Quantity of CO2 Emissions in the Life Cycle of a Highway Infrastructure

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Abstract: The complexity of climate change and its evolution during the last few years has a positive impact on new developments and approaches to reduce the emissions of CO2. Looking for a methodology to evaluate the sustainability of a roadway, a tool has been developed. Life Cycle Assessment (LCA) is being accepted by the road industry to measure and evaluate the environmental impacts of an infrastructure, as the energy consumption and carbon footprint. This paper describes the methodology to calculate the CO2 emissions associated with the energy embodied on a roadway along its life cycle, including construction, operations and demolition. It will assist to find solutions to improve the energy footprint and reduce the amount of CO2 emissions. Details are provided of both, the methodology and the data acquisition. This paper is an application of the methodology to the Spanish highways, using a local database. Two case studies and a practical example are studied to show the model as a decision support for sustainable construction in the road industry.

Keywords: LCA, LCI, Highways, Roads, CO2 Emissions, Methodology

INTRODUCTION AND OBJECTIVE

There is strong evidence to indicate that carbon dioxide and other greenhouse gases are accumulating at unprecedented concentrations in out atmosphere contributing to global climate change. Evidence is equally strong that human activities, mainly the burning of fossil fuels, are driving force in this process (IPCC 2007). While different industries contribute varying amounts to total anthropogenic greenhouse gases, it is incumbent upon each to understand its contribution and search for sensible ways to reduce overall greenhouse gas production. The aim of this paper is the development of a methodology to determine the amount of CO2 emissions of a highway, allowing providing solutions that can improve the energy footprint and reduce its emissions.

The Relative Impact of Road Construction

There are nearly 40 million kilometers of roads worldwide. Spain, the 52nd largest country by total area, contains 681,298 km of roads ranking it 10th worldwide in km of roadway (CIA 2011). The 40% of them are highways (December 2008) (D.G. de Carreteras 2010). Road infrastructure continues increasing at a rapid rate in Spain: over the last 35 years highway construction has increased over four-fold. Spain ranks noticeably lower in other forms of transportation infrastructure: airports (35th), railways (18th), and waterways (65th). All of this highlights the importance of roads and especially their predominant position in Spain.

In addition to providing access and mobility, roads can have a large impact on surrounding ecosystems and overall environmental quality and are responsible, both directly and indirectly, for energy consumption and CO2 emissions (Ortiz et al. 2009; Muench and Anderson 2011). It is important for the road industry to be aware of these impacts and their nature.

Broadly speaking, in Spain the transportation sector is responsible for 40% of the national energy consumption, and within this sector, road transport is responsible for 80% of the total (OFICEMEN 2011). Moreover, transportation energy use, which is the highest of any sector, is almost entirely dependent (over 99%) upon imported oil as the source (IEA 2011). Within road transport, it is likely that embodied energy in civil works of roads may directly constitute the 5% of energy consumption compared with the 95% of vehicle operation. However decisions made in design, construction and maintenance can significantly impact energy expended and greenhouse gases emitted

Goal

Spain must seek a long-term strategy to minimize energy consumption and greenhouse gas emissions while still meeting the needs of the traveling public (AENOR 2011; European Commission 2011). To achieve this, this paper provides a methodology that can calculate, measure and associate values to all aspects involved in the creation of an infrastructure. Only what is measurable is subject to review, change and improve. This investigation is a first step in the direction to reduce CO2. Those parameters will allow establishing criteria to develop more sustainable infrastructures (European Commission 2011).

What is new in this methodology is the consideration of an infrastructure as a whole dimension, counting all the life cycle. That means that the aim is to include CO2 emissions associated with the construction, maintenance and disposal of a standard Spanish roadway. Due to this, it can be applied in new roads, as a design assistance that identify more sustainable techniques, and also to existing roads, helping to reduce CO2 emissions in the maintenance phase or compensate them.

The character of the tool is comparative. As will be seen, different construction alternatives can be studied within a project (e.g., one pavement structure versus another), and also different design alternatives (e.g., the merits of building a bridge). Ultimately, information provided can shed light on how best to reduce and compensate the carbon footprint of Spain's roadways.

