and gasoline fuel and their average fuel efficiency. A combination of the Spanish road traffic survey (SRTS), the permanent road freight transport survey (PRFTS), the road transport passenger transport observatory (RPTO) and the fuel-efficiency data from the Copert model (Kouridis *et al.* 2000; Ntziachristos, Samaras 2000), based on the Corineair methodology (EMEP/CORINEAIR 2009), are used to estimate annual fuel consumption by road vehicles and engine technologies. These macro-level estimates of fuel consumption could independently be cross-checked with the records of fuel purchases.

In 2004, 9415 million liters of gasoline (consumed by motorcycles, vans and cars) and 25281 million liters of diesel (consumed by trucks, buses, vans and cars) were sold in the whole country (AT 2009). According with the Copert model, optimized for the Spanish interurban network and traffic conditions, and cross-checked with the fuel purchases, the following interurban fuel efficiencies were considered: 0.06 liters/motorcycle-km, 0.13 liters/gasoline van-km, 0.09 liters/gasoline car-km, 0.29 liters/truck-km, 0.28 liters/bus-km, 0.12 liters/diesel van-km and 0.07 liters/diesel car-km (Table 1).

As the only road transport modes which use both gasoline and diesel fuels are vans and cars, I have to break up the vehicle-km of these modes by fuel type. This is done knowing the registered vans (DGT 2009) and assuming that gasoline and diesel vans are used equally. In 2004, there were 737 thousand gasoline vans (32%) and 1592 thousand diesel vans (68%) and the corresponding travelled distances were 6979 million gasoline van-km and 14831 million diesel van-km. These vans consumed 942 and 1763 million of liters of gasoline and diesel respectively. Finally, the traffic of cars and corresponding energy consumption was obtained by differences knowing the proportion of the interurban energy consumption of road transport over the whole energy consumption. According to the National Emission Inventory (NEI) from the Spanish Ministry of Environment (MMA 2010), 78% of CO_2 emissions from road transport and subsequent energy consumption corresponds to interurban traffic ($7344 \cdot 10^6$ liters of gasoline and $19719 \cdot 10^6$ liters of diesel). The NEI is the main source of Spanish data on atmospheric emissions for all sources. For the road transport sector is compiled according to Corineair's guidelines and relies on activity data and survey data on fuel efficiency. Finally, in 2004 there were 67327 million gasoline car-km which consumed 6323 million of liters and 119532 million diesel car-km and 8501 million of liters related.

Table 1. Distribution of traffic (10^6 vehicle-km), fleet (10^3 vehicles), fuel consumption (10^6 liters) and fuel efficiency (l/100km) in road transport in Spain by fuel and vehicle types, 2004–2007 (source: self-preparation from MF (2009a), MF (2009b), DGT (2009) and AT (2009))

Transport mode	Interurban traffic (10^6 veh.-km)	Fleet (10^3 veh.)	Consumption (10^6 liters)			Fuel efficiency (l/100 km)
			Inter	Urban	Total	
Gasoline engines (2004)						
Motorcycles	1229	1612	80	43	122	6.5
Vans	6979	737	942	235	1177	13.7
Cars	67327	12035	6323	1783	8106	9.4
All	75535	14385	7344	2071	9415	9.7
Diesel engines (2004)						
Trucks	30482	2420	9054	578	9632	29.7
Buses	1424	57	400	55	455	28.1
Vans	14831	1592	1763	588	2351	11.8
Cars	119532	7507	8501	4367	12868	7.1
All	166269	11576	19719	5562	25281	11.9
Gasoline engines (2007)						
Motorcycles	1751	2311	113	61	174	6.4
Vans	7317	677	999	250	1248	13.5
Cars	55912	11625	5251	1481	6732	9.2
All	64980	14613	6363	1795	8158	9.5
Diesel engines (2007)						
Trucks	35510	2766	10548	673	11221	29.5
Buses	1660	61	467	64	530	28.0
Vans	19020	1759	2249	750	2999	11.7
Cars	135566	10135	9642	4967	14609	7.0
All	191756	14660	22906	6454	29366	11.7

Table 1 shows the distribution of the energy consumption estimates, by transport mode and engine technology for the years 2004 and 2007, together with the activity data and related fleet. In 2004, the energy consumption of the 26 million road vehicles was 34696 million liters of fuel (mostly diesel and gasoline). From this amount, the consumption of cars (19.5 millions) was 54%, the 2.4 million of trucks consumed 33%, vans 10% and buses and motorcycles 3%. Trucks consumed the 60% of the energy used by cars. The urban consumptions constitute the 22% of the total consumption (MMA 2010), from which 73% corresponded to diesel engine vehicles. The interurban consumption was obtained from the activity data multiplying by the fuel efficiency. This fuel efficiency varies depending on vehicle and engine types and the values were obtained from Copert. The urban and total consumption were obtained by differences from the interurban consumption knowing the share of interurban energy consumption (MMA 2010): 80% gasoline-vans, 78% gasoline-cars, 94% trucks, 88% buses, 75% diesel-vans and 66% diesel-cars.

2.3. Transport Intensity

Once a global analysis has been made of the dimension of the problem from the energy viewpoint, the next step is to analyze the intensity, as the absolute figures depend to a considerable extent on the increase in the units transported (passengers and freight) in each mode of transport (Orasch, Wirl 1997; Advenier *et al.* 2002). This is done by merging the data for transport performance with the data for energy consumption and subsequent emissions (CO_2 and pollutants). The result is what is understood by intensity (consumption of resources), and also expresses efficiency (understood as energy and/or environmental). Energy intensity is determined by two factors: the energy required to move the vehicle and the use of the vehicle's capacity (Pérez-Martínez, Sorba 2010). The energy required to move the vehicle is determined by the fuel consumption, transport conditions (traffic and geography) and the vehicle's characteristics (model and size). The use of the vehicle's capacity depends on the levels of occupancy and load of each individual vehicle, the relative use of each type of vehicle, and the distribution of the different types of vehicles within the fleet of vehicles as a whole (Léonardi, Baumgartner 2004). In addition, the concept of environmental intensity must be defined for each of the air pollutants (and for CO_2), as well as for sound contamination (Saricks *et al.* 2003). Environmental intensity is measured in emissions of each pollutant (and of CO_2) for the same units of transport.

