Carbon foot print evaluation in tunneling construction using conventional methods

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HIGHLIGHTS

- A simplified CO_2 calculation model is proposed and calibrated, and then it is used to analyze CO_2 emission of different tunnels.
- Emissions rates in $kgCO_2/m$ for tunnels under different conditions are given.
- Main CO_2 emission is related to manufacturing of concrete for the support/lining.
- RMR and cross section (S) are the main tunnel parameters affecting CO_2 emissions.

ABSTRACT. The construction sector is one of the most relevant related to the emissions of the greenhouse gases (GHG). Within this sector, the weight of tunneling construction is significant considering the resources employed (for example, tunnel construction represents about the 25% of the total concrete used in civil works in Spain). Nevertheless, it seems that there is still a gap to make the calculations of these emissions for each specific tunnel during its design and later during its construction, taking into consideration the specific parameters that influence them.

The present work provides the fundamentals for applying in a simplified way the Life Cycle Assessment method (LCA). A simplified calculation model is propose to estimate the CO_2 emissions of each step of the construction phase in the case of tunnels advanced through medium to low strength rockmass by conventional methods (drilling and blasting, roadheader or hydraulic breaker hammer). The CO_2 emissions can be calculated by estimating the amount of diesel, electrical energy and materials consumed, and then using the conversion factors to CO_2, from well recognized organizations or more domestic sources (as some Spanish institutions).

The simplified calculation model has been tested with data of a real tunnel and then it is used to analyze CO_2 emissions of different tunnels to determine the influence of different factors. The main conclusion is that, for this kind of tunnels, the most relevant contribution to CO_2 emissions is that associated to the fabrication of concrete used in the support and lining of the tunnel which represents, in average, about 80% of the total.

Keywords. Carbon footprint; Life cycle assessment; Tunnel construction

1. INTRODUCTION

The construction sector is one of the most relevant in the emissions of the greenhouse gases (GHG). After Huang et al (2018), the total CO_2 emission of the global construction sector (which includes building and infrastructures) was 5.7 billion tons in 2009, contributing 23% of the total CO_2 emissions produced by the global economics activities. It is therefore important that this sector significantly reduces its consumption of energy and materials by identifying low-impact methods (Fedele and Severini, 2015). One of the most relevant activities within this sector is the tunnelling construction; for example, in the case of Spain, Galán et al (2010) estimate that 25% of the total concrete used in civil works in Spain is related to tunnels.

An important factor to take into consideration around tunnelling construction is to ensure that its sustainability has been taken into consideration during its planning and design. According to Sterling et al (2012) it is generally accepted that these underground facilities are good for the economy, for the society development and contribute to reduce the CO2 emissions but, might be detrimental for the underground environment resources like space, materials, water and energy. Maximizing the use if these facilities for different purposes (i.e.: transportation, network cables, electricity and sewers), ensuring that the amount of energy and resources used for the construction of the facility is balanced by the savings got during its life comparing to surface infrastructures and ensuring its positive impact in the neighborhood improving the quality of their life, should be the key factors to take into consideration for that evaluation. Authorities may also play key role to manage the underground works to ensure its sustainability, having a planning defined with potential corridors for future underground activities should avoid potential conflicts with future developments.

According to Zhang et al (2016), governments and researchers have shown more concern to the GHG emissions during tunnels construction, during last ten years. However, these concerns have not been translated into detailed calculations of these gases, before and during their construction, and no specific actions were requested, either from governments or the industry for its reduction. As it is pointed out in Li et al, (2015), in tunnel engineering at present, CO_2 emissions (the most important of the GHG) are generally estimated during the planning design stage or obtained by statistics of total emissions after completion; however, the different amount of emissions in each ring and relevant influential factors are seldom considered. From all this information above, it seems that there is still a gap to make the calculations of these emissions for each specific tunnel during its design and later during its construction, taking into consideration the details and the differences between each one of them. That should be the first step to help to develop plans to reduce those emissions caused from these activities and develop specific actions to reduce those values as much as we can, or achieve specific targets, and make this activity more sustainable in the long term.

It will be useful if this analysis is done during the design phase of any new project. Having the planned emissions calculated during the design phase, will allow the engineers with the opportunity to reduce or mitigate such impact, looking for alternative equipment and plans to lower the emissions, and providing a control target level of emissions in the execution phase (Ahn et al, 2010).

The emissions related to the tunnel construction have been calculated since several years ago. For example, Li et al, (2011) made the calculation of the CO_2 emissions per meter for a new highway tunnel construction in China, and concluded that the endogenous CO_2 emissions are mainly from construction equipment powered with fossil fuel combustion motors, during the tunnel building period. These emissions from construction fossil fuel include gas, diesel, oil, coal and asphalt. The oriented-diesel CO_2 emissions are at high level with the proportion of over 90% in comparison with other fuel types in tunnel building.

During the same year Miliutenko et al, (2011), in Sweden, started to use the Life Cycle Assessment (LCA) method, rarely used at that time, including not only the emissions during the construction phase but also during its operation. This study sought to improve understanding of the life cycle energy use and greenhouse gas emissions of transport infrastructure, using the example of a road tunnel. Two levels of analysis were used: 1) detailed data inventory for the construction of rock tunnels; and 2) screening assessment for the life cycle phases of the whole tunnel infrastructure (including their main parts: concrete and rock tunnels). The first level of analysis showed that production of materials (i.e. concrete and asphalt) made the largest contribution to Cumulative Energy Demand (CED) and Global Warming Potential (GWP). The second level of analysis indicated that concrete tunnels had much higher CED and GWP per lane-meter than rock tunnels. Moreover, the operational phase of the tunnel was found to have the highest share of energy use and GHG emissions throughout the tunnel life cycle.

Huang et al, (2013), using the LCA method quantified in Norway (country that has the goal to be carbon neutral by 2050) the emissions, per meter of rock tunnels, during its whole life, including the operational part. Later, in Huang et al (2015), they estimate the CO_2 emissions related to excavation of tunnels in good rock masses (no support or lining is needed). These results were used later by Fremo (2015), to calculate the emissions in the Byasen tunnel, during its construction and operation. At the same time, this study is comparing the potential emissions for this facility and its use, with the goals set in the Trondheim municipality's environmental program, where the tunnel was constructed. More recently Huang et al (2020) continued the previous work and analyze the CO_2 emissions related to the support in drill and blast tunnelling in medium hard rock mass considering only two contributions: bolting and spraying concrete (shotcrete).

Lee et al. (2016) identified the seven tunnel work steps (from twenty tunnels studied) that are causing the main environmental load during their construction: lining concrete, shotcrete works, tunnel portals and open cut excavations, drainage works, steel-pipe-reinforced multistep grouting, muck hauling operations and rock bolt works. Moreover, the analysis confirmed that these seven major work types account for 89.22% of the entire environmental impact. Later Lee et al. (2017) have developed a model based on LCA method that can estimate the environmental load through information available in the early design phase which allows making decisions on design alternatives. These calculations are based on the existing information in a database that includes the environmental loads per unit calculated based on the standard quantities and required resources by major work types. This information allows making decisions on design alternatives, looking for options with lower environmental impact. In this way, Lee et al. (2016, 2017) method not only estimates the CO_2 emissions but also more complex environmental parameters.

In a recent work, Xu et al (2019) describe the CO_2 emissions related to tunnels excavated by drilling and blasting excavated in rock masses with different strength. They carried out a global analysis taking into account all the different tunneling phases: advance support, tunneling (excavation), rock support, lining, ventilation and lighting. The analysis concluded that tunnels with weak rock conditions generate more GHG emissions in construction, and rock support and lining were the major emission processes.

There are also some studies around these emissions with slurry shield Tunnel Boring Machine (TBM) only during the construction phase not including the operational part. For example, Li et al, (2013), describes the CO_2 emissions in a tunnel built in Shanghai, pointing out the differences between the emissions of different machines and the importance of the driving speed for the fuel consumption during the construction period. In the same way, Li et al, (2015), uses the carbon coefficient method to calculate the emissions for a tunnel construction. The results from this tunnel showed very detailed information of the emissions per ring of shield tunneling of which 93% are from the materials used. There were also important actions taken in this project to reduce these emissions during its construction.

Finally it has to be pointed out that several works have estimated the CO_2 emissions related to tunnel construction in wider analysis of railway infrastructure as, for example, Chang and Kendall (2011), Tuchschmid et al (2011), INECO (2012), Morita et al (2012) or Fedele and Severini (2015).

Nevertheless, there is a leakage of data or methodology information in these works and they only give a global value of emissions and does not allow estimate the emissions related to different tunnelling tasks.

Although a number of studies have been carried out during last years, no many of these studies have been published; moreover, it can be considered that the number of works that we can find in the specialized literature is rather low for the relevance and complexity of the topic. Effectively, both the number of the parameters that have influence, operating and economical ones, and its dependence of the specific area or region in which the civil work is carried out make interesting different studies in order to represent the variability of the problem. Several countries or regions are represented by corresponding studies (USA, China, Sweden, Norway, Korea, Italia…etc.) but it is desirable to extent results to more regions and to more conditions because in some cases the results of these regions are not completely useful in others. For example, the Carbon footprint of a road tunnel excavated through a very strong rock mass in Norway by drilling and blasting is much less that a similar tunnel through a weak rock mass in Spain excavated by hydraulic breaker hammer.

In this way, the authors have detected a gap of studies or results related to tunnels excavated through medium to low strength rock masses by conventional methods in which several aspects such as different rock mass strength, different excavation system or different cross section, are taken into account; moreover, only one published work which faces the problem in this way, Xu et al (2019), has been found. On the other hand, the CH_4 emissions that occur in some cases during tunnel excavation, is a special parameter that has to be also taken into account. Several published papers study this topic due to the relevance for safety and ventilation design, Rodríguez et al (2011), Copur et al (2012), Baldini (2017), Zhang (2019)…etc, nevertheless, it is not usually to analyse the problem from an environmental point of view as in Rodríguez et al (2012).

The present work provides the fundamentals of a procedure or method to estimate the CO_2 emissions of each step of the construction phase in the case of tunnels advanced by conventional methods. This calculation model does not include the emissions during the rest of the life of this facility (operation, maintenance and the dismantling and removal of the tunnel at the end of its life), focusing only in the construction part.

The objective is to define a method to calculate CO_2 emissions suggesting different formulae to determine the amount of energy and materials used in a tunnel under construction, in the same way that there are methods to design the tunnel ventilation or tunnel support.This method should not be considered a simplified Life Cycle Assessment (LCA) but a complementary one. The LCA establishes a frame but does not define specifically how to calculate materials or energy.

On the other hand, there are some relevant differences with the LCA. The full application of LCA method should include the environmental impact throughout the product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. from cradle to grave); however there are some particularities that make tunnelling construction different from other activities or industries. Following to Shillaber et al. (2016b) neither maintenance operations of the civil infrastructure nor demolition and end of life disposal are included in the life cycle for most ground improvement applications and foundation types. On the other hand, only CO_2 emissions are estimated; other environmental impacts such as other emissions to air (i.e. SO_x or NO_x gasses), emissions to the water (i.e. BOD, Phenol…etc.) or emissions to land (i.e. solid wastes) are not taken into account.