Conceptual Basis of Life Cycle Assessment (LCA) of Roads

The methodology and the study process have started from the application of the Life cycle assessment (LCA) as a methodology for evaluating the environmental load of processes and products during their life cycle from cradle to grave (Tillman 2000). It gives a complete picture of the interaction between an activity and the surrounding environment, and the consequences of human activity. LCA methodology is defined in the standard series ISO 14040 (CEN. 2006:14040) and consists in four distinct analytical steps: defining the goal and scope, creating the inventory, assessing the impact and interpreting the results. This last stage identifies significant issues, evaluates findings to reach conclusions and formulate recommendations. Importantly, this paper focuses only on CO2 emissions. Other inputs and outputs and their impacts are not considered. This methodology has been used in the building sector (Ortiz et al. 2010) since 1990 but has only recently received attention for road infrastructure.

To obtain the goal, a LCA methodology has been applied to the Spanish roads. Due to it is a very complex system, this paper will focus in the explanation of the first step: the study and development of the Life Cycle Inventory (LCI). This tool will end up giving an inventory of CO2 emissions that can be helpful to compare different highways.

To define this LCI tool and its limitations, some determinations will be explained:

The Lifecycle of a Road

The methodology that has been developed considers the following characteristics:

1. Materials production. Includes each step in the materials manufacturing process, from extraction to their transformation into road construction materials. Notably, this paper does not include materials transportation to the project location because of the difficulty of finding general data for roadways.
2. Construction. Includes the onsite process to commissioning work. The machinery energy includes consumption of energy during use. It is related to the power, type of engine and type of fuel.
3. Use phase. Includes all activities that occur while the highway is in place and operating. The objective of this study is the road itself, with its own lifetime and maintenance. The traffic associated, with a distinctive lifetime, is a different system and has to be treated separately. Maintenance phase. Includes rehabilitation and reconstruction activities that occur during the life of the roadway, including material use, construction machinery and transportation.
4. End of life phase. Includes demolition, disposal in a landfill and transportation to a recycling facility. Highways do not have a well-defined demolition. Usually, when a highway is significantly degraded, it becomes a road with a lower traffic category or it can fall into disuse; but rarely is it demolished.

The three phases of the life cycle of the highways are also divided in nine chapters that would facilitate the study:

- LP (land preparation)
- FC (foundation construction)
- PV (paving)
- PP (protection and sing posting)
- DR(drainage)
- IL (illumination)
- VI (viability)
- GR (gardening)

Due to this, the result allows to obtain independent sums of CO2 emissions associated to each chapter and life cycle phase. This makes comparison and conclusions easier, and allows going back into the process and obtaining better results.

The analysis period was chosen as 50 years. This is sufficiently long to include most major activities in the life of a typical roadway. Other LCA literature tends to choose analysis periods of between 40 and 50 years (Stripple 2001; Treloar et al. 2004; Roudebush 1996; Mroueh et al. 2000).

Scenarios (S)

Roadway LCA of the whole process is not static; it varies since each highway has its own function and different design characteristics. These variances have to be defined and they are related to all fixed elements that have no possible alternatives: those are the Scenarios (S). They described the already fixed situations determined by the intervention (Gonzalez and García Navarro 2009). These elements are directly related to the implantation site and the cultural and social environment, and are based on the climate and geographic conditions, construction techniques, type of intervention (roads specific characteristics) and also depend on the country and its regulation. Notice that one highway can pass through different scenarios, so they have to be defining in the previous studies of the highway.

The definition of general characteristics of Scenarios are based on the Spanish Regulations (D.G. de Carreteras 2003) and also related with climate: pluviometry (with average annual precipitation more or less than 600 mm), winter variability (chance of snow or ice), altitude (more or less than 1,200 m above the sea), type of soil (geological risk or not), slope (flat (2%), hilly (2% to 5%) or very hilly (>5%)) and ADT (more or less than 4,000 vehicles Average Daily Traffic).

Functional Units (FU)

The definition of the Functional Units (FU) is one of the most important parts of the LCA. The ISO Standard 14040 defines the functional unit as the "quantification of the role (function) of a system, service or activity, which is used as a reference unit in the LCA study" (CEN. 2006: 14044). The objective of the division in FU is to simplify complex systems, as a highway, in smaller parts that can be studied easily. A FU will be a design element associated with an energy index and an amount of CO2 emissions. That will make the comparison between them easier.