3. Methodology

To estimate the energy consumption and emissions of the Spanish interurban road transport I use a similar methodology as in the national emission inventory (NEI) from the Spanish Ministry of Environment based on the IPCC inventory practice guidance (IPCC 1995), the EU Corineair report (EMEP/CORINEAIR 2009) and the National Inventory Submissions (UNFCCC 2010). To make the inventory, I have to use category-wise vehicle and fuel consumption statistics (i.e activity data and fuel purchases) from official publications and from 2004 to 2009 (MF 2009a; AT 2009). The EU Corineair energy and emission coefficients, adapted to the Spanish traffic conditions, driving standards and fuel characteristics, have been used to estimate the energy consumption and emission inventories. The EU Corineair coefficients have been based on an energy value approach for standard fuels, as heat values could be different from one country to another.

The fuel consumption statistics from the road transport sector, available in tons of gasoline and diesel (or liters of fuel) have been converted to energy units (tera-joules, TJ or peta-joules, PJ) through the fuel specific net caloric value (NCV). Analogously, the emissions are estimated in millions of tons (Mt) or kilotons (kt) of CO_2 or pollutant from the energy consumption through the carbon emission factor (CEF) and pollutant specific emission coefficient (PEC). The NCV, CEF and PEC values used in this paper are given in Table 2.

The energy consumption and emissions, for a vehicle type i, fuel j and pollutant k, have been estimated using the following expressions:

$$E_{i,j}=\sum_{\mathrm{i}}\sum_{j} f_{i,j}\cdot NCV_j\cdot D_{i,j}; \tag{1}$$

$$C_{i,j}=E_{i,j}\cdot CEF_j; \tag{2}$$

$$P_{i,j,k}=E_{i,j}\cdot PEC_{i,j,k}, \tag{3}$$

where: $E_{i,j}$ is the interurban energy consumption, expressed in tera-joules (TJ = 10^{12} Joules); $f_{i,j}$ is the fuel consumption, in grams of oil equivalent per vehicle-kilometer (goe/veh-km); NCV_j is the net calorific value of fuel j, in mega-joules (MJ = 10^6 Joules) per gram of oil equivalent (MJ/goe); $D_{i,j}$ is the traffic performance, in million of vehicles-km; $C_{i,j}$ are the CO_2 emissions, in tons of CO_2 equivalent (tCO_2eq.); CEF_j is the carbon emission factor of fuel j, in tons of CO_2 equivalent per tera-joule (tCO_2eq./TJ); $P_{i,j,k}$ are the emissions of pollutant k (carbon monoxide CO, oxides of nitrogen NO_x, particles matter PM and non-methane volatile organic carbon NMVOC), in kilograms of pollutant; $PEC_{i,j,k}$ is the gas-specific emission coefficient, in kilograms of pollutant per tera-joule (kg/TJ).

Transport intensities are used to estimate vehicular emissions related to transport performances and are described as the amount of species emitted (Equations 1–3) per vehicle kilometer driven (Table 1) or per passenger/ton kilometer travelled. This study presents intensity data for CO_2, CO, NO_x, PM and NMVOC, as estimated in 2004–2009.

I have developed an inventory of energy consumption, CO_2 emissions and pollutants (CO, HC, NO_x, PM) for the interurban road transport in Spain for the period 2004–2009 using Equations 1–3. I address the uncertainties in the estimation of emissions by an appropriate allocation of activity and fuel data across different types of road vehicles (Kühlwein, Friedrich 2005; Saari *et al.* 2007). Therefore, I use appropriate country specific Corineair emission factors providing ranges of uncertainties of the estimates by a cross check with the road fuel sales. Fig. 3 summarizes the approach used in Spain to estimate CO_2 and pollutant emissions from interurban road transport on a macro country basis. In the approach, I use an arrow to track the different stages at the calculation. The dotted narrow represents the cross check procedure from the fuel sales. From the approach I can see that energy consumption and emission estimates strongly depend on input parameters, such as traffic performance, fuel efficiency and emission factors (carbon and pollutant). These parameters define

Table 2. Net calorific values, carbon emission factors and pollutant emission coefficients used for gasoline and diesel by vehicle types in Spain (source: IPCC emissions coefficients (1995) and this paper

Fuel and vehicle type	NCV[a] (TJ/10^3 tons)	CEF[b] (tCO_2 eq./TJ)	PEC[c] (technology)			
			CO (kg/TJ)	NO_x (kg/TJ)	PM (g/TJ)	NMVOC (kg/TJ)
Gasoline all	44.8	85.7	3,780.2	314.3	696.0	262.1
Cars	44.8	85.7	3,309.4	288.8	604.2	259.6
Vans	44.8	86.5	7,012.9	970.1	549.0	385.2
Motorcycles	44.8	86.7	8,181.4	305.5	8671.2	480.8
Diesel all	43.3	65.6	120.6	636.6	25362.1	32.7
Cars	43.3	65.6	29.5	320.1	22847.5	7.2
Vans	43.3	65.6	193.5	294.8	41594.0	24.1
Trucks	43.3	65.6	152.8	809.9	24308.2	41.4
Buses	43.3	65.6	173.8	899.8	25507.9	55.3

Notes: [a]Net calorific value of fuel *j*; [b]Carbon emission factor of fuel *j*; [c]Emission coefficients of pollutant *k* emitted by a road vehicle *i* running with fuel *j*