As it is defined in the "ISO Standard 14040:2006 Environmental management — Life cycle assessment — Principles and framework", there are four phases in an LCA: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) life cycle interpretation. In the present work, the calculation procedure of CO_2 emissions is not described following this scheme but it is described following the typical task organization in a tunnel, which is more comprehensible and easy to understand. Nevertheless, the correspondence with standard phases of a LCA could be established approximately as follows.

Sections 1 and 2 of the present work give the main information of the phase 1 “Goal and scope definition” of the LCA method, defining the objectives of performing the LCA study, the application areas of the LCA results, the potential audience, the data category…etc.

Section 3 is equivalent to the phase 2 of the LCA “Life cycle inventory analysis”, which involves the collection and quantification of inputs and outputs of materials and energy associated with a product system under study, and phase 3 “Life cycle impact assessment” which is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts (in this case, Carbon footprint).

Finally, sections 4, 5 and 6 can be considered the phase 4 “Life cycle interpretation” of the LCA in which results of previous phases are analysed, key issues that contribute significantly to the environmental impact (Carbon footprint) of the product system are identified and finally conclusions are drawn and recommendations made as to the environmental aspects.

2. BRIEF DESCRIPTION OF THE CALCULATION METHOD ASSUMPTIONS

The main features of the proposed method are described here below:

- **Flexible.** Can be used for three different methods to advance a tunnel (drilling and blasting, hydraulic breaker hammer and roadheader), and for the tunnel specifics (dimensions, length, RMR, amount of materials used, etc.). It will possible to adjust the conversion factor to CO_2 using the country or region specifics.

- **Easy to implement**. No special skills around CO_2 emissions are needed for its use. Its simplicity is based on the following: a) the use of the conversion factor method (from recognized organizations), to convert the amount of energy and materials consumed into CO_2 emissions; b) only account for the CO_2 emissions and not for other GHG like CO; c) focus on the tasks to construct the tunnel.

- **Provide a holistic view of the CO_2 emissions**. This approach will make a complete analysis of the emissions for every single step of the tunnel construction, not only the ones associated with the advancing cycle and supporting, but also will include all the energy consumption from the rest of the equipment needed for this work: the fan for the tunnel ventilation, the pumping system, the WWT plant and all the other services needed (lighting, offices and external facilities).

- **Use the actual best practices in the civil industry**. We will follow the general guidance given by Shillaber et al, (2016a) for the civil underground works.

The scope of the study is to assess the CO_2 emissions associated to the excavation of a stretch of a tunnel that starts at length L_O and finishes at length L_F. A ratio of CO_2 emissions per m of tunnel can be deduced easily by dividing the total emissions produced in this stretch by its length (L_F-L_O). Other assumption is that all parameters, such as cross section or rock mass quality, remain constant.

The simplified calculation model or procedure reproduces the standard phases during tunnel construction: excavation, rock waste removal, support installation and lining; moreover the other auxiliary services or facilities are taken into account.

The contribution to the total CO_2 emissions of the tunnel related to the excavation, rock waste removal and auxiliary services represent less than 20%. Nevertheless, the emissions for each phase are estimated in order to determine their relative weight. Only the emissions related to the energy, both electricity and fuel, necessary for the work of the machinery are estimated. In these phases or tasks the quantity of material consumed is not relevant and the emissions related to manufacturing or maintenance of the machinery is not taken into account.

On the contrary, a huge amount of materials are used during the support installation and lining. For this reason only the CO_2 emissions related to the manufacturing and transport of the materials are calculated and the energy spent by the machinery in these tasks is neglected. A schematic overview of the system boundary is shown in Figure 1.

The CO_2 emissions can be estimated assuming three different excavation methods: 1) drilling and blasting, 2) roadheader, and 3) hydraulic breaker hammer. The model include the emissions due to the fabrication and transportation of the required materials for the supporting and final lining of the tunnel as well as the calculations of the emissions of the electrical energy consumed by the different motors that move the fans for the ventilation, the pumping system to remove the water from the tunnel (in the case of descending slope), the waste water treatment (WWT) plant, the illumination of the tunnel and the rest of the facilities at the outside area near the tunnel portal. Other factors that have been also taken into consideration are the driving speed of the different diesel driven equipment, and the slope of the tunnel, that will increase the diesel consumption, especially during the transportation with the trucks fully loaded. Finally, because of its importance when the tunnel passes through a methane bearing strata (Rodriguez et al, 2010), the calculations of the methane emissions, expressed as CO_2 equivalent, have been included.

The CO_2 emissions were calculated by estimating the amount of diesel, electrical energy and materials consumed, and then using the conversion factors to CO_2, from well recognized organizations or more domestic sources (as some Spanish institutions). As it has been said, the operations and maintenance part it is not include into the calculations as the main focus of this work is the tunnel construction, meeting the design specifications (size, length, slope, construction timing, etc.) and defining a simplified model that could be used for all potential tunnel constructors or engineers in charge of the design, which is a different area than the operations and maintenance of this infrastructure later on.

On the other hand, neither demolition nor reuse or disposal of the materials used during the tunnelling construction, are considered in the calculations. The practice used normally is "abandon in place", closing all potential access to inside**.**

The simplified model is tested with data of a real tunnel constructed in Spain, and then it is used to analyse CO_2 emissions of different tunnels to determine how different factors can influence the amount of emissions released. The model is also tested with data of the bibliography. Finally, the more relevant results are pointed out in the conclusions.

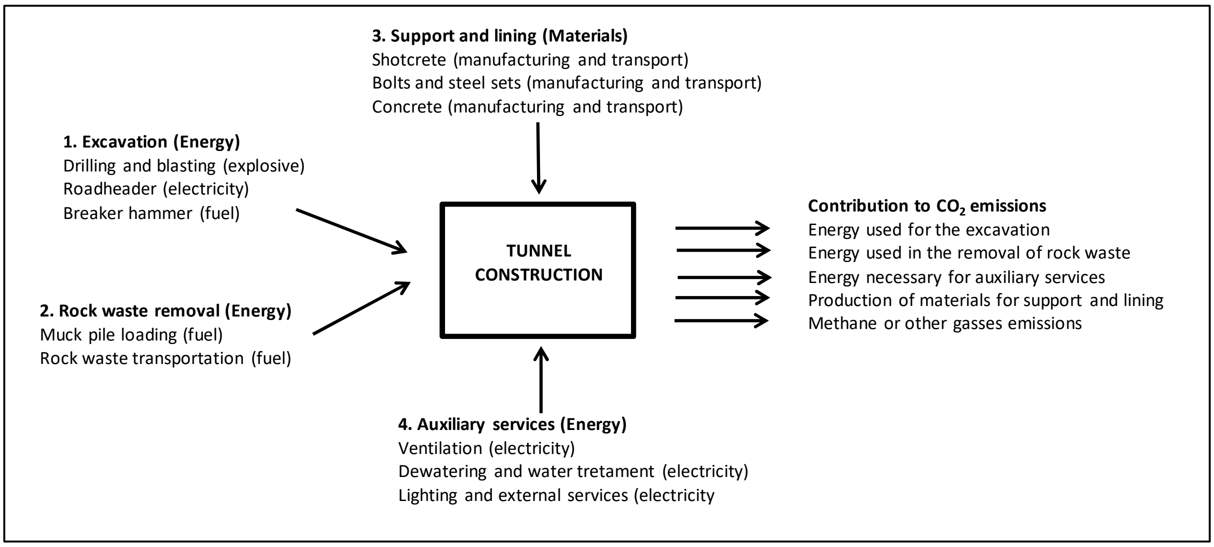

Figure 1: Schematic overview of the system boundary

3. CO_2 EMISSIONS CALCULATION PROCEDURE

The aim of this work is to briefly describe the fundamentals of this simplified LCA that anyone can use to calculate the emissions associated to the construction of a tunnel taking into consideration the specific conditions in each country or region. There are five sources of CO_2 emissions during the construction of a tunnel: the diesel and electrical energy consumed, explosives (used during the drilling and blasting advancing method), the materials used for supporting and lining, and the methane if the tunnel cross the carboniferous strata.

3.1. Emissions released during the excavation (advancing cycle)

3.1.1. Excavation by Drilling and Blasting method (D&B)

The emissions will come from energy consumed by the equipment used for this task, the jumbo (used to drill the blasting holes) and the platform (used to load the explosives), and the CO_2 released during blasting (Rodríguez et al, 2017).

The jumbo has two sources of emissions. The first is the diesel fuel consumed to move in and out this equipment of the tunnel in every cycle. The calculations will be based on both classical and recent researches by Gómez de las Heras (1995) and Posada-Henao (2015). For equipment speeds between 5 to 25 km/h, the diesel consumption DC_j (in grams) will be the result of multiplying its weight M_j (in tons) by the distance the equipment goes back and forth $2 \times d$ (where d is the distance from the working face to the portal in km) and by the fuel consumption per ton moved and km ran C_g (in g/t×km):

$$DC_j = M_j \times 2 \times d \times C_g \qquad (1)$$

A simplified formula to asses C_g is derived in the appendix.

The sign of the slope will be negative when the equipment goes downwards and will be positive upwards. The consumption in grams can be translated into liters, using the diesel density (833 g/l). The CO_2 emissions (DE_j) can be calculated multiplying the consumption of this equipment by its conversion factor (r_D):

$$DE_j = (DC_j / 833) \times r_D \qquad (2)$$

A typical value for r_D is 3.25 $kgCO_2$ per liter of fuel (Shillaber et al, 2016b) for mining equipment. Nevertheless, it can vary depending on the region and data used; for example, based on investigation carried out by López and Sánchez (2008) in Spain, this value is of about 2.63 $kgCO_2/l$. These equations will be applied for all diesel driven equipment that we will study later.

The second source of emissions is the electricity consumed by the jumbo. It uses an electrical motor to drill the blasting holes, and to calculate the energy consumption (EC_J) in kWh the following expression is used:

$$EC_J = NP \times LF \times t \qquad (3)$$

Where NP is the nominal power in kW, LF is the load factor (%), and t is the working time in hours. The timing needed for the drilling operation will depend on the RMR value (high values make the speed lower, while low values allow the machine to drill the holes faster), and the number of rock drill units. The normal power of each rock drill unit is about 25 kW. The emissions (EE_J) can be calculated multiplying the consumption of the electricity by its conversion factor (r_E):

$$EE_J = EC_J \times r_E \qquad (4)$$

A typical value for r_E is 0.267 kg CO_2 per kWh according to the Spanish institute IDAE (2011). This factor reaches 0.66 $kgCO_2/kWh$ when electricity is produced by an electric generator. As these values depend on the specific regional characteristics, other authors suggest different emissions rate: i.e. Shillaber et al. (2016b) suggest a conversion factor 0.981 $kgCO_2/kWh$ for electric generators.

These equations will be applied for all electrical equipment that we will study later.

The total emissions of the jumbo during its work will be:

$$TE_J = DE_J + EE_J \tag{5}$$

The platform to load the explosives uses diesel to move in and out of the tunnel and to load the explosives into the blasting holes in every cycle. Its consumption (DC_{PL}) will be the same as (1), and its emissions (TE_{PL}) will be calculated as shown in (2).