This division has been based in the geometry, traffic levels, purposes (e.g. main lanes, accesses, roundabouts...) and of course, in the characteristics that produce more CO2 emissions. They are grouped into three categories as follows:

- Those that are concerned with the section of road and firm (different width). Each one is also divided depending on the number of lanes (1, 2, 3 or 4) and the radius of curvature (r1, r2 and r3).
  - FU TRUNK
  - FU ACCESS
  - FU ROUNDABOUTS
- The auxiliary infrastructures of the highway.
  - FU BRIDGE. The division is made based on the span width, knowing that this is the chapter that produces more CO2 emissions.
    - P1 (span less than 25 m)
    - P2 (span between 25 to 50 m)
    - P3 (special design and construction cases)
  - FU TUNNEL. The division is based on the type of soil that has to be digging out.
    - TB. Soft soil
    - TM. Middle soil
    - TD. Hard soil
  - FU UNDERPASS. Two typical constructions for underpass have been chosen, based on the use, size and structure. Any other can be defined as one of them.
    - PI.M wildlife and roads (bigger structure)
    - PI.P little animals and drainage (small structure)
  - FU OVERPASS. As the previous FU, it has been studied two typical overpasses, based on the size and construction typology.
    - PS.CAM for secondary roads (asphalted)
    - PS.CAR which is a rural path (not asphalted)
- Maintenance buildings for the highways:
  - FU TOLL. Divided in three types: toll area (PY) defined by the number of lanes, toll gates (PP) defined by the ADT, and the building tolls (E).
  - FU BUILDINGS. There are many types of buildings, but their influences in the amount of CO2 emissions are small. It is based in the use. Therefore two types have been defined:

maintenance building (EM) with no installation charge, and the control building (EC) with offices in it.

Nine systems of functional units are obtained. Each one is organized into subsystems and will be analyzed in the phases defined before: construction, maintenance and deconstruction. Each one has its own variations in their definition, being system 1 (trunk) the most used in a roadway. The unit of measure will be the kilometer, except in systems 6, 7, 8 and 9 whose definition is per item.

Table 1: Functional Units

HIGHWAY								
ROAD SECTION			AUXILIARY INFRASTRUCTURE				EDIFICATIONS	
SIST 1	SIST 2	SIST 3	SIST 4	SIST 5	SIST 6	SIST 7	SIST 8	SIST 9
trunk	access	round-about	bridge	tunnel	underpass	overpass	toll	buildings
FU.C1	FU.R1	FU.RT1	FU.P1	FU.TB	FU.PI.M	FU.PS.CAM	FU.PJ.PY	FU.EC
FU.C2	FU.R2	FU.RT2	FU.P2	FU.TM	FU.PI.P	FU.PS.CAR	FU.PJ.PP	FU.EM
FU.C3	FU.R3	FU.RT3	FU.P3	FU.TD			FU.PJ.PE	
FU.C4	FU.R4	FU.RT4						

Data Source

Once the highway is divided into FU, each one is organized in a structure of chapters based on the conventional work units. Every unit is associated with a quantity of CO2 emissions (tons of CO2 emissions) and it is measured by a unit (meter, square meter, kilogram, unit...)

The conversion of each chapter and work unit into tons of CO2 emissions is based in a Spanish online database BEDEC 2010 (BEDEC. ITEC. 2011), created by the Technological Institute of Catalonia (ITeC). Although other studies have been considered as a model for the structure of the tool. Greenroads (Washington University) is an environmental rating system that has several credits of CO2 and energy counting related to pavements and based in other tool, PaLATE (Berkeley University). In Europe it can be found ROAD-RES (Denmark University) (Birgisdóttir 2005) and the UK Asphalt Pavement Model (Huang et al. 2009). These tools are very specific to the their respective country, with different electricity mixes, production practices, pavements designs, available materials, maintenance practices, and so, the effect of local climate on pavement design and maintenance will create different results depending on the location (Santero et al. 2011).