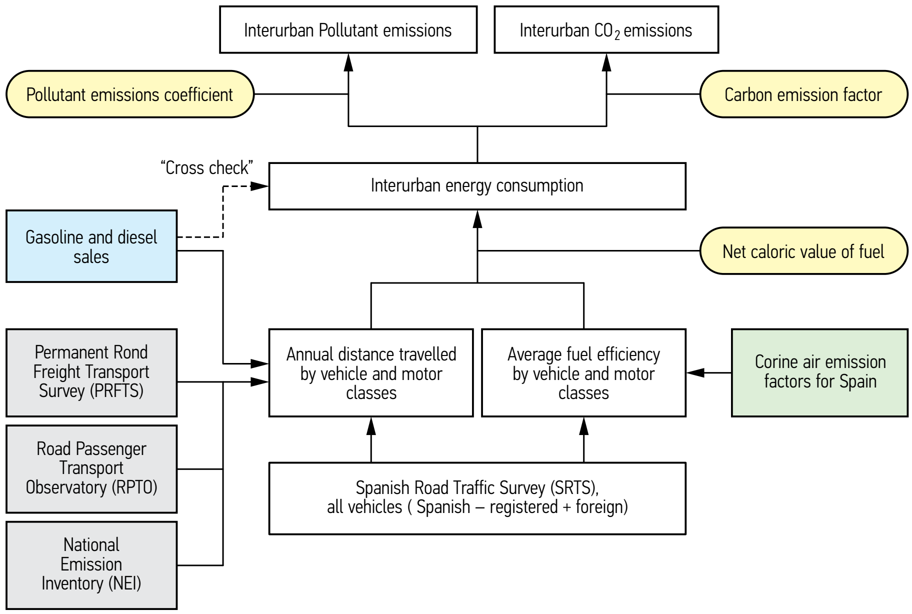

Fig. 3. Approach used for the calculation of interurban estimates of CO_2 and pollutant emissions from road vehicles

the accuracy of the estimates and can be used to cross-check the results, additionally to the dataset of road fuel sales. Some of the input parameters are really difficult to determine, depending on several variables and adding uncertainty to the estimates. For instance, PECs are determined by mileage, age and technology of vehicles.

4. Results

4.1. Energy Consumption and GHG Emissions

Fig. 4a shows the estimates of CO_2 emissions from the Spanish interurban road transport in the period 2004–2009 broken up by fuel type. The estimates were calculated by the author using data reviewed from different official national sources (Fig. 3): vehicle activity data using the SRTS, national environmental inventories (NEI) estimates for the interurban road transport (share over the total emissions) and fuel efficiency estimates using the Corineair emission factors optimized for Spain. The CO_2 emissions from interurban road transport have decreased by –1.6% from 68.0 million tons (Mt) in 2004 to 66.9 Mt in 2009, with a compounded annual growth rate of –0.3% during this period. The CO_2 emission trends from fuel consumed by all categories of vehicles have been presented in the Fig. 4a. Diesel-engine vehicles, with an average share of 73.0%, have dominance in the total estimated energy consumption and CO_2 emissions from interurban road transport.

Variations in CO_2 estimates are mainly due to differences in vehicle activity (carbon emission factors from the different vehicles remain constant). There is an upward trend in CO_2 emissions from diesel vehicles from 2004 to 2007, oppositely to gasoline vehicles, showing the continuing dieselization of the Spanish fleet. The estimates offer a comprehensive measure of CO_2 emissions for road transport within Spain, and the small deviation respect the CO_2 emissions from the fuel sales, 18.9% gasoline and –10.9% diesel engines (2004), confirms the robustness of the estimates. This difference can be attributed mainly to errors of allocation of the activity data within vehicle classes and engine technologies. Even with the small level of uncertainty shown in this paper, the current estimates need to be improved upon in the future, especially in the case of gasoline engines.

The energy consumption and subsequent CO_2 emissions from the interurban road transport represent a dynamic phenomenon with changing conditions. I try to capture these changing conditions at the national level using the 'bottom up' approach from the conceptual model represented in Fig. 3. In this approach I incorporate the factors that influence emissions, such as driving conditions (i.e. speed and road type distribution of activity data), engine technologies (i.e. emission control standards), fuel qualities, fleet age distribution of the activity data and inspection and maintenance practices (i.e. technical inspections of vehicle at regular intervals), by the Corineair emission factors optimized for Spain. This procedure contrasts with the 'top down' IPCC (1995) methodology used by the National Emissions Inventory (MMA 2010).

The growth of the activity data in the interurban road transport, specially related to diesel engines between 2004–2007, partially counteracted the improvement in vehicle fuel economy and the total energy consumption and CO_2 emissions have slightly decreased during 2004–2009.

4.2. Emissions of CO, NO_x, PM and NMVOC

CO, NO_x, PM and NMVOC are important local pollutants that participate also as ozone precursors affecting the global atmospheric chemistry. In this paper, I generate emission inventories of these four pollutants, for the years 2004 to 2009, using fuel, vehicle and pollutant specific emission coefficients given in Table 2. CO emis-