The CO_2 produced during the blasting of the explosives will be calculated multiplying the amount of explosive (m_{exp}) used during the construction of the tunnel, by its conversion factor (r_{ex}):

$$E_{exp} = m_{exp} \times r_{ex} \tag{6}$$

The conversion factor r_{ex} is about 0.258 $kgCO_2$ per kg of explosive used (manufacturers Maxam 2015, Orica 2015). Only gasses produced in the explosion are taken into account, because the explosive is considered here as a kind of energy and no a material. If emissions due to manufacturing should be included, this rate should be 2.0 $kgCO_2$ per kg of explosive (after Orica 2019). In the case of tunnels with a cross sectional area bigger than 60 m^2, the amount of explosives needed according to different researchers (Cardu and Seccatore, 2016) varies from 0.5 to 1.5 kg/m^3. The total emissions produced during the advancing cycle with this method will be:

$$TE_{DB\,=}\,TE_J + TE_{PL} + E_{exp} \tag{7}$$

3.1.2. Excavation with Roadheader (RH)

The roadheader uses electrical energy to perform its task. The cutting head is moved by an electrical motor, and the energy consumption and the CO_2 emissions will be given using the formulas (3) and (4):

$$EC_{RH} = NP \times LF \times t \tag{8}$$

To calculate the load factor *LF*, we need to take into consideration the RMR of the tunnel strata (Toraño J., 1994). For the timing working *t*, in hours, we need to measure the real timing that the equipment is running, and it will depend mainly on the quality of the rock, if that is good we can spend most part of that working with the equipment, however if the quality is bad, we will spend most part of the timing work installing the support at the face with a very few use of this equipment. The emissions (EE_{RH}) can be calculated multiplying the consumption of the electricity by its conversion factor (r_E):

$$EE_{RH} = EC_{RH} \times r_E \tag{9}$$

3.1.3. Excavation with Hydraulic Break Hammer (HBH)

The hydraulic breaker hammer uses a Diesel engine to perform its work. Several studies were done around its diesel consumption, and for the typical equipment of 1500 kg and 18 KW, on a 25t excavator its consumption is about 36 liters/hour (Rodriguez et al, 2017). The emissions (DE_{HBH}) will be calculated multiplying its consumption rate (36 liters/h), by the number of working hours *t* and by the diesel conversion factor r_D, as follows:

$$DE_{HBH} = DC_{HBH} \times r_D = 36 \times t \times r_D \quad (10)$$

For the working time, it will also depend on the quality of the rock as we mentioned above. For each specific case, the working time needs to be measured and the emissions will be evaluated.

From the three methods of advancing the one that seems to have a better performance (from the CO_2 emissions point of view) is the D&B method which emissions are almost 10 times lower than the HBH (Rodríguez et al. 2017).

3.2. Emissions released during Loading and Transportation

The CO_2 emissions will come from the diesel consumption by the loaders and trucks, and we will split them into the following two categories: muck pile loading and transportation.

3.2.1. Muck pile loading

The emissions will come from the diesel consumed by the loader that is taking the muck pile into the truck or dumper that is waiting to be loaded. Regarding the diesel consumed by the loader, we will use 0.15 liters/h per kW of net equipment power (Salam et al, 2015). Then the diesel consumption (DC_{MPC}), in liters, will be:

$$DC_{MPC} = 0.15 \times NP \times t \quad (11)$$

Where *NP* is the net equipment power in kW, and *t* is the number of hours working.

Regarding the truck or dumper waiting on low motion to be loaded, can be considered to be negligible, only 2.64 l/h are used. Then, the consumption of the truck (in liters) in waiting mode will be:

$$DC_{TLM} = 2.64 \times t \quad (12)$$

The CO_2 emissions of this task DE_L, can be calculated using the conversion factor r_D:

$$DE_L = (DC_{MPC} + DC_{TLM}) \times r_D \quad (13)$$

3.2.2 Rock waste transportation

The emissions will come from the diesel consumed by the truck or dumper from the front of the tunnel to the waste dump. The equipment used to transport the rock removed from the face of the tunnel to the outside dump will use diesel, and we can use to calculate their emissions the same formulas in (1) and (2), but having into consideration the weight of the truck and the rocks to go outside of the tunnel, and just the weight of the truck to return to the face of the tunnel (Gomez de las Heras 1995, and Posada-Henao 2015). If the distance from the working face to the portal is *d*, the distance from the portal to the out waste dump is *d'*, the truck weight is M_t and the rock weight is M_r, in tons, the diesel consumption in grams will be:

$$DC_T = (M_r + M_t) \times (d+d') \times C_g + M_t \times (d+d') \times C_g \quad (14)$$

We will consider the speed of 10 and 30 km/h inside and outside the tunnel respectively. The emission will be calculated multiplying the consumption by the CO_2 conversion factor r_D:

$$DE_T = (DC_T/833) \times r_D \tag{15}$$

Some useful formulae to assess the order of magnitude of the fuel consumption of out of road vehicles and trucks can be found in the appendix.

3.3 Emissions caused by other services and tunnel facilities

All these emissions will come from the electrical energy consumed by the electrical motors of all other services and tunnel facilities as for example tunnel ventilation (EC_{TV}), water pumping (EC_{WP}), waste water treatment plant (EC_{TP}), tunnel lighting (EC_{TL}), or external services (EC_{ES}) such as offices, workshops, air compressors, etc. In this case, the formulas (3) and (4) can be used to calculate the energy consumed and the CO_2 emissions respectively.

The use of electrical energy from the network and if possible from a supplier with as much renewable sources as possible, will help to reduce the emissions.

Some useful formulae to assess the order of magnitude of the electrical energy consumption in ventilation system, tunnel dewatering system, water treatment plant and external services and tunnel illumination can be found in the appendix.

3.4 Emissions released from materials used

The materials considered are concrete and steel used in the tunnel for supporting and the final lining. To calculate the emissions released due to this activity first we need to calculate the amount of materials needed. Once we have the amounts of steel M_{st}, that includes the steel arches M_s and rock bolts M_b, and concrete needed M_c, that includes shotcrete M_{sh} and lining concrete M_L, the total CO_2 emission ME can be calculated using the conversion factors, r_{st} and r_c respectively.

$$ME = M_{st} \times r_{st} + M_c \times r_c \tag{16}$$

The conversion factors r_{st} and r_c are 1.82 and 0.136 $kgCO_2$ per kg of steel or concrete respectively after Shillaber et al. (2016b). Values in the same order of magnitude, 1.63 and 0.159 $kgCO_2/kg$ respectively, have been used to estimate the Carbon footprint of a high-speed railway in Spain (INECO, 2012). The amount of concrete and steel needed for the support and lining depend on the section of the tunnel, rockmass strength (RMR) and depth of the tunnel. It must be calculated for each specific case. In the case of a tunnel with cross section of 100 m^2 , the amount of steel needed varies from 100 kg/m when the rockmass is strong (RMR>65) to 3000 kg/m or even more in a weak rockmass (RMR<30). In the case of the concrete, the thickness of the shotcrete used for the support varies from 5 cm (RMR>65) to 30 cm (RMR<30) while for the final lining we will consider, normally, 35 cm of concrete. It has to be taken into account that the mass of concrete can be strongly influenced by the over-excavation; it can be estimated as it is described in the appendix or it can be predicted from Innaurato et al (1998), Mohammadi et al. (2015) or Mottahedi et al (2018).

Finally, to calculate the emissions due to the transportation from the production factories to the construction site we will use an approach based on Lopez and Sánchez (2008) results. The consumption, in grams, will be given using the following formula:

$$C_g = 15 - v/20 \tag{17}$$

Where C_g is the amount of diesel consumed (grams) per ton transported and km driven and v is the speed of the truck. Taking into consideration two different roads, the outside and the inside of the tunnel, the amount of diesel consumed will be:

(outside) $$Cg_{MatO} = d_o \times (m_T + m_L) \times (15- v_o/20) + d_o \times m_T \times (15- v_o/20) \quad (18)$$

(inside) $$Cg_{MatI} = d_i \times (m_T + m_L) \times (15- v_i/20) + d_i \times m_T \times (15- v_i/20) \quad (19)$$

Where: d_o is the distance travelled outside in km, v_o is the speed of the truck outside of the tunnel (we can consider here the average speed of 60 km/h), d_i is the distance travelled inside in km, v_i is the speed of the truck inside of the tunnel (10 km/h), m_T and m_L are the weight of the truck and the load respectively.

The total emissions of this part will be:

$$E_S = ME + [(Cg_{MatO} + Cg_{MatI}) /833] \times r_D \quad (20)$$

In a long term, a quantity of CO_2 is captured by concrete of the lining. This phenomenon has been studied by different researchers, i.e. Haselbach (2008), and in Spain by Galán (2011). By applying her method, the conclusion is that after a long time only the 2% of the CO_2 generated during the production of concrete could be captured by the concrete of the tunnel lining, due to the carbonization process. For this reason, this CO_2 reduction is not considered and, in this way, we are being more conservative.

Some useful formulae to assess the order of magnitude of the materials consumption (steel and concrete) can be found in the appendix.

3.5 Methane emissions

When the tunnel is constructed through Carboniferous strata, there is an important methane release that has a major impact in the total number of CO_2 emissions. They will be calculated converting the methane released, from the mass rock affected by this construction, into CO_2 equivalent using the conversion factor 25 (for a period of 100 years), given by the IPCC (2007). To calculate the methane emissions, we will use the specific methane release (s_{met}) for a ton of rock removed from the tunnel face (Rodriguez et al, 2010). If we calculate the amount of material to be removed (M_R), we can calculate the amount of methane released from the tunnel, and using the conversion factor to CO_2 equivalent (r_{met}) we will obtain the CO_2 emissions.

$$E_{met} = s_{met} \times M_R \times r_{met} \quad (21)$$

s_{met} was in average 31.4 m^3 of methane per t (equivalent to 20.6 $kgCH_4/t$) in the case studied in Rodríguez et al (2010), which can vary from one region to another. The conversion factor r_{met} (methane to CO_2) is 25 $kgCO_2$ per kg of methane.

A schematic overview of the simplified calculation procedure is given in Table 1.

Table 1: A schematic overview of the calculation procedure

	Energy and materials consumption			
Task	**Fuel (liters)**	**Electricity (kWh)**	**Materials (kg)**	**Equations**
Excavation				
Jumbo	$DC_J/833$	EC_J	-	(1), (3)
Platform	$DC_{PL}/833$	-	-	(1)
Explosive	-	-	m_{exp}	
Roadheader	-	EC_{RH}	-	(8)
Breaking hammer	DC_{HBH}	-	-	(10)
Loading and transportation				
Loader	DC_{MPC}	-	-	(11)
Truck or dumper	$DC_{TLM} + DC_T/833$	-	-	(12), (14)
Tunnel facilities				
Tunnel ventilation	-	EC_{TV}	-	(3)
Water pumping	-	EC_{WP}	-	(3)
Water treatment plant	-	EC_{TP}	-	(3)
Tunnel lighting	-	EC_{TL}	-	(3)
External services	-	EC_{ES}	-	(3)
Materials (support/lining)				
Concrete	-	-	M_c	
Steel	-	-	M_{st}	
Materials transportation	$(Cg_{MatO}+Cg_{MatI})/833$	-	-	(18), (19)
Methane emissions				
Methane emissions	-	-	$s_{met} \times M_r$	(21)

	CO_2 Total Emissions			
Task	**Fuel ($kgCO_2$)**	**Electricity ($kgCO_2$)**	**Materials ($kgCO_2$)**	**Equations**
Excavation	$[(DC_J/833)+(DC_{PL}/833)+DC_{HBH}] \times r_D$	$(EC_J+EC_{RH}) \times r_E$	$m_{exp} \times r_{exp}$	(4) to (10)
Loading and transportation	$[DC_{MPC}+DC_{TLM}+(DC_T/833)] \times r_D$	-	-	(13) to (15)
Tunnel facilities	-	$(EC_{TV}+EC_{WP}+EC_{TP}+EC_{TL}+EC_{ES}) \times r_E$	-	(4)
Materials (support/lining)	$[(Cg_{MatO}/833)+(Cg_{MatI}/833)] \times r_D$	-	$M_c \times r_c + M_{st} \times r_{st}$	(16) to (19)
Methane emissions	-	-	$s_{met} \times M_r \times r_{met}$	(21)

4. VALIDATION OF THE METHOD

The described simplified model or procedure has been used to estimate the CO_2 emissions during the construction of a tunnel and then they are compared with real emissions determined from real materials and energy consumption. The tunnel taken as a reference is a double tube tunnel in Northwest of Spain. The studied stretch (only one tube) is of about 1000 m in length (from 1200 m to 2200 m chainage), being the slope of about 1% upwards. The depth was 125 m in average.