The BEDEC 2010 gives technical specifications, certifications and environmental data for each element, material and construction processes. Each work item is obtained from the addition of materials and machinery that is involved. Nowadays is the most complete database of energy embodied, CO2 emissions and material waste in Spain. The energy and CO2 emission for this database has been calculated in collaboration with the ICAEN (Catalan Institute of Energy), the iMat (Construction Technology Center) and the Polytechnic University of Catalonia. The information is based in European databases (Ecoinvent 1.3, Simpro 7.0, Inventory of Carbon and Energy (ICE)), different associations of the Constructions Industry and the Institute of environmental sciences (CML).

The factor to convert the energy in CO2 emissions and the Spanish energy mix comes from the Energy Institute of the Spanish Ministry (IDAE 2011).

To obtain the average of each unit, several Spanish projects carried out by different companies (OHL, IRIDIUM and ABERTIS C) have been studied. Different Spanish highways, with three different scenarios, have been analyzed: M–12, AG–56, AP–6, M–45, AP–4 and CM–42. While a highway has a mountain-scenario, with more chance of snow and rain, another belongs to a typical scenario of the coast, wet and warm, and others pass through the interior of Spain with thermal oscillation and dry climate. With all these data it has been created a pattern that defines each FU at all different scenarios. It also define the data base for every Spanish highway design.

Application and Validation

This section discusses how the study will achieve the stated objectives. To address this goal, two different analyses have been done based in a hypothetical Spanish scenario with the following characteristics: flat terrain (<2%), average altitude of 600m (<1200m), average annual precipitation less than 600mm, no snow and ADT less than 4,000 vehicles. Regarding to this scenario and the Spanish Regulations for Road Construction, the road section will have a wearing course with discontinuous bitumen pavement M–10 type, with a 0032 construction section (semi-rigid), with 25 cm of asphalt layer plus 30 cm of soil cement as a sub-base (D.G. de Carreteras 2003).

Analysis 1: Study and Comparison of different FU. Influence of Several Features in the CO2 Emissions

The work has resulted in a computer model that has been used to analyze a hypothetical functional unit called FU.C2.i.r located on the scenario described. The FU belongs to the Road Section category and it is part of the road trunk. The number 2 is related to the number of lanes (3,50 m wide plus an external shoulder of 2,50 m and an internal shoulder of 1,00m), the letter "i" is for illuminated FU and the "r1" is referred to the maximum radius of curvature (almost straight). The length chosen is 1 kilometer with 15 m of width esplanade, and a width stabilization of 0, 5 m. Drainage, sanitation and pipes are made by concrete. The asymmetric lights are on steel staffs of 10 m high, with mains with buried pipe and a box of regulation. The vertical and horizontal signposting and safety barriers are designed following the institutional laws (D.G. de Carreteras 2011).

An overview of the total CO2 emissions divided into construction, maintenance and deconstruction in a life cycle perspective is shown in Table 2.

Table 2: CO2 Emissions of FU.C2.i.r1

FU.C2.i.r1	Construction		Maintenance		Deconstruction	
	tn CO2	%	tn CO2	%	tn CO2	%
land preparation	397.20	2.1%	21.27	0.1%	94.73	0.5%
foundation construction	0.92	0.0%	12.13	0.1%	5.64	0.0%
paving	6,136.32	33.0%	8,431.18	45.3%	555.51	3.0%
protection/sing posting	200.73	1.1%	83.87	0.5%	46.14	0.2%
drainage	378.30	2.0%	8.19	0.0%	51.56	0.3%
illumination	20.33	0.1%	1,190.75	6.4%	13.42	0.1%
viability	0.00	0.0%	869.47	4.7%	0.00	0.0%
gardening	59.82	0.3%	18.71	0.1%	0.05	0.0%
	7,193.62	39%	10,635.57	57%	767.05	4%
TOTAL	18,596.24					

This chart present the results obtain from the methodology. The table blends partial values from each chapter with the total values from the three phases of the life cycle of this FU. But the most interesting results are the percentage.