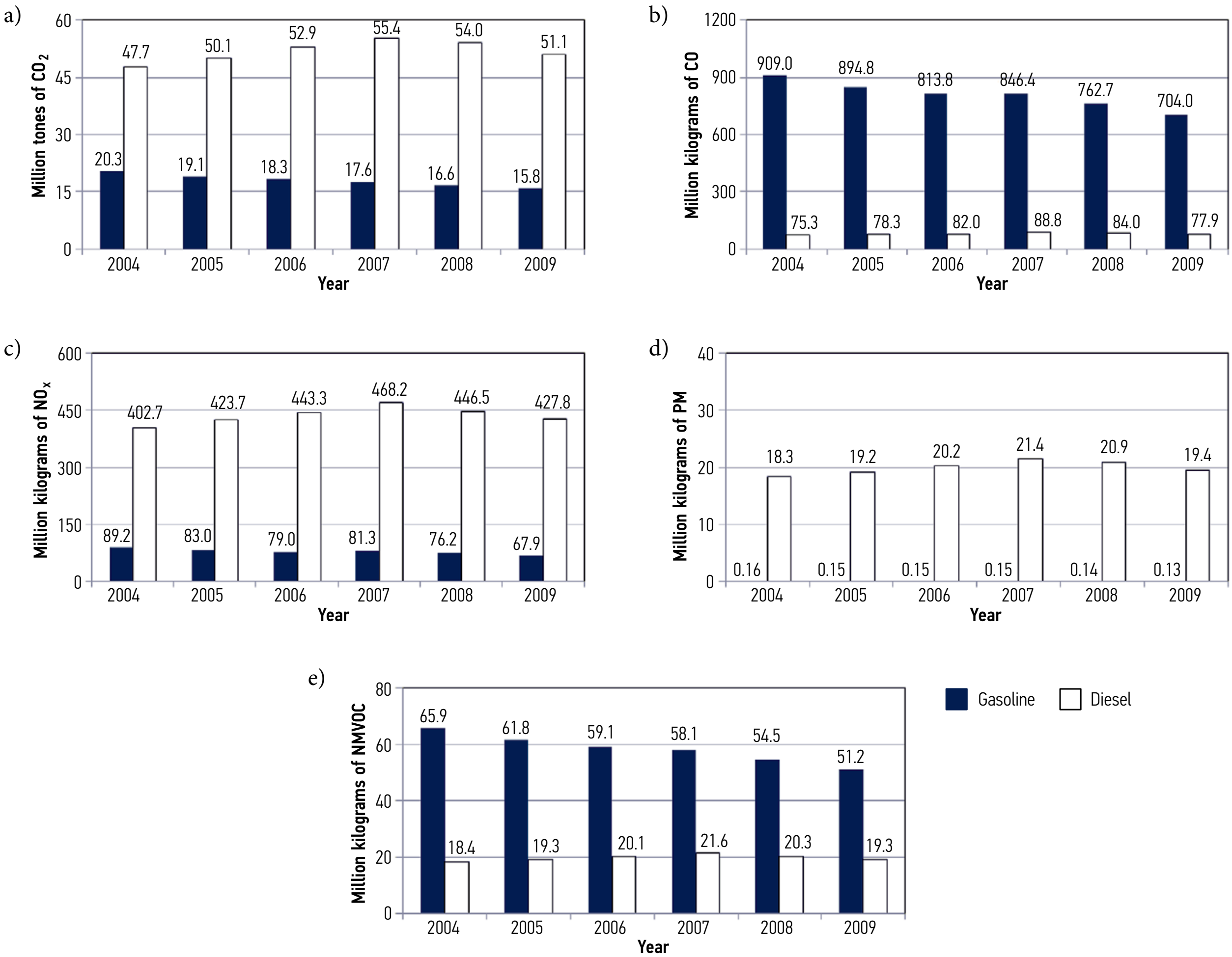

Fig. 4. Estimates of CO_2 and pollutant emissions from the Spanish interurban road transport by fuel type, 2004–2009

sions have decrease from 984 million kilograms (mkg) in 2004 to 782 in 2009 (–20.5%, Fig. 4b), mainly due to the decreasing consumption of gasoline fuel (–22.2%). Similarly, NMVOC emissions have shown a decrease from 84.3 mkg to 70.5 mkg during the same period (–16.4%, Fig. 4e). Gasoline engine vehicles emit more CO and NMVOC per unit of energy than diesel vehicles. The NO_x emissions have been found to increase slightly from 491.9 mkg to 495.7 (0.8%, Fig. 4c), due to the increasing diesel fuel consumption (7.3%) but a lower rate. Finally, PM emissions have increased from 18.5 mkg to 19.6 (5.9%, Fig. 4d) at a similar rate than the increase of diesel fuel consumption. Diesel engine vehicles emit more NO_x and PM per unit of energy than gasoline vehicles. The annual growth of emissions for these pollutants has been found to oscillate between –3.8% (CO) and 1.0% (PM) during 2004 to 2009. The increase of NO_x and PM and the decrease of CO and NMVOC in the growth rates have been attributed to similar consumption patterns of diesel (1.2%) and gasoline (–4.1%) from 2004 onwards.

Almost 91% of the total interurban CO emissions have been emitted by gasoline vehicles. Similarly, gasoline vehicles have been estimated to contribute nearly to 75% of the total NMVOC emissions from the interurban road transport. Oppositely, more than 84% of the total NO_x emissions and more than 99% of PM emissions from the interurban road transport sector have been estimated to be contributed by diesel-powered vehicles. Emission controls have been in force in Spain since 1993 together with the EU emission standards (EURO 1). Oxidation catalysts and unleaded gasoline for emissions control were introduced in 1996 (EURO II standards) for gasoline passenger cars. It has been reported that the CO emissions per driven kilometer from gasoline vehicles with no emission controls (previous to EURO standards) are higher than the emissions from vehicles with emission controls (IPCC 1995). After the year 2000 (EURO III), in passenger car vehicles, three way catalytic converters have been introduced helping to reduce CO emissions even more. The influence of the measures of the EURO standards in improving emissions has been incorporated in the paper's approach through the Corineair emission factors optimized for Spain.

Since 2005, the EU emission standards (EURO IV) have become more limiting, and the country-specific pollutant emission coefficients for gasoline and diesel driven vehicles have been reduced considerably. According to EU emissions standards for passenger cars since 2005, new gasoline-powered cars are only allowed to emit 0.1 g/km (NMVOC), 0.08 g/km (NO_x) and 1.0 g/km (CO). Similarly, new diesel-powered cars are only allowed to emit 0.05 g/km (NMVOC), 0.25 g/km (NO_x), 0.5 g/km (CO) and 0.025 g/km (PM). According to the European Commission, the emission standards of new heavy duty vehicles have been reduced by 88% (between 1982 and 2007), 95% (1982–2007), 97% (1982–2007) and 98% (1992–2007) for CO, NMVOC, NO_x and PM, respectively (Berg 2003). However, NO_x and PM emissions have increased together with the increase in diesel consumption despite technological improvements in vehicles in the period 2004–2009.