The tunnel was excavated through a medium strength rockmass, RMR=35–40, formed basically by quarzitic rocks. The excavation cross sectional area is 79.6 m^2 (circular shape with excavation diameter of 10 m). The excavating method was drilling and blasting with a typical powder factor of 0.6 kg of explosives per m^3 of excavated rock. The muck was removed from the tunnel by means of articulated trucks with a load capacity of 24 t and Diesel engines of 200 kW of power. The electrical energy was obtained by means of two electrical generators of 815 kVA each one. There was no presence of gas methane.

To validate the proposed procedure, four contributions to CO_2 emissions were selected: a) use of explosive, b) fuel consumption of articulated trucks, c) concrete used in the support and the lining and d) electrical energy used in the tunnel (drilling, ventilation, water treatment…etc.). The explosive is considered as energy, no as a material, and no emissions due to its manufacturing are included.

In Figure 2, the real accumulated quantity of CO_2 emitted to the atmosphere due to the explosive detonation between 1200 and 2200 m sections is represented as a function of excavated tunnel length. It has been calculated from real amount of explosive used in the tunnel. As it can be seen, it varies almost linearly with the length because the amount of explosive per m of tunnel is practically constant. The CO_2 emission rate, 12 kg/m, can be considered very small or even negligible. In the same graph the accumulated CO_2 for all the length of the tunnel, estimated following the procedure, is also represented showing that the model is accurate enough.

In Figure 3, the real accumulated quantity of CO_2 emitted to the atmosphere due to the articulated trucks used to remove the rock from the tunnel is represented as a function of excavated tunnel length. It has been calculated from real amount of diesel fuel used by the articulated trucks. As it can be seen, the relationship is not linear because the number of trucks and the distance increase with the tunnel length. The CO_2 emission rate, which varies from 200 to 300 kg/m, can be considered small. In the same graph the accumulated CO_2 estimated for all the length of the tunnel is also represented showing that the model is also accurate enough in this case.

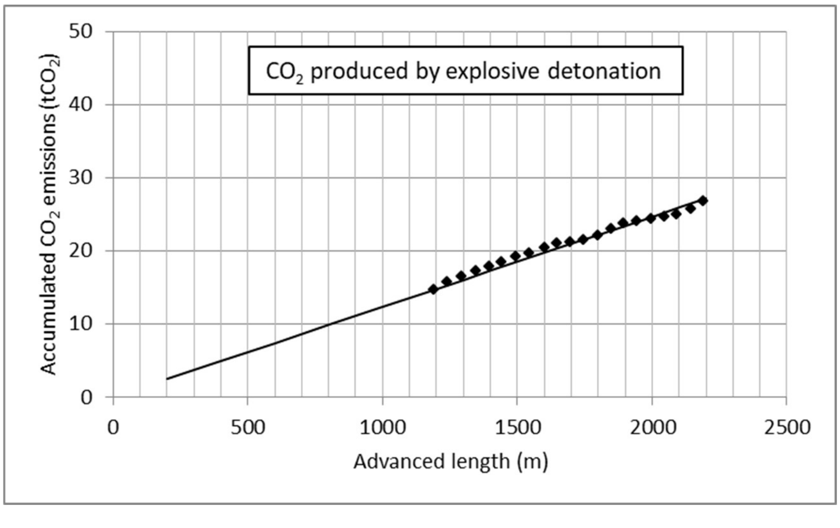

Figure 2: CO_2 produced by explosive detonation

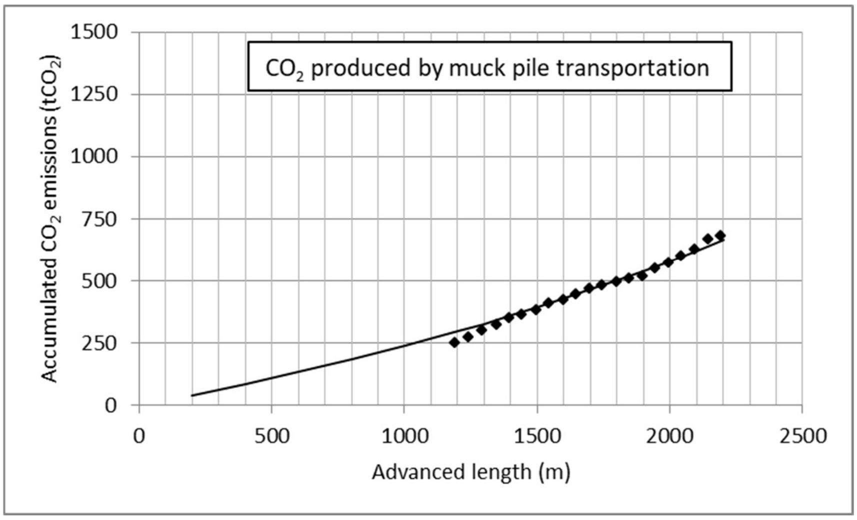

Figure 3: CO$_2$ produced by muck pile transportation

In Figure 4, the real accumulated quantity of CO$_2$ emitted by the mobile electric generators is represented. It has been calculated from real amount of diesel fuel used by them. Also in this case, the relationship is not linear because the energy necessary for the construction of 1 m of tunnel increases with the tunnel length. The CO$_2$ emission rate, which varies from 600 to 900 kg/m, can be considered also small. In the same graph, the estimated CO$_2$ is also represented. It should be considered that the electricity generated in this way produces a bigger amount of CO$_2$.

Finally, the emissions related to the concrete used in the tunnel is estimated and compared with real data. In Figure 5, the real accumulated quantity of CO$_2$ emitted to the atmosphere during the manufacturing process of the concrete used for the support and the lining is represented. As it happened with the explosive, it varies almost linearly with the length because the amount of concrete per m of tunnel is practically constant. This is the main contribution and represents about the 80% of the total emissions in the tunnel being the CO$_2$ emission rate almost 9500 kg/m. As in the previous case, the estimation carried out with the approach can be considered good.

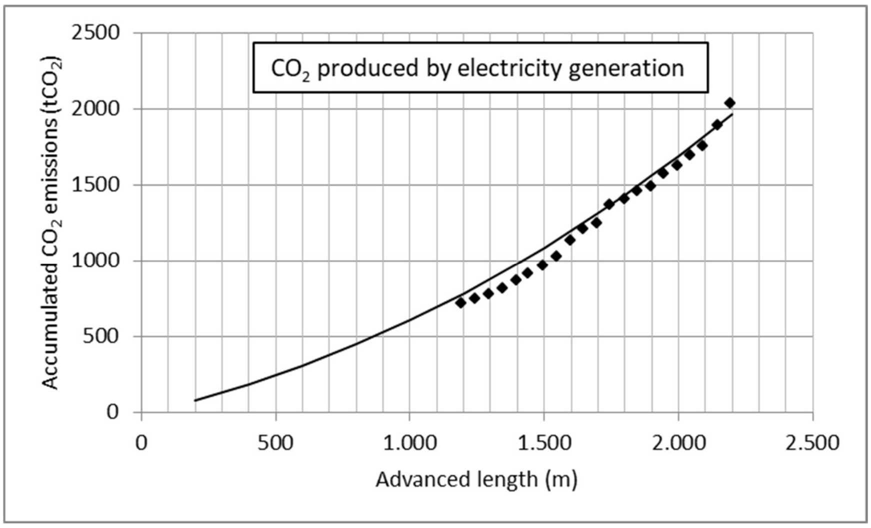

Figure 4: CO$_2$ produced by electric generators

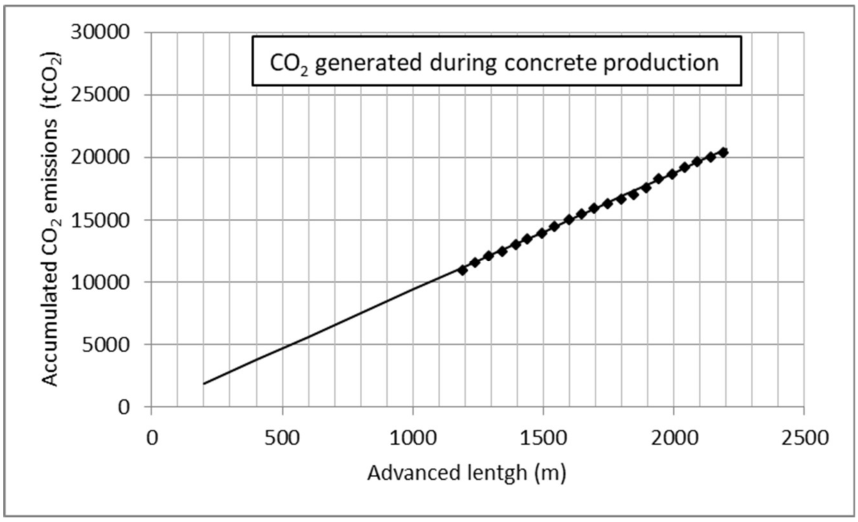

Figure 5: CO_2 generating during concrete production process

In Figure 6, the total CO_2 emissions related to explosives, transportation, concrete and electricity are represented. In the same graph, the estimation for these factors is also represented which is in good agreement with the reality. On the other hand, the described simplified LCA has been used to estimate the total emissions including other factors as for example the fabrication of the steel for the support elements or the use of the excavator in mucking tasks.

In Figure 7 a graphic with the total emission rate, which is the result of dividing, at a given moment, the total accumulated emissions by the tunnel length, in $kgCO_2$ /m is shown. The emission rate can be considered constant. The simplified LCA method was used to estimate both the emission rate due only to the factors previously analysed and the one due to all the contributions.

A summary of the causes of the Carbon footprint in this tunnel in particular are the following: when tunnel reaches 2200 m in length, the total emission rate is 12,500 $kgCO_2$/m of which, approximately, 85% comes from the materials (80% from concrete and 5% from steel), 5% comes from loading and transportation and 10% comes from generation of electricity.