The total CO2 emission in construction, maintenance and deconstruction of a 1 km long road during 50 years has been calculated to 18,596 ton of CO2. Of the total emissions, the 50 years of maintenance accounts for a large part of the emissions (57%). These emissions originate from the maintenance of the pavement (45%) and slightly of the road lighting (6%). The other chapters appear to be relatively small contributor to the overall impact.

The construction has also a dominant impact in the life cycle of this FU, with a 39% of the total emissions. The road surface and paving has again the main influence, with a 33%, while the rest almost represent less than a 1%.

The final disposal or deconstruction of a road accounts only for a small part of the total emissions (4%). It is normally included in the maintenance of the road because most of them have no final end. Instead they are reconstructed or replaced by a new road while the old road remains in operation. However its measurement is important because we are allowed to know the amount of material that can be recycled. And this energy could count as a subtraction of the total amount.

In connection with the analysis of the results it should be pointed out that the conditions are very complex and that this study only reflects specified cases, namely those which are described by the input data that has been used in the model. The analysis is also a first application of a complex model which should be regarded as a first research model of the conditions which are present in a road system seen from a life cycle assessment perspective.

Due to these results, it is known the items with more percentage of CO2 emissions. The studies about reduction strategies mush me done on them.

To continue testing the tool, there have been made several changes in the characteristics of the same Functional Unit FU.C2 (radios of curvature, lands slope and type of illumination).

Table 3: CO2 Emissions of FU.C2

FU.C2			Construction		Maintenance		Deconstruct		Total	
			tn CO2	%	tn CO2	%	tn CO2	%	tn CO2	%
r1	ilu	flat	7,193.62	39%	10,635.57	57%	767.05	4%	**18,596**	100%
r1	n-ilu	flat	7,173.29	43%	8,927.82	53%	753.63	4%	**16,855**	100%
r3	ilu	flat	8,239.92	42%	10,737.82	54%	853.58	4%	**19,831**	100%
r1	ilu	hilly	7,740.06	40%	10,648.65	55%	949.53	5%	**19,338**	100%
r1	ilu	v.hilly	8,457.68	42%	10,671.18	53%	1,170.33	6%	**20,299**	100%

Looking at the percentages, the variations through them are very small. The dominating activity for the emissions of CO2 is the maintenance of the highway, with an average of 55%. The construction is the second largest source of the total emissions (40%) and the deconstruction accounts only for a small part of the total emissions (5%).

Regarding the total values, there are some variations showing that the tool provide logical results, and giving the first solutions for CO2 reductions. FU with no illumination have lower amount of CO2, especially in the use phase. The amount of emissions decreases in 2.000 ton of CO2 for each kilometer of a highway. This is due to the lighting energy costs. Switching to energy saving lamps (IED) or light only when and where is necessary, will be a good reduction strategy, although the construction will have more embodied energy. Also, a brighter road surface can however require less illumination intensity and thus a reduce use of electric power.

It should be born in mind that the emission calculation from the electrical production is based on Spanish average production.

A smaller radio of curvature leads a wider section which means more quantity of asphalt and, logically more emissions. According to the chart above, the differences between the minimum radio (r1) and the maximum radio (r3) are 1.000 ton of CO2. All these emissions go into the construction phase, with no variations in the maintenance.

Regarding to the slope, the affection is only in construction, because of the amount of soil, but the maintenance is the same.

The next comparison is to realize the differences between functional units from the same category: the Road Section: trunk (C2), accesses (R2) and roundabouts (RT2). Following the regulations, the truck section is measured with an ADT>4000 heavy vehicles per day. The other two are measures with and ADT between 2000 and 4000 vehicles. That means that C2 has thicker asphalt section than the others.

Table 4: CO2 Emissions of FU.C2, FU.R2 and FU.RT2

			Construction		Maintenance		Deconstruct		Total	
			tn CO2	%	tn CO2	%	tn CO2	%	tn CO2	%
C2										
r1	ilu	Flat	**7,193.62**	39%	**10,635.57**	57%	**767.05**	4%	**18,596**	100%
R2										
r1	ilu	Flat	7,193.62	42%	9,314.82	54%	722.90	4%	**17,231**	100%
RT2										
r1	ilu	Flat	7,246.85	41%	9,668.78	55%	742.88	4%	**17,659**	100%

In the calculations, RT2 width has been assumed bigger than C2 and R2 due to the smaller radio of curvature since the car needs more space to make the turn. Even so, this fact doesn't make many variations in the total emission. The significant change is related to the thickness of the road. The size is measured according to the ADT that could oscillate between the truck FU and the access FU. That change means 1.000 ton CO2 from the total amount, especially in the maintenance phase. The construction phase remains about the same. This demonstrates again the importance of the maintenance phase and its management in the study for the reduction.