The average age of diesel fleet is about 7.1 years, lower than the age of the gasoline fleet (about 11.3 years, Fig. 5). There is no much room for further improvements in the emissions of atmospheric pollutants due to technological improvements in diesel vehicles contrary to gasoline-powered vehicles. Regarding energy consumption and associated CO_2 emissions, there is still some margin of improvement, both for diesel and gasoline vehicles, due to consumption constraints in new EURO V standards by 2010 (Ruzzenenti, Basosi 2009).

4.3. Transport Intensities

Fig. 6a shows that from 2004 to 2009 there has been a –5.5% decrease in the CO_2 intensity of diesel interurban transportation, expressed in terms of grams of CO_2 emitted per vehicle kilometer. Similarly, there has been a –0.6% decrease in the intensity of gasoline interurban transportation. The slight intensity decrease in the interurban road sector could result from the increment of vehicles' sizes. Regarding intensities of pollutants (Figs 6 b–e), expressed in terms of grams of pollutant emitted per vehicle kilometer, the most significant decrease in pollutant intensity was achieved in the diesel vehicle sector and CO (–8.9%), whereas pollutant intensity increased in the gasoline vehicle sector and PM (5.9%). Pollutant intensities decreased in diesel-powered vehicles by –7.9% (NMVOC), –6.6% (PM) and –6.4% (NO_x). Similarly, pollutant intensities decreased in gasoline-powered vehicles by –2.8% (NO_x), –1.1% (CO) and –0.7% (NMVOC). The efficiency gain in the diesel vehicle sector could result from the improvement of emission standards. The emission estimates per vehicle kilometer obtained in this work are similar to the emis-

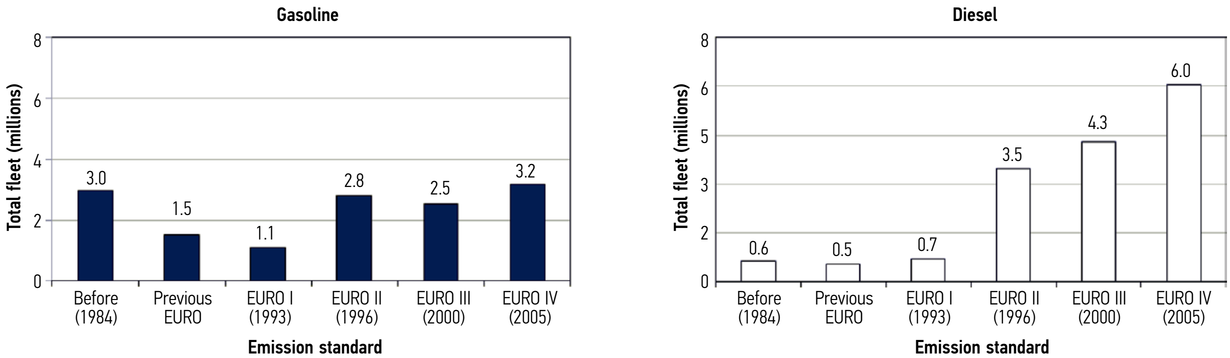

Fig. 5. Vehicle fleet in Spain by fuel type and emission standards (situation at 31/12/2009)

Table 3. CO_2 and pollutant intensities estimated for gasoline and diesel technologies by vehicle types in Spain, average values for 2004–2009 (source: this paper)

	Gasoline			Diesel			
Intensity	Motorcycle	Gasoline van	Gasoline car	Truck	Bus	Diesel van	Diesel car
CO_2 (g/veh-km)	181.0	380.8	259.5	718.2	679.9	285.9	171.97
CO_2 (g/p-km, t-km)[a]	120.6	761.6	146.6	99.7	27.3	571.8	97.16
CO (g/veh-km)	17.1	30.9	10.0	1.7	1.8	0.8	0.08
CO (g/p-km, t-km)[a]	11.4	61.8	5.7	0.2	0.1	1.7	0.04
NO_x (g/veh-km)	0.6	4.3	0.9	8.9	9.3	1.3	0.84
NO_x (g/p-km, t-km)[a]	0.4	8.5	0.5	1.2	0.4	2.6	0.47
PM (10^{-3}g PM/veh-km)	18.1	2.4	1.8	265.9	264.2	181.2	59.85
PM (10^{-3}g /p-km, t-km)[a]	12.1	4.8	1.0	36.9	10.6	362.3	33.81
NMVOC (g/veh-km)	1.0	1.7	0.8	0.5	0.6	0.1	0.02
NMVOC (g/p-km, t-km)[a]	0.7	3.4	0.4	0.1	0.0	0.2	0.01

Notes: [a]Vehicle intensities per passenger kilometer (p-km) and per ton kilometer (t-km) were estimated from the intensities per vehicle kilometer (veh-km) using the following occupation rates and loading factors: 1.5 passengers per vehicle (p/veh, motorcycles); 0.5 tons per vehicle (t/veh, gasoline and diesel vans); 1.8 p/veh (gasoline and diesel cars); 7.2 t/veh (trucks) and 24.9 p/veh (bus).