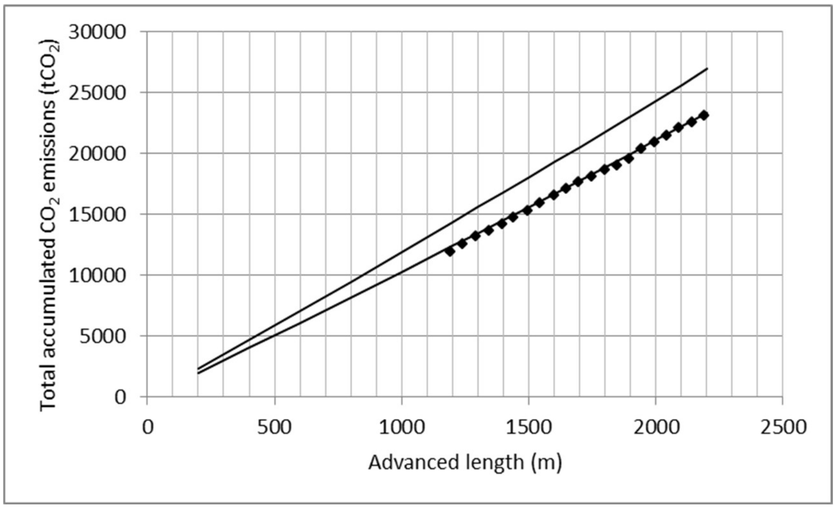

Figure 6: Total CO_2 produced during the tunnel construction

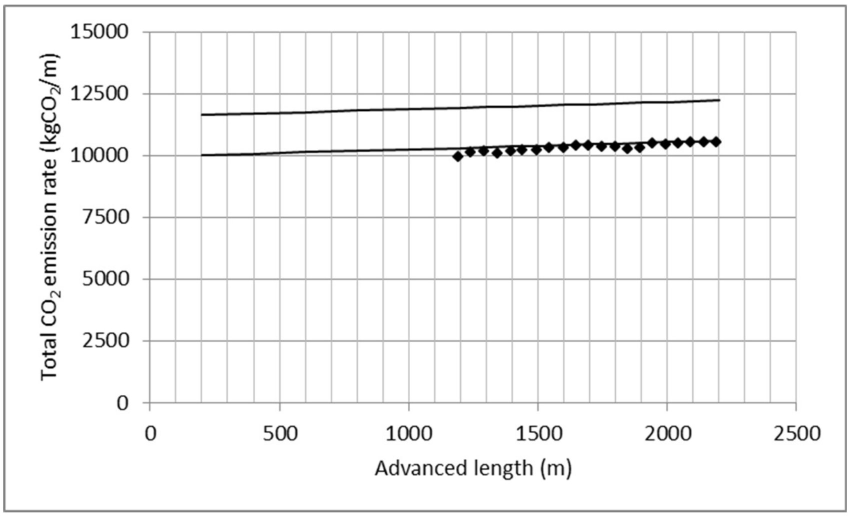

Figure 7: Total CO_2 emission rate for the tunnel in construction

5. APPLICATION OF THE METHOD TO THE ANALYSIS OF SEVERAL CASES

The described method allows carry out a sensitivity analysis varying the value of different parameters. Nevertheless, in the reality, the typical design parameters of a tunnel do not vary totally freely. Due to different reasons, they are related to each other and only some combinations of them are really frequent. For example, the longest tunnels in Spain are railway tunnels in which the cross section is usually about 80 m^2 (a circle with a diameter of 10 m); it is not realistic to analyse a tunnel of 10 km in length with a cross section of 20 m^2. In the same way, tunnels with a big section (120 m^2 or more) are usually highway tunnels with three lanes and they are always short tunnels (less than 1 km). For this reason, an analysis of seven tunnels, representative of the most frequent combination of tunnel parameters in Spain, is carried out rather than a typical sensitivity analysis.

Seven different tunnels excavated in Asturias (Northwest Spain), were selected to see the influence of different parameters. The main characteristics of these tunnels are the following:

1) Somao tunnel (Conto, 2008). Tunnel used for road transportation in the A-8 highway in Spain, with a length of 466 m, its section is quite big (142.5 m^2) because it has 3 tracks, its RMR value is low between 25 and 45, and the advancing method was mostly hydraulic breaker hammer.

2) Fresno tunnel (Fernández, 2008). Tunnel used for road transportation in the A-63 highway, with a length of 940 m, its section is also rather big (125 m^2), its RMR value was even lower than the previous case, between 25 and 40, and the advancing method used was also mostly the hydraulic breaker hammer.

3) Fabares tunnel (De Luís and Ugarte 2003, Rodríguez et al 2017). Tunnel used for road transportation in the A-64 highway, with a length of 1922 m, its section is smaller than before (92 m^2), its RMR value varies 30 and 55, and all the different conventional advancing methods have been used (drilling and blasting, roadheader and hydraulic breaker hammer).

4) Padrún tunnel (García Arango et al, 1993). Tunnel used for road transportation in the A-66 highway, with a length of 1762 m, and a section of 88.5 m^2, its RMR value varies 25 and 55, and

mostly the drilling and blasting method was used. This tunnel crosses the Carboniferous ground and produces an extra amount of CO_2 emissions due to the release of the methane contained.

5) Santiuste tunnel (Almazán, 2001). Tunnel used for road transportation in the A-8 highway in Spain, with a length of 500 m, its section is 113.7 m^2, its RMR value varies 25 and 65, and the drilling and blasting and hydraulic hammer methods were used depending on the RMR value.

6) Peñaflor tunnel (Cano, 2003). Tunnel used for road transportation in the A-63 highway, with a length of 695 m, its section is 99 m^2 (111 m^2, at the middle point), its RMR value is between 20 and 50, and drilling and blasting method was mostly used for its construction.

7) Folledo tunnel (Míguez et al, 2007). This is an access gallery to the main Pajares tunnels in the high-speed railway in Spain. It was chosen because it is quite different from the others. With a length of 2021 m, its section is lower, only 54 m^2, and its slope is rather high, 13% descending. Its RMR varies between 35 and 70, and only the drilling and blasting method was used for its construction.

In all cases, values of conversion factors more related to Spanish conditions have been used (Table 2). In the analysis, it has been used the same quality of materials for all tunnels, which is a realistic assumption for these typical tunnels. Nevertheless, a specific analysis of the relevance of the concrete strength on the CO_2 emissions, safety and costs can be found in Rodríguez et al (2019).

Table 2: Summary of conversion factors

Conversion factor	Symbol	Units	Value	Source
Diesel engines	r_D	$kgCO_2/l$	2.63	López and Sánchez (2008)
Electricity	r_E	$kgCO_2/kWh$	0.267 – 0.660	IDAE (2011)
Explosive (energy)	r_{ex}	$kgCO_2/kg$	0.258	Maxam (2015), Orica (2015)
Steel manufacturing	r_a	$kgCO_2/kg$	1.63	INECO (2012)
Concrete manufacturing	r_h	$kgCO_2/kg$	0.159	INECO (2012)

The summary of the ratio emissions for these tunnels (kg/m) calculated following the described simplified method can be seen in Table 3 (D&B is Drilling and Blasting; RH is Roadheader and HBH is Hydraulic Breaker Hammer). Each tunnel analysed was divided in several stretches (5 to 14) with the same cross section, excavation method, rock mass strength, depth...etc. and the CO_2 emissions for each stretch was estimated. Finally the sum of contributions of all stretches divided by the total length of the tunnel is the average value or emission rate shown in the Table 3.

Some specific conditions must be considered to better understand the different emission rates between similar tunnels. For example, methane emissions (27% of the total) have considered in Padrún tunnel because it was excavated through Carboniferous strata; this fact makes its emissions quite higher. On the other hand, and due to the presence of gypsum and expansive anhydrites, the thickness of the lining of the Fabares tunnel was 40 cm while the Santiuste and Peñaflor was 30 cm. This difference makes this tunnel to produce more emissions than the others even having a smaller section.

In Table 4 the value of CO_2 emissions in the tunnels are classified according the three most relevant contributions. Observe that the materials take more than 75% in all cases and in average it is greater than 80%.

Table 3: Summary of emissions rates (kgCO_2/m)

Tunnel	RMR	Excavation Method used (%)			Length (m)	Cross Section (m^2)	Emissions rate (kgCO_2/m)
		D&B	RH	HBH			
Somao	25-45	10	0	90	466	142.5	15,284
Fresno	25-45	0	0	100	940	125	14,417
Fabares	30-55	18	72	10	1922	92.1	10,276
Padrún	25-55	98	0	2	1762	88.5	10,261
Santiuste	25-65	60	0	40	500	113.7	8,710
Peñaflor	21-50	44	0	56	695	99.4	8,260
Folledo	35-70	100	0	0	2021	54	4,293

Table 4: Most relevant contributions to the CO_2 emissions

Tunnel	Materials used (concrete and steel) KgCO_2/m (%)	Auxiliary facilities KgCO_2/m (%)	Advancing activities KgCO_2/m (%)
Fabares	9,087 (88%)	473 (5%)	423 (4%)
Folledo	3,533 (82%)	243 (6%)	252 (6%)
Fresno	11,747 (81%)	1303 (9%)	904 (6%)
Padrún*	6,809 (66%)	458 (4%)	264 (3%)
Peñaflor	6,304 (76%)	1166 (14%)	492 (6%)
Santiuste	7,531 (86%)	555 (6.5%)	560 (6.5%)
Somao	12,801 (85%)	1257 (8%)	993 (7%)
Average value	10,753 (83%)	832 (8%)	604 (6%)

*Methane emissions in this tunnel (27% of the total) make the % values lower than the rest. Not considered for the average value

From these results, it is easy to infer that, under typical conditions, the parameters that more influence the emission are the rockmass quality (*RMR*) and the cross-sectional area (*S* in m^2). The reason is that these parameters strongly influence the thickness of the support and lining and consequently on the final quantity of concrete used. In Figure 8 the importance of the RMR and tunnel section is shown. The center of each circle represents a given pair (*S*, *RMR*) and the diameter of the circle is proportional to the emission rate. These results can be used as guidance in earlier stages of a project as it is shown in Table 5.