Finally, Table 5 shows the variation in emissions of different functional units, from different categories. These results demonstrate the different behavior of the diverse constructions that integrate a highway. And it can be also compared with the C2 functional unit.

Table 5: CO2 Emissions of FU.P2, FU.PJ.PY and FU.PJ.E

	Construction		Maintenance		Deconstruct		Total	
	tn CO2	%	tn CO2	%	tn CO2	%	tn CO2	%
FU.P2.bridge	14,852.39	59%	7,669.49	31%	2,571.21	10%	**25,093**	100%
FU.PJ.PY. toll area	5,843.85	34%	10,740.17	63%	543.79	3%	**17,128**	100%
FU.PJ.E. building toll	311.10	20%	1,194.51	76%	64.13	4%	**1,570**	100%

The total emissions of a P2 bridge (with spans of 40m) are 25.000 ton of CO2. Comparing with FU.C2, the construction phase becomes very important (doubles it) and also the deconstruction phase (triples). The maintenance phase is the only that reduce its influence from the 60% to the 30%.

To give an example for a toll building, it has been chosen a real example of one of the highways that have been studied (200 m2 office building). This value shows the little influence of this infrastructure comparing to a kilometer of a two lane functional unit. (1.500 ton the building and 18.500 ton the FU.C2)

For the toll area, an example with 6 lanes traffic is chosen, which 10.000m2 of asphalt surface, including the acceleration and deceleration area. To verify this result, a FU.C2 with 11.000 m2 of asphalt has been calculated and the result (18.500 ton of CO2) has similar values with the toll area (17.200 ton).

By these examples, the tool developed has been tested. The situation for a complete road system is very complex and the analysis in this study covers only some simplified cases, focused on a method in which the construction, maintenance and deconstruction have been broken down to small process units. This will help achieving different alternatives to reduce the amount of emissions: changing materials, machinery, construction techniques, maintenance management, illumination, recycling, etc. Further work should be able to verify and improve the results from this model.

Analysis 2: Comparison of Project Alternatives

Three cases of study have been studied to realize how this tool behaves with large projects and aid for a more sustainable design. The first case study will show the importance of an infrastructure, measure it by CO2 emissions. The second, the influence of design in the quantity of CO2 and, in the third, the traffic will be inserted.

The first case study (Table 6) is an example of a Spanish highway between Madrid and Barcelona (650 km). The distribution has been summarized in several FU, as it is showed in the following chart, with its amounts of CO2 emissions.

Table 6: CO2 Emissions of Spanish Highway

	type of FU	ton CO2/FU	uds/FU	total	
	FU.C2	18,596.26	1300	24,175,138.00	
	FU.R2	17,231.34	80	1,378,507.20	
	FU.RT2	17,658.51	30	529,755.30	
	FU.PJ.PY	17,126.81	6	102,766.86	
	FU.PJ.E	1,569.74	6	9,418.44	
	FU.P2	25,093.09	60	1,505,585.40	
TOTAL				27,701,171.20	ton CO2

The total emissions in its 50 years are more than 27 million tons of CO2 emissions. This example serves to show the high value of emissions that means an implantation of a highway, without taking into account the traffic flowing through it. But it also helps to detail the parts with more emissions: the truck. With a small change in its design, the total reduction on the total can have important dimensions.

In the second case (Table 7), two different design options have been studied for the same highway. An unreal postulation has been propose, where a designer can chose between a bridge of 1,5 km (both directions) or a 40 km highway (both ways), with 20 km of accessed lanes, 2 km of roundabout lane, 2 toll areas and two buildings tolls (one for each direction).