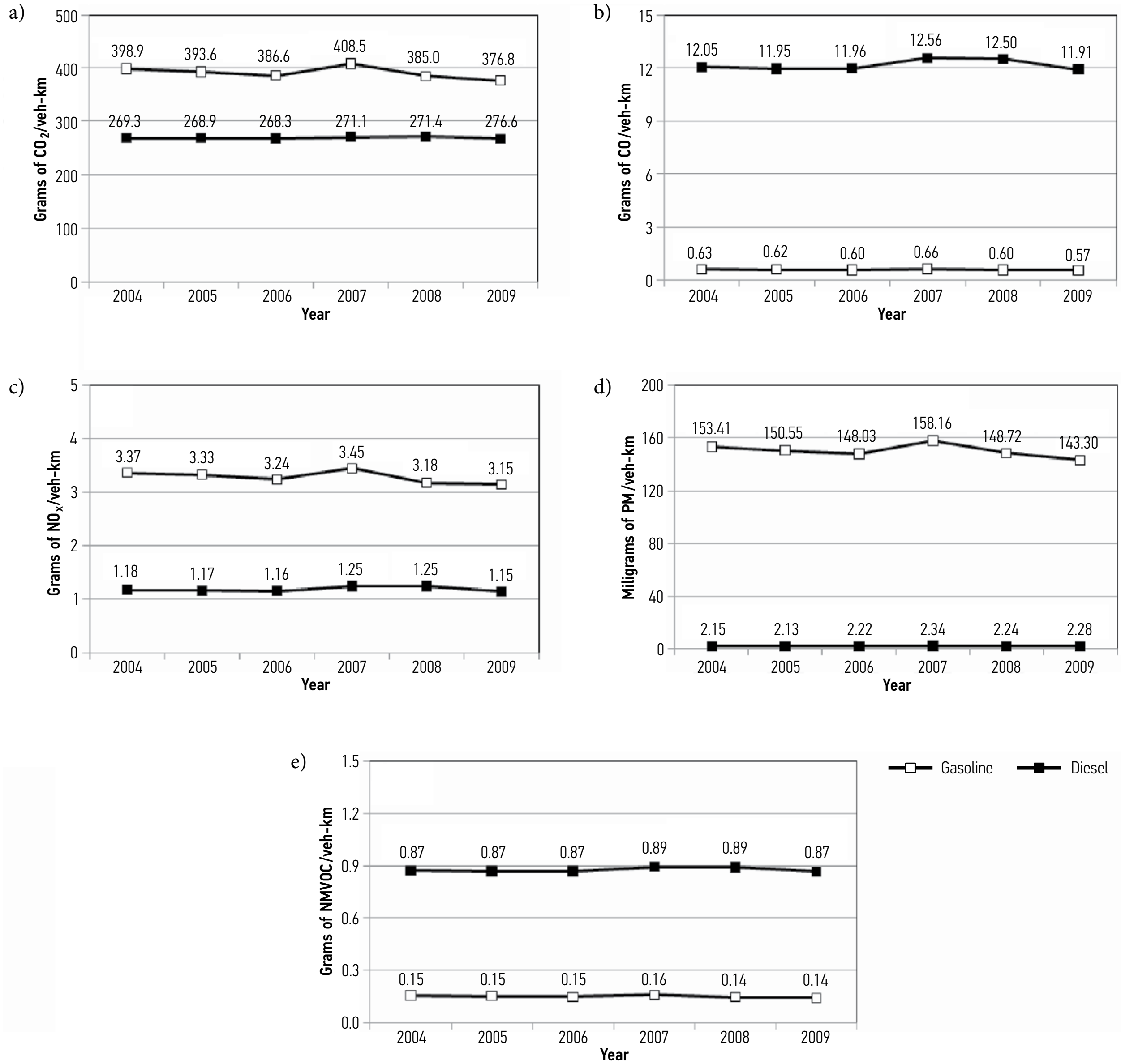

Fig. 6. Estimates of CO_2 and pollutant intensities from the Spanish interurban road transport by fuel type, 2004–2009

sion factors published in other studies (Kristensson *et al.* 2004; McGaughey *et al.* 2004).

Results of CO_2 and pollutant emissions per passenger and ton-kilometer for each interurban road mode for Spain are shown in Table 3. The aggregate of Spain's trucking requires 99.7 grams of CO_2/t-km. This value is similar to the values that have been reported by other studies (Lenzen 1999; Pimentel *et al.* 2004; Steenhof *et al.* 2006). Similarly, the aggregate of Spain's gasoline and diesel car transport required 146.6 and 97.2 grams of CO_2/p-km, respectively. These values are similar to the values found in the literature (Van Wee *et al.* 2005). Values reported in Table 3 represent mean values of the six year period 2004–2009. Although, year through, CO_2 efficiencies of interurban road vehicles and fuels have improved due to technology improvements, at the same time power and size of new vehicles are increasing, which is the reason why there has been no net significant saving in average consumption per ton and passenger-km. In general, mass-passenger transport modes emit less CO_2 than individual-private modes (27.3 vs. 97.2÷146.6 g CO_2/p-km). In freight transport, trucks emit much less CO_2 per t-km than vans (99.7 vs. 571.8÷761.6). Interurban road modes present a high variation in emissions of pollutants depending on vehicle and fuel types: buses have pollutant intensity values similar to trucks for CO and NMVOC, and gasoline cars present values of over 5 g CO/p-km and 0.4 g NMVOC/p-km. The most inefficient interurban transport modes, both for CO_2 and pollutant emissions, in gasoline and diesel technologies are gasoline vans (761.6 g CO_2/t-km, 61.8 g CO/t-km, 3.4 g NMVOC/t-km) and diesel vans respectively (571.8 g CO_2/t-km, 2.6 g NO_x/t-km, $362.3 \cdot 10^{-3}$ g PM/t-km). Differences in CO_2 and pollutant emissions between passenger and freight transport modes are similar in gasoline and diesel-powered vehicles. Differences in emissions between transport modes are partially explained by vehicle occupation rates (passengers) and loading factors (freight).

Technical efficiency gains, vehicles and fuels, and practices such as increasing the average size of trucks could increase the overall efficiency of interurban transport considerably (Pérez-Martínez 2009). Future improvements in interurban road efficiency have not to be offset by important changes in the structure and regulation of the road transport sector itself because of increasing competition, technological improvements to vehicles and improvements in operational factors. At this respect, new electronic engines increase efficiency by controlling key functions (such as the delivery of fuel) while helping to monitor critical engine parameters and diagnostic functions (Ang-Olson, Schroeer 2002). New Spanish fleet, which is powered by electronic engine management systems, could improve efficiency by better vehicle monitoring and diagnostics (telemetric systems).