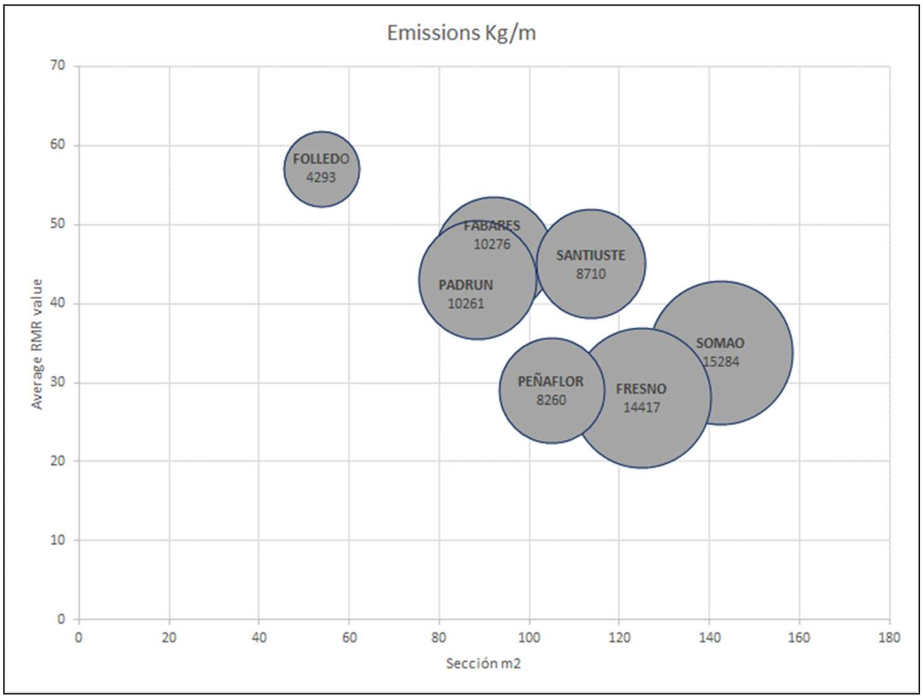

Figure 8: Influence of the *RMR* and the tunnel section *S* in the emissions ratio

Table 5: CO_2 emissions related to tunnels in northern Spain

Tunnelling conditions	**Total emission rate ($kgCO_2/m$)**
VERY FAVOURABLE: tunnel of small cross section (60 m^2), strong rockmass, excavated by drilling and blasting, electricity supplied by a company	5,000
FAVOURABLE: tunnel of medium cross section, medium to strong rockmass, possibility of excavating by drilling and blasting, electricity supplied by a company	8,000
STANDARD: tunnels with cross section of 100 m^2 excavated by conventional methods through medium strength rockmass, electricity supplied by a company	10,000
UNFAVOURABLE: big cross section (greater than 120 m^2), weak rockmass (RMR<30), excavated mainly by hydraulic breaker hammer, a strong support is necessary, and/or electricity production by means of electrical generators	15,000

These emission rates are according to other data that can be found in specialized literature. For example, Chang and Kendall (2011) estimated that CO_2 emissions in the construction of 49 km of tunnels of a high-speed rail system in USA would be 637,793 tCO_2, that is 13,016 $kgCO_2/m$. Tuchschmid et al (2011), give the values of 169,619 or 282,699 $kgCO_2$ per km of tunnel and year for single and double track tunnel in Europe respectively; taking into account that the lifespan used was 60 years, this becomes in 10,177 $kgCO_2/m$ and 16,962 $kgCO_2/m$ respectively. In INECO (2012) a railway section in Spain of 11.2 km in length in which 9.53 km corresponded to tunnels was analysed and the total estimated emissions were 106,861 tCO_2 (practically all from tunnels) from which a ratio of 11,213 $kgCO_2/m$ can be deduced. Morita et al (2012), analysing Carbon impact from construction of rail infrastructure give a value of 14,300 $kgCO_2/m$ for a conventional tunnelling in Japan. Finally, Fedele et Severini (2015) estimate that the total emissions for 33,6 km of tunnels excavated by conventional methods in Italy were 499,994 tCO_2, that is, the emission ratio is 14,860 $kgCO_2/m$. Nevertheless, the above mentioned studies only give one representative value of CO_2 emissions and not a range of values according to different conditions as in the Table 5.

On the other hand, results obtained from perfectly explained and developed LCA works published, cannot be used directly in a first estimation because they are not totally representative due to different conditions studied or different regional characteristics. For example, Miliutenko et al (2012) give an average emission ratio of 8,855 $kgCO_2/m$ in tunnels in rock, which is similar to those in Table 4, but give an average value of 35,298 $kgCO_2/m$ in the case of tunnels with concrete lining, which is much higher than similar tunnels in northern Spain. Huang et al (2015) present results for different tunnel section and length, but only for tunnels in strong rock in which emissions can be so low than 1200 $kgCO_2/m$ which would not representative of a typical tunnel in Spain. More recently, in Huang et al (2020) they analysed tunnels through weaker rockmasses varying the CO_2 emissions between 1000 and 3500 $kgCO_2/m$. Nevertheless, these results cannot be directly used because the only analyse the contribution of shotcrete and bolting.

Other study, Lee et al (2017), defines also a range of CO_2 emissions which vary with length between 9,700 and 14,300 $kgCO_2/m$; nevertheless the variation is only due to the contribution of the open cut parts on both portals of the tunnel which is constant for all tunnels studied (approximately 60 m in each side); the representative value is really only one: for long tunnels in which this influence is less, the value is of approximately 10,000 $kgCO_2/m$ which is close to the Spanish standard conditions but does not represent other conditions.

Moreover, results of previous experiences, although they are very useful, cannot be compared directly because they have been estimated by different teams and with different criteria or even different methodology. On the contrary, results in Table 4 are homogeneous and they can be compared directly. Independently of the absolute value, from results of Table 4 we can say that a tunnel constructed under very favourable conditions will produce approximately 1/2 of emissions of a standard tunnel or 1/3 of emissions of a tunnel in the worst conditions.

From all mentioned above, the use of results summarized in Table 4 allow us to carry out more accurate estimation during first phases of the project than using data of other experiences.

The results of the present study are in the same way that those presented previously by Xu et al (2019), who found that the construction emissions of the five 1-km highway tunnels were between 6220 and 17,010 t CO_2. For this reason, the results will be used in the following section in order to test the developed procedure.

6. TESTING THE PROCEDURE WITH OTHER CASES

Using the model with data of Huang et al (2015)

In Huang et al (2015), they estimate the CO_2 emissions related to conventional excavation of tunnels in good rockmasses. The tasks considered by them in drill and blast tunnelling are: dirlling and blasting, loading and hauling, scaling, and ventilation. They consider that no support or lining is needed from it can be deduced that rockmass quality is of about Q= 100 after Grimstaad and Barton (1993) which is equivalent to RMR=80 after Barton and Bieniawski (2008).

The developed model is used in several of the tunnels with the characteristics shown in the Table 6 and then are compared with the results presented by Huang et al. (2015).

Table 6: Main characteristics of the tunnels selected from Huang et al (2015)

Tunnel reference	**Cross section (m^2)**	**Length (m)**	**RMR**
T1	40	3000	80
T2	70	3000	80
T3	100	3000	80
T4	120	3000	80
T5	67	6000	80
T6	67	8000	80

If we use the model as if these tunnels were excavated in Spain, the calculated emissions were of about 5 times bigger than those calculated by Huang et al (2015) as it is shown in Figure 10 (left). This fact is due to some typical assumptions related to tunnelling in Spain are considered as for example the use of a support even in strong rock masses, some over-breaking due to blasting is produced, and a lining of concrete 35 cm in thick. If the analysis is repeated but without taking into account neither the support nor the lining, the results are practically the same of those from Huang et al (2015) as it is shown in the same Figure 10 (right). Although the developed model does not take into account some CO_2 sources like the machinery manufacturing, it takes into account other CO_2 emissions like those related to waste transportation, that are in the same order.

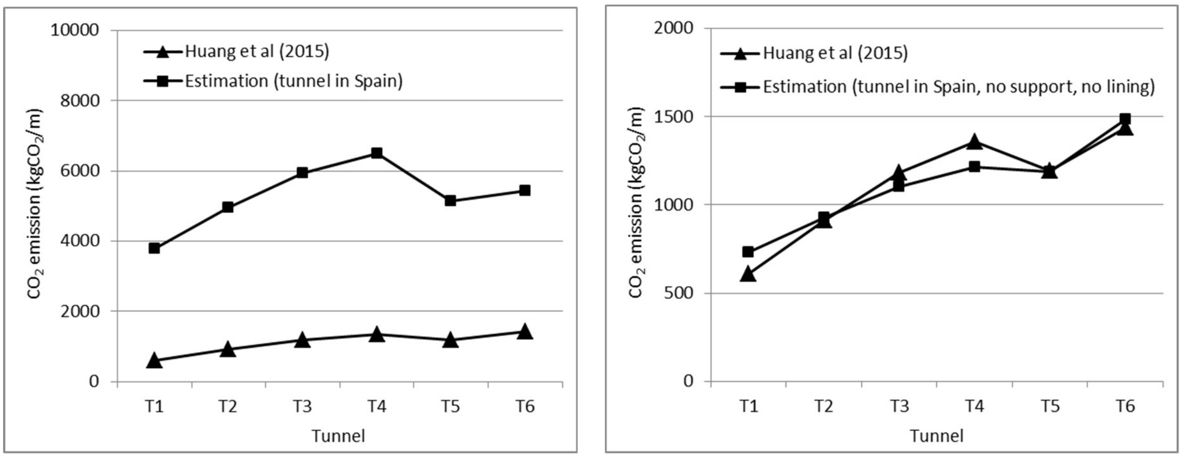

Figure 10: Testing the model with results of Huang et al (2015)

Using the model with data of Huang et al (2020)

More recently, Huang et al (2020) analyse the CO_2 emissions related to the support in drill and blast tunnelling considering only two contributions: bolting and spraying concrete (shotcrete). They assume tunnels excavated under hard rock conditions varying the Q index between Q=0.2 and Q=100. (it can be assumed that RMR varies between RMR=40 and RMR=80).

The tunnels shown in the Table 7 are taken as reference to compare the results; RMR values are deduced from Barton and Bieniawski (2008).

If the model is used as if the tunnels were excavated in Spain, the calculated CO_2 emissions would be in average 5 times those calculated by Huang et al. (2020) as it is shown in the Figure 10 (left). The difference is mainly due to the model consider all the contributions to CO_2 emissions (excavation, mucking, support, lining, ventilation…etc). If the analysis is repeated but considering only the same

CO_2 sources that are considered by Huang et al (2020), bolting and concrete spraying, the results are in the same order as it can be seen in Figure 10 (right).

Table 7: Main characteristics of the tunnels selected from Huang et al (2020)

Tunnel reference	Cross section (m^2)	Length (m)	RMR
S1	54	3000	65
S4	54	3000	45
S9	76	3000	65
S12	76	3000	45
S17	100	6000	65
S20	100	8000	45

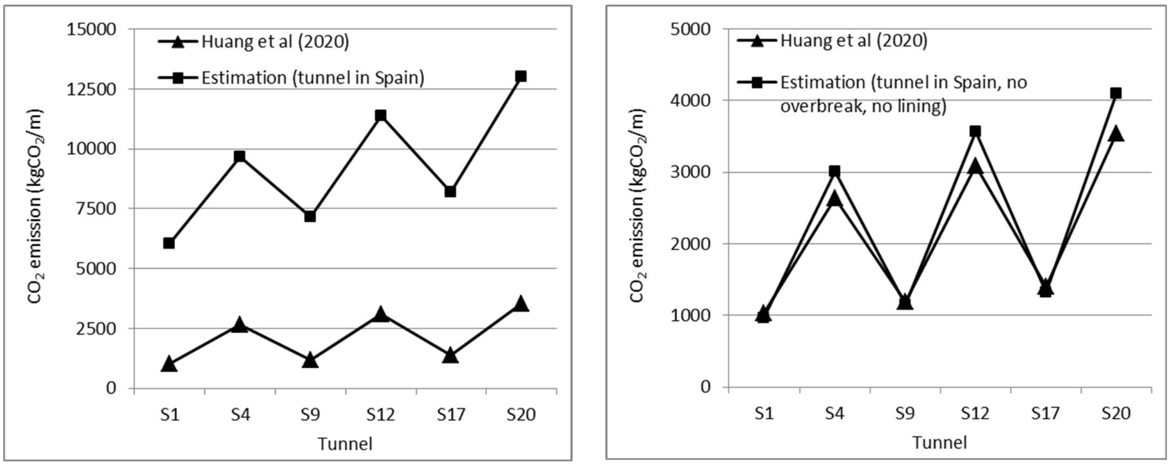

Figure 10: Testing the model with results of Huang et al (2020)

Using the model with data of Xu et al (2019)

Finally the model will be used with data from Xu et al (2019) who describe tunnels excavated in a similar way that in Spain. The tunnels are excavated by drilling and blasting, with the following phases: advance support, tunnelling, rock support, lining, ventilation and lighting.