Table 7: CO2 Emissions of 2 Options for Spanish Highway

	type of FU	ton CO2/FU	uds/FU	total	
	FU.C2	18,596.26	80	1,487,700.80	
	FU.R2	17,231.34	20	344,626.80	
	FU.RT2	17,658.51	2	35,317.02	
	FU.PJ.PY	17,126.81	2	34,255.62	
	FU.PJ.E	1,569.74	2	3,139.48	
TOTAL option 1				**1,905,039.72**	ton CO2
	FU.P2	25,093.09	1.50	37,639.64	
TOTAL option 2				**37,639.64**	ton CO2

In this case, the results are clear about the emissions that can be saved using the option 1. Building a bridge means shorter route and therefore less emissions, with five times less energy that the other option. As it has been said, this is an unreal example but it shows how useful this tool could be in the design phase.

This work is a preliminary study where the road system has been studied in terms of life cycle assessment methodology. The contribution from traffic during the same time period was not included. Due to the Sightline Research (Williams-Derry 2007) a small introduction has been made.

As seen in the first part of the Analysis 1, the estimation of constructing a two lane-km of highway, maintaining it for 50 years and demolishing it, releases roughly 18.500 tons of CO2. Some road-building proponents often suggest than adding lanes to a highway will reduce greenhouse gas emissions. By easing congestion, they argue, next lanes will reduce the amount of fuel that vehicles waste in stop and go traffic, leading to lower releases of climate warming gases from cars and trucks. This Sightlane study expects a reduction associated with highways expansion (including both congestion created by construction and maintenance, and congestion relieved after construction) by 7.000 ton CO2 in all the life cycle.

To verify this information, we need to count how much CO2 you increased in all the LCA with a one-lane more. The result (with the methodology developed in this paper) is 23.230 ton CO2 for three lanes, which means 4.720 ton CO2 more than a two lanes highway. Adding the reduction from the Sightlane study, the total amount means that constructing another lane in a highway can reduce the emissions in 2.000 ton CO2 per kilometer. That is a very interesting result for future highways.

This application shows how this tool could be used with other studies for making comparatives that can help in the CO2 reduction of a highway and makes them be more sustainable.

Result and Conclusions

This paper shows a methodology applied to calculate CO2 emissions associated with the energy embodied on a roadway along its life cycle. These infrastructures are technically relatively complex.

Specific circumstances for roads that make them different from other products are for example that each studied object is unique and the variations are significant due to geo-technical conditions, geographic location of the road, meteorological conditions, traffic intensity etc. Due to the varying conditions, the possibility of using a static life cycle model is limited. The work has instead focused on a method in which the construction, maintenance and deconstruction of the road have been broken down to small process units, structured by chapters. Applying the results to different combination of functional units for the same path, may establish comparisons, balances or alternatives considering emissions as one of the aspects to be assessed. Details were provided of both, methodology and database, developed for this purpose.

The methodology was tested in different case studies to show some results obtained. Each one assist to find different solutions to reduce the energy footprint, and making roadways more sustainable.

Regarding partial results of each Functional Unit, these allow for a more successful solution in the emissions reduction plan, focusing on the chapters with more emissions (changing materials, machinery, construction or maintenance techniques...). An example of partial results is the CO2 emissions associated to the LCA of 1 kilometer road with two lanes during 50 years. Within the total value of 18.594 ton CO2, the main value is the 80% caused by the road paving-45% maintenance activities, 33% construction and only the 2% deconstruction-.

Regarding total results of the Functional Units, this methodology allows to associate CO2 emissions to all different functional units. For example, within the cases studied, 1 kilometer of a bridge has 25.000 ton CO2 associated in 50 years, while 1 km of a road with the same characteristics has 18.594 ton CO2. This information helps in the selection of different alternatives routes with less CO2 emissions.

Still there is a room for improving the quality of data fed to this LCA study. Its application in road practice is relatively new, and so inventory data for some material and processes are yet to be verified. The data comes from more than one source and the compatibility need to be studied. The application to other cases will enlarge the database and will permit the validation of the study by comparing with other similar existing methodologies and also through real case studies. A step has been done initiating a study of the impacts of roads in the production of CO2 emissions. This can be applied to other environmental impacts and even to other types of civil works.

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