4.4. Emission Trends and Sensitivity Analyses

Table 4 presents statistical data of the emission estimates together with the related linear regression analysis. The mathematical linear model enables the forecast of some trends, discovering some features and values on CO_2 and pollutant emissions by vehicle fuel technology. The F-statistic presented in the analysis of variance (ANOVA) summary of the linear model in Table 4, for CO_2 emissions of gasoline vehicles, is highly significant (at the 0.05 level) and indicates that the emissions for the six years period are different and decreasing over time. Similarly, the emission estimates of the four pollutants for the six years period show a decreasing and highly significant trend. In the case of diesel vehicles, the ANOVA for the six years period shows that the differences in emissions of CO_2 and pollutants are not significant at the 0.05 level.

Significant differences among the two vehicle fuel technologies and emissions are also observed in the coefficients of variation (CVs). In the gasoline vehicles, the average emissions and the CV in 2004–2009 were 17.9 Mt CO_2 equivalent and 9.2%. In the diesel vehicles, the CVs figures are lower, with a mean of 51.9 t CO_2 equivalent and a CV of 5.4% (similar to the CVs of the four pollutants). In 2004–2009, 435.4 million kg NO_x (5.2% CV) and 19.9 million kg PM (5.8% CV) among the years showed narrower differences, and the trend was generally undefined, negative between the first period of time (2004–2007, increased emissions) and positive between the second time period (2007–2009, decreased emissions). There are more differences among the gasoline vehicles and pollutants, with means of 809.3, 79.4, 0.147 and 58.4 million kg pollutant equivalent and CVs of 8.7, 9.0, 7.1 and 8.9%, in CO, NO_x, PM and NMVOC, respectively.

These trends represented in the six years period indicate that there has indeed been a statistically significant improvement in energy consumption, and subsequent emissions, in terms of CO_2 and pollutants related to gasoline vehicles. Though there has been a decrease in emission levels related to diesel vehicles between the second time period (2007–2009), the whole investigated period has shown non-defined trends. The decrease in CO_2 and pollutant emission levels related to diesel vehicles, from the second time period onwards, is also an indicator that transport amelioration policies have been somehow effective although masked by the current economical crisis at the national level.

A sensitivity analysis for the input parameters which define energy consumption and emissions (Equations 1–3) was performed to give a measurement of the accuracy of the result estimates, shown by the contribution to variance and the rank correlation coefficients (Table 5). A sensitivity analyses was done additionally to cross-check with national dataset of road fuel sales. Sen-

Table 4. Summary of linear trend analysis for Spanish interurban road transport emissions from 2004–2009 (source: this paper)

	CO_2 emissions (10^6 t)		CO emissions (10^6 kg)		NO_x emissions (10^6 kg)		PM emissions (10^3 kg)		NMVOC emissions (10^6 kg)	
	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel
Descriptive statistics (n = 6)										
Avg.	17.9	51.9	809.3	81.1	79.4	435.4	147.9	19,914.9	58.4	19.8
Min.	15.8	47.7	704.0	75.3	67.9	402.7	134.5	18,337.0	51.2	18.4
Max.	20.3	55.4	909.0	88.8	89.2	468.2	162.2	21,440.8	65.9	21.6
SD	1.7	2.8	70.6	4.9	7.1	22.5	10.5	1,151.3	5.2	1.1
CV[a]	9.2	5.4	8.7	6.1	9.0	5.2	7.1	5.8	8.9	5.5
Linear regression										
Adj. R^2	0.993	0.194	0.931	0.048	0.836	0.271	0.828	0.132	0.975	0.019
F	760.1	2.2	68.8	0.772	26.5	1.5	25.1	1.8	196.0	0.9
p	<0.001	0.212	0.001	0.429	0.007	0.290	0.007	0.255	<0.001	0.395

Note: [a]Coefficient of variation (100·SD/Avg.)

sitivity analysis can be used to evaluate the contributions of the input parameters to the variance of emission estimates. The results show that the input parameters, NCV, CEF, PEC, mean consumption and traffic performance, have a significant effect on emissions. CO_2 emissions of gasoline cars and NO_x emissions of diesel cars are the most sensitive to NCV of fuel (Table 5). CEF is the second most influential parameter concerning vehicle emissions. Among vehicle and fuel technologies, sensitivity analyses show similar contribution to variance and correlation coefficients except for input parameter traffic (0.233 in gasoline cars and CO_2 emissions vs. 0.075 in diesel cars and NO_x emissions). NO_x emissions of diesel cars are less sensitive to traffic performance than CO_2 emissions of gasoline cars. Increasing input parameters by 10%, the emissions increased significantly by 13.3%.

Table 5. Sensitivity analysis for Spanish interurban road transport emissions upon parameter changes (Equations 1–3): CO_2 (gasoline car) and NO_x (diesel car) (source: this paper)

Input parameters	Contribution to variance	Rank correlation
Gasoline car: CO_2 emissions (10^6 t)		
NCV[a] (TJ/10^3 t)	0.295	0.531
CEF[b] (tCO_2 eq./TJ)	0.238	0.476
Mean consumption (l/100 km)	0.234	0.473
Traffic (10^6 veh-km)	0.233	0.472
Diesel car: NO_x emissions (10^6 kg)		
NCV[a] (TJ/10^3 t)	0.340	0.555
NO_x[c] (kg/TJ)	0.313	0.533
Mean consumption (l/100 km)	0.271	0.496
Traffic (10^6 veh-km)	0.075	0.261

Notes: [a]Net calorific value; [b]Carbon emission factor; [c]Emission coefficient of NO_x

5. Conclusions

This paper attempts to make an accurate, country-base, CO_2 and pollutant emissions inventory. Based on interurban road transport counts from the NRTS, I multiply the vehicle-km data, for different vehicle types and engine technologies, by the fuel efficiency coefficients and emission factors, derived from the Corineair and Copert models and optimized for the Spanish driving conditions, to estimate the energy consumption, and consequent emissions, by the interurban road transport (Equations 1–3). An effort was done to allocate correctly the fuel sales across different categories of vehicles operating on the interurban Spanish roads.