The necessary characteristic of the tunnels in order to use the model are shown in the Table 8, in which RMR is deduced from shotcrete thickness for different support used.

Table 8: Main characteristics of the tunnels selected from Xu et al (2019)

Tunnel reference	Cross section (m^2)	Length (m)	RMR
T1	78.80	1000	60
T2	82.60	1000	40
T3	97.48	1000	40
T4	98.90	1000	35
T5	101.72	1000	30
T1	78.80	1000	60

If CO_2 emissions are calculated by means of the proposed model using typical values of parameters for Spain, the results are quite different although the tunnels are similar (Figure 11, left). The main difference is the effect of over-excavation that Xu et al (2020) do not take into account. If this contribution is not considered, and if it is assumed a lining with a thickness of 40 cm (instead of 35 cm of the Spanish case) the results are very similar as it is shown in the Figure 11 (right).

In this case the calculated results are slightly under the results of Xu et al (2019) due mainly to local factors such as the CO_2 emission related to electrical energy (990 gCO_2/kWh in China against 267 gCO_2/kWh in Spain).

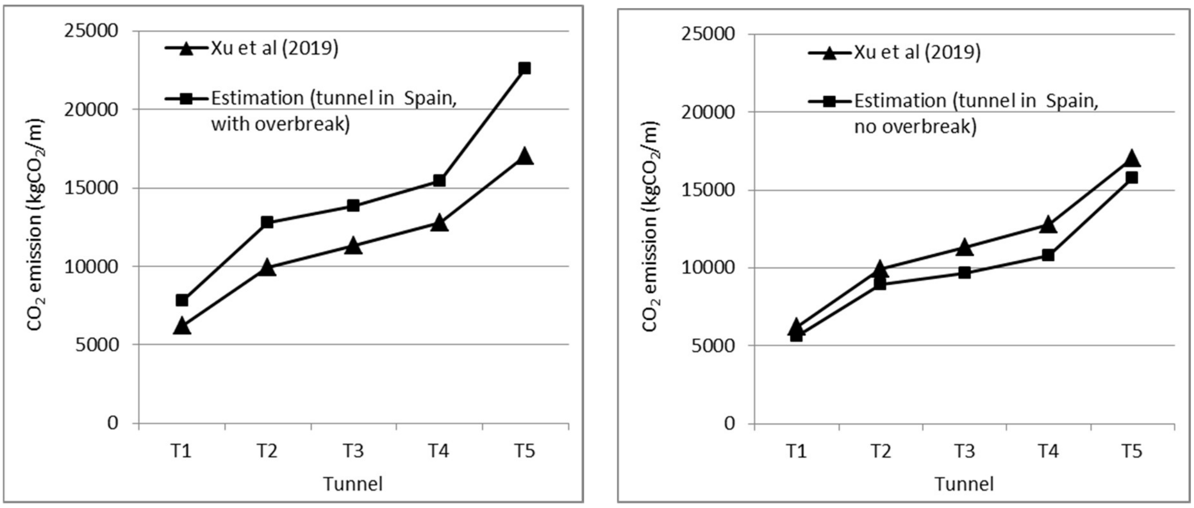

Figure 11: Testing the model with results of Xu et al (2019)

7. CONCLUSIONS

In the present work, the fundamentals of a procedure or calculation method to estimate the Carbon footprint during the construction of a tunnel by conventional methods is described and it is validated with data of a real tunnel; then it is used to analyze some real tunnels to estimate the order of magnitude of CO_2 emissions in different cases and determine the influence of different factors; finally it is tested with results obtained from the scientific literature.

Because the contribution of the concrete and steel to CO_2 emissions is about the 80% of the total, the Carbon footprint of a tunnel can be easily estimated if the total amount of concrete and steel used is known. It is important to point out that the volume of over-break is relevant and it should be considered.

In general terms, a typical value of the CO_2 emission rate for tunnels excavated by conventional methods through medium strength rockmass under similar conditions of the tunnels in northern Spain, expressed as kg of CO_2 emitted to the atmosphere per meter of tunnel advanced, is 10,000 $kgCO_2/m$.

This value can grow up to 15,000 $kgCO_2/m$ under worse conditions: big cross section (greater than 120 m^2), weak rockmass (RMR<30) which is excavated mainly by hydraulic breaker hammer and needs a strong support, or electricity production by means of electrical generators.

On the contrary, if the conditions are better (smaller cross section, medium to strong rockmass, possibility of excavating by drilling and blasting or electricity supplied by a company), the CO_2 emission is reduced to about 8,000 $kgCO_2/m$ and even more (in the case of tunnels of less level of responsibility).

From the three advancing methods studied, the one that seems to have a better performance (from the CO_2 emissions point of view) is the drilling and blasting system.

By using the proposed procedure or method, an absolute value of CO_2 emissions can be obtained; nevertheless, due to lots of variables evolved, this value can vary from one place to another. A good procedure is to use the method to compare different alternatives for a tunnel rather than evaluate the absolute value for the Carbon footprint of a given tunnel.

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REFERENCES

Ahn C., Xie H., Lee S., Peña-Mora F. (2010). Carbon footprints analysis for tunnel construction processes in the pre-planning phase using Collaborative Simulation. Construction Research Congress 2010, pp. 1538-1546.

Almazán J.F., Aparici F., Romana M. (2001). Túneles de Santiuste. Ingeopres – num 92. Abril 2001, pp. 26-32.

Bandini A., Berry P., Cormio C., Colaiori M., Lisardi A. (2017). Safe excavation of large section tunnels with Earth Pressure Balance Tunnel Boring Machine in gassy rock masses: The Sparvo tunnel case study. Tunnelling and Underground Space Technology 67 (2017) 85–97.

Barton N., Bieniawski, Z.T. (2008). RMR and Q – Setting records. Tunnels and Tunnelling International, February 2008, pp. 26-29.

Cano, A.J. (2003). Túnel de Peñaflor: 2º tubo. Master Thesis. University of Oviedo.

Chang B., Kendall A. (2011). Life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system. Transportation Research Part D, 16 (2011) 429–434.

Cardu M, Seccatore J. (2016). Quantifying the difficulty of tunnelling by drilling and blasting. Tunnelling and Underground Space Technology 60 (2016) pp. 178-182.

Conto Iglesias, S. (2008). Proyecto de ejecución de un túnel para tres calzadas por medios mecánicos. Master Thesis. University of Oviedo.

Copur H, Cinar M, Okten G, Bilgin N. (2012). A case study on the methane explosion in the excavation chamber of an EPB-TBM and lessons learnt including some recent accidents. Tunnelling and Underground Space Technology 27 (2012) pp.159–167.

De Luís P., Ugarte E. (2003), "Excavación con rozadora en los túneles de Fabares". Ingeniería de Túneles (Ingeotúneles) vol. 6. C. López-Jimeno Ed., Madrid, pp. 453-471, 2003.

Fedele P., Severini M. (2015). Carbon footprint in construction, the experience of Italferr. *Ingegneria Ferroviaria*, year 2015, p. 20.

Fedele P. Severini M. (2014). L'impronta climatica nelle construzzioni. L'experienza de Italferr. Italferr, Grupo ferrovie dello stato italiane, 22 p.

Fremo O. (2015). Life Cycle Assessment of the Byasen tunnel in Trondheim, Norway. Master Thesis. Norwegian University of Science and Technology, Department of civil and transport engineering. Trodheim (Norway), 2015. 103pp.

Fernández Antomil, N. (2008). Cálculo y diseño del sostenimiento del túnel El Fresno (Autovía Oviedo – La Espina). Master Thesis. University of Oviedo.

Galán I., Andrade C., Prieto M., Mora P., López J.C., San Juan M.A., 2010. Estudio del efecto sumidero de CO2 de los materiales de base cemento. Cemento y Hormigón, Revista Técnica. 130 p.

Galán García, I. (2011). Carbonatación del hormigón: combinación de CO2 con las fases hidratadas del cemento y frente de cambio de pH. PhD Thesis, Universidad Complutense de Madrid.

García-Arango I., Hacar F., Abellá A. (1993). Estudio para los túneles de "El Padrún", Asturias. Revista de Obras Públicas nº 3318, Febrero 1993.

García Arias, I. (2014). Diseño del esquema de voladura para el túnel de Santiuste. Master Thesis. University of Oviedo.

Greenhouse Gas Protocol (GHG) 2001. Estándar Corporativo de Contabilidad y Reporte de Gases de Efecto Invernadero (WRI/WBCSD). Edición revisada 2001. Link: http://www.ghgprotocol.org/files/ghgp/public/protocolo_de_gei.pdf

Gómez de las Heras, J. (1995). Manual de arranque, carga y transporte en minería a cielo abierto. Editado por Instituto Tecnológico Geominero de España. 2ª Edición, 604 pp. Madrid, 1995.

Grimstad, E., Barton, N. (1993). Updating of the Q-system for NMT. In: International Symposium on Sprayed Concrete. Fagernes, Proceedings, pp. 46–66.

Haselbach L.M. and S. M. (2008). Potential for carbon adsorption on concrete: Surface XPS analyses. Environmental Science and Technology, 2008. 42(14): p. 5329-5334.

Huang L., Bohne R., Bruland A., Drevland P., Salomonsen A. (2013). Life Cycle Assessment of Norwegian standard road tunnel. The 6th International Conference on Life Cycle Management in Gothenburg 2013.

Huang L., Bohne R., Bruland A., Drevland P., Lohne J. (2015). Environmental impact of drill and blast tunnelling: life cycle assessment. Journal of Cleaner Production 86 (2015) 110-117.

Huang L., Krigsvoll G., Johansen F., Liu Y., Zhang X. 2018. Carbon emission of global construction sector. Renewable and Sustainable Energy Reviews. Volume 81, Part 2, January 2018, pp. 1906-1916.

Huang L., Drevland P., Bohne R., Liu Y., Bruland A., Manquehual C.J. (2020). The environmental impact of rock support for road tunnels: The experience of NorwayScience of the Total Environment 712 (2020) 136421.

Innaurato, N., Mancini, R., Cardu, M., 1998. On the influence of rock mass quality on the quality of blasting work in tunnel driving. Tunn. Undergr. Space Technol. 13 (1), 81–89.

Instituto para la Diversificación y Ahorro de la Energía (IDAE). Factores de conversion de la Energia. Ministerio de Industria, Turismo y Comercio. 2011. Link: http://www.idae.es/uploads/documentos/documentos_Factores_Conversion_Energia_y_CO2_2011_0a9cb734.pdf

INECO (Ingeniería y Economía) and ECODES (Ecología y Desarrollo). 2012. "Huella de carbono de la construcción de una línea ferroviaria de alta velocidad". Link: http://ecodes.org/documentos/Informe_Huella_Carbono.pdf

Lee, J., Shim, J. A., and Kim, K. J. (2016). Analysis of environmental load by work classification for NATM tunnels." Journal of the Korean Society of Civil Engineers, Vol. 36, No. 2, pp. 307–315.

Lee, J., Kim K.J., Kim E.W., Kim H.R. (2017). Environmental load estimating model of NATM tunnel based on standard quantity of major works in the early design phase. Journal of the Korean Society of Civil Engineers. DOI: 10.1007/s12205-017-1795-z.

Li Q.S., Li L., Bai Y. (2013). CO2 emissions during the construction of a large diameter tunnel with a slurry shield TBM. Proc. World Tunnel Congress 2013, Geneva (Switzerland), Anagnostou and Ehrbar Eds., Taylor and Francis Group.

Li Q., Bai Y., Li L. (2015). Study of influential factors and measures for low carbonization during the construction of shields tunnels. Modern tunnelling technology, 52(3), 2015, pp. 1-7.

Li Q., Bai Y., Ridoiut A., Jiang Z. (2014). Comparative analysi of CO2 emissions of steel bar and synthetic fiber used in shield tunnel segment. Proc. Third Conference on Civil Engineering and Urban Planning, Mohammadian et al Eds., Wuhan (China), 2014.

Li X., Liu J. Xu H., Zhong P. (2011). Calculation of endogenous carbon dioxide emission during highway tunnel construction: A case Study. International Symposium on Water Resource and Environmental Protection, May 2011, Xian (China), pp. 2260-2264.

Liao S.M., Yang Y.H., Chen L.S., Xu J. (2012). Carbon Emission Reduction Oriented Optimization of Tunnel Construction in China. Proc. ITA-AITES World Tunnel Congress 2012, Bangkok, Thailand.

López J.M., Sánchez J. (2008). Consumo de energía y emisiones asociadas al transporte por coche y camión. Monografias Enertrans, número 12

Maxam, “Riodin technical brochure”, Maxam Europe S.A., Madrid, 2015. (www.maxam.net)

Míguez R., Benito A., Angona A. (2007). Túneles de Pajares. Galería de acceso de Folledo. Revista de Obras Públicas nº 3.474, 2007, pp 33-54.

Miliutenko S., Akerman J., Bjorklund A. (2012). Energy use and greenhouse gas emissions during the Life Cycle stages of a road tunnel - the Swedish case norra lanken. European Journal of Transport and Infrastructure Research, 12(1), 39-62.

Mohammadi, M., Farouq, M.H., Mirzapour, B., Hajiantilaki, N., 2015. Use of fuzzy set theory for minimizing overbreak in underground blasting operations – a case study of Alborz Tunnel, Iran. Int. J. Min. Sci. Technol. 25 (3), 439–445.

Morita Y., Shimizu K., Yamasaki T., Kato H., Shibahara N. (2012). A Study on the Life Cycle Assessment for Evaluating Carbon Impact from Construction of Rail Infrastructure. Association for European Transport and Contributors 2012, 16 p.

Mottahedi A, Sereshki F, Ataei M. 2018. Overbreak prediction in underground excavations using hybrid ANFIS-PSO model. Tunnelling and Underground Space Technology 80 (2018) 1–9.

Orica, “Eurodyn 2000 Technical Data Sheet”, Orica Explosivos Industriales S.A. (Orica Group), Spain, 2015. (www.orica.com)

Posada-Henao J.J. (2015). Effects of road slope and vehicle's weight on truck's fuel consumption. 5th International Symposium on Highway Geometric Design, Vancouver, Canada, June 2015.

Rodriguez R., Lombardia C. (2010). Analysis of methane emissions in a tunnel excavated through Carboniferous strata based on underground coal mining experience. Tunelling and Underground Space Technology 25 (2010). Pages 456-468

Rodríguez R., Díaz-Aguado M.B., Lombardía C. (2012). Compensation of CH4 emissions during tunneling works in Asturias: a proposal with benefits both for local councils and for the affected population. Journal of Environmental. Management. 104, pp. 175 - 185.

Rodríguez R., Tosal A., Pérez F., Díaz-Aguado MB. (2017). Advancing rate and carbon footprint related to different excavation methods in conventional tunnelling (Fabares tunnel, Asturias, Spain). International Conference on NexGen Technoclogies for Mining and Fuel Industries 2017 (NxGnMiFu 2017). February 15-17, 2017, Vigyan Bhawan, New Delhi, India.

Rodriguez R, Fernández P, Pérez F, Malagón B. 2019. Relevance of the concrete used for the support and lining in tunnels excavated through different rockmasses from safety, economic and environmental point of view. The 2019 International Conference on Tunnels and Underground Spaces - ICTUS19 (included in the 2019 World Congress on Advances in Structural Engineering and Mechanics), Jeju Island, Korea, September 17 - 21, 2019.

Salam A., Greberg B., Skawina B., Gustafson A. (2015). Analysing energy consumption and gas emissions of loading equipment in underground mining. Canadian Institute of Mining, Metallurgy and Petroleum Journal (CIM Journal), vol. 6, No 4, 2015. pp. 179-188.

Shillaber C., Mitchell J., Dove J. (2016a). "Energy and Carbon Assessment of Ground Improvement Works. I: Definitions and Background". Journal of Geotechnical and Geoenvironmental Engineering, vol 142 (3) pp. 04015083-1 – 04015083-9, 2016.

Shillaber C., Mitchell J., Dove J. (2016b). "Energy and Carbon Assessment of Ground Improvement Works. II: Working model and example". Journal of Geotechnical and Geoenvironmental Engineering, vol 142 (3) pp. 04015083-1 – 04015083-9, 2016.

Sterling, R., Admiraal, H., Bobylev, N., Parker, H., Godard, J.P., Vähäaho, I., Rogers, C.D.F., Shi, X., Hanamura T. (2012). Sustainability Issues for Underground Space in Urban Areas. Proceedings of the ICE - Urban Design and Planning, Volume 165, Issue 4, Dec. 2012. pp. 241–254.

Standard ISO 14040:2006: "Environmental management — Life cycle assessment — Principles and framework".

Standard EN-15643-5: "Sustainability of construction works - Sustainability assessment of buildings and civil engineering works - Part 5: Framework on specific principles and requirement for civil engineering works"

The Intergovernmental Panel on Climate Change (IPCC). Section: 2.10.2 Direct Global Warming Potentials. Climate Change 2007: Working Group I: The Physical Science Basis. 2007. Link: https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

Toraño J. (1994) Máquina de ataque puntual WAV-250. Fabricación y ensayo de la máquina para avance para el avance de galerías de pequeña sección. Canteras y Explotaciones 331, pp. 48-59.

Tuchschmid M., Knörr W., Schacht A., Mottschall M., Schmied M. 2011. Carbon Footprint and environmental impact of Railway In-frastructure. International Union of Railways (UIC), 2011, 87 p.

Xu J., Guo C., Chen X., Zhang Z., Yang L., Wang M., Yang K. (2019) Emission transition of greenhouse gases with the surrounding rock weakened – A case study of tunnel construction. Journal of Cleaner Production 209 (2019) 169-179.

Zhang X. (2016). Carbon-emission assessment of large shield tunnel based on data-mining methodology. World Tunnel Congress 2016, San Francisco (USA).

Zhang K., Zheng W., Xu C., Chen S. (2019). Risk assessment of gas outburst in tunnels in non-coal formation based on the attribute mathematical theory. Geomatics, Natural Hazards and Risk 10 (2019), pp. 483–504

Zheng J., Liang L. Lu M. (2015). Research on evaluating methods for carbon emissions of the long distance water diversion project based on Life Cycle Assessment. Advances in Energy Science and Equipment Engineering, Zhou, Patty and Chen Eds., Taylor & Francis Group, London. Pp 1499-1502.

APENDIX – FORMULAE TO ESTIMATE THE AMOUNT OF MATERIALS AND ENERGY

The design of the blasting, transport, support, ventilation, lighting, dewatering and other systems in a tunnel is a complex task that has to be carried out by engineers or technicians with experience. The following is only an approach to estimate the quantity of materials and energy used in order to estimate with accurate enough the CO_2 emissions. The formulae presented here should not be used for direct design of the systems.

A.1. Formulae to assess the Materials (steel and concrete) consumption

Mass of steel

Let us assume a tunnel that has advanced from an initial length L_0 to a final length L_f. If the tunnel a cross section is S (in m^2) the total lateral area of the tunnel corresponding to the lining is in m^2:

$$A_{LL} = \left(L_f - L_0\right) 2\pi \sqrt{\frac{S}{\pi}} \qquad \text{(A.1)}$$

And the lateral area A_{Ls} on which the support is installed is in m^2:

$$A_{LS} = c_{RMR}\, A_{LL} \qquad \text{(A.2)}$$

c_{RMR}= 0.75 if RMR>30 and there is no support on the floor (invert) or c_{RMR}= 1.0 for RMR≤ 30. Using the recommendations of Romana (2014), the mass of steel related to bolts per square meter of tunnel wall m_b can be estimated approximately in kg/m^2 as follows:

$$m_b = 0.0065\,(100 - RMR)^2 \qquad \text{(A.3)}$$

In the same way, the mass per square meter and the total mass of steel related to steel sets are:

$$m_s = 120 - 2.1\,RMR \qquad \text{(A.4)}$$

It is assumed that in Spain is common to use steel sets only when RMR ≤ 50.

And the total mass of steel is in t:

$$M_{st} = (m_b + m_s)\ A_{LS} \qquad \text{(A.5)}$$

Mass of concrete

The design thickness of the sprayed concrete t_d, in cm, can be estimated by:

$$t_d = 35.5 - 0.4\,RMR \qquad \text{(A.6)}$$

only for RMR ≤ 80 because when RMR> 80 shotcrete is not used.

On the other hand, there is significant quantity that has to be used to fill the void due to over-excavation; it can be assumed that the thickness of the over-excavation is about twice the theoretical thickness of the support:

$$t_{oe} \approx 2\, t_d \qquad \text{(A.7)}$$

which also includes the proportion of shotcrete which is lost because the rebound when it is applied. It is a conservative value based on our own experience and other authors as Innaurato et al (1998), Mohammadi et al. (2015) or Mottahedi et al (2018). Then, the total thickness of shotcrete t_{sc} is in cm:

$$t_{sc} \approx 3\, t_d = 106.5 - 1.2\,RMR \qquad \text{(A.8)}$$

Assuming a typical density of 2.3 t/m^3, total mass of shotcrete per square meter is, in t/m^2:

$$m_{sc} = 0.023\ (106.5 - 1.2\ RMR) \tag{A.9}$$

In general terms, in Spain the thickness of the lining does not depend on the rockmass quality. A typical value is t_L= 35 cm for highway tunnels and t_L= 40 cm for railway tunnels. Assuming a density 2.3 t/m^3, the mass of concrete per m^2 of wall tunnel is in t/m^2:

$$m_c = 0.023\ t_L \tag{A.10}$$

And the total mass of concrete used for support and the lining is:

$$M_c = (m_{sc}\ c_{RMR} + m_c)\ A_{LL} \tag{A.11}$$

A.2. <u>Formulae to assess the fuel consumption</u>

Out of road vehicles

The power in kW necessary to move a mass m (in metric tonnes) with a speed of v (km/h), on a road with a slope i (in %) and a friction coefficient f_R (in %), is:

$$P_{TR} = \frac{m\ g\ v}{360\ \eta_{TR}}\ (f_R \pm i) \tag{A.12}$$

being η_{TR} the overall performance, g the gravity acceleration and m is the total moved mass (truck+load).

If c_l is the specific consumption in l/kWh (or litters of fuel spent to produce one kWh), and d_g is the fuel density (in g/l) the fuel consumption (in g/h) will be:

$$C_L = \frac{c_l\ m\ g\ v\