The interurban road transport in Spain has been estimated to emit 68.0 Mt of CO_2 equivalent emissions in 2004 that decreased to 66.9 Mt in 2009 at a similar annual rate than the total national CO_2 equivalent emissions which have reportedly been decreased from 420.4 Mt in 2004 to 367.5 Mt in 2009. Thus, the interurban road transport has contributed almost 30% to the national CO_2 equivalent emissions during 2004–2009 period. Similarly, the emissions of pollutants (ozone precursor gases, acidifying substances and other gases having negative impacts on human health and ecosystems) have decreased (for the case of CO and NMVOC) or increased at a lower rate than traffic performance (NO_x and PM) due to the improvement of the technologies of vehicle engines and fuels. The decrease of CO and NMVOC and the increase of NO_x and PM have been attributed to consumption patterns of gasoline and diesel.

The estimated upward trend in CO_2 and pollutant emissions between 2004 and 2007 is due to dieselization of the Spanish fleet. Therefore, the emissions are correlated to the diesel consumption; consequently it is the downward trend between 2007 and 2009, related also to the Spanish economic recession and decrease in transport activity. CO_2 emissions of gasoline vehicles and the total emission of related pollutants followed a downward trend. CO_2 intensities decreased in diesel (–5.5%) and gasoline vehicles (–0.6%) as well as pollutant intensities: CO gasoline (–1.1%), NMVOC gasoline (–0.7%), PM diesel (–6.6%) and NO_x diesel (–6.4%).

CO_2 and pollutant emissions of gasoline vehicles during the period 2004–2009 are different, highly statistically significant and decreasing over time, oppositely to the emissions of diesel-powered vehicles. Input parameters such as NCV, CEF, PEC, mean consumption and traffic performance have a significant effect on emissions, both for gasoline and diesel vehicles.

6. Discussion and Research Needs

It results evident from the conceptual approach proposed in this paper that the activity data, along with the country specific emission factors and related fuel consumption, must be disaggregated at the maximum levels by fuel sources and vehicle categories in order to accurately estimate the country transport interurban emissions. Following this conceptual procedure I can reduce the uncertainties associated to the activity data and emission factors at a national level for road vehicles and engines using fossil fuels. These emission factors are adapted to the records of gasoline and diesel fuel purchases. However, this integration is complicated and some assumptions must be made because the traffic counts do not distinguish between engine technologies for cars and vans (in Spain buses and trucks use mostly diesel as well as motorcycles use gasoline) and also fuel purchases data, mostly gasoline and diesel, are not split between transport modes.

The country specific emission factors presented in this work, based on laboratory conditions and measurements, yield lower values for diesel vehicles and higher values for gasoline vehicles than corresponding fuel sales-based estimates. This is likely the result of a failure to reproduce completely the real driving conditions, specially appropriate speed flow relationships, on interurban roads.

It is important to develop accurate emission inventories for the interurban road transport in order to implement and propose policy and technological options for suitable amelioration measures. It is difficult for policy-makers to develop emission amelioration strategies for interurban transport when emission estimates are not accurately determined. For this main reason, in this paper I try to develop a conceptual model which reduces the uncertainties in the emission estimates of the interurban road transport in Spain through addressing the issues related to activity data by distributing the vehicle and fuel types and right determination of vehicle and fuel base emission factors for Spain.

Until now, dieselization was one of the EU's main strategies to reduce CO_2 emissions for meeting its greenhouse gas target under the Kyoto protocol. However, dieselization leads to more energy consumption and use of intensive choices (bigger vehicles), cancelling some of the expected benefits. Dieselization has also collateral environmental problems and leads to larger emissions of pollutants (basically NO_x and PM). Amelioration of Spain CO_2 and pollutant emissions must be fulfilled without extending dieselization.

Even though the emission values estimated from this paper present a deviation lower than 20% respect the fuel sales estimates, there is still some margin to improve the accuracy of the estimates and some research needs are identified. First, there is a need to define clearly the scope of the estimates according with the different interests, from the policy-makers point of view to the public and academic interests. Second, the estimated emission values need to be constantly reviewed as new methods of data collection (i.e. measurements of traffic flows) and data manipulation (Kumapley, Fricker 1996). Third, there is a need to homogenize the activity data, in terms of vehicle-kilometer, of the different data sources, from the survey of road freight transport (data provided by Spanish truck operators) and observatory of road passenger transport (data provided by passenger transport operators) to the road vehicle traffic survey (based on automatic measures collected at regular intervals) (Izquierdo *et al.* 2005). Fourth, I could propose to collect data of gasoline and diesel sales differentiating by vehicle types in order to cross the check more accurately, on bottom up basis, the emission estimates for interurban road transport.

Finaly, I have to review, in a dynamic way, the emissions factors optimized for Spain. For this task, I can use 'on-board' vehicle data to find the relationships between road and fuel types, vehicle categories, traffic driving conditions, CO_2 and pollutant emissions. In this line, the application of telemetric permits the online real-time monitoring of the road vehicles' location, speed, fuel consumption and related emissions while travelling on the interurban roads (Baumgartner *et al.* 2008). Because of telemetric, I can differentiate road energy consumption and emissions by different road types and driving conditions (Rakha *et al.* 2001). Data from the telemetric systems can provide a more realistic modeling of the interurban road energy consumption and emissions and may complement laboratory based test-cycle analysis.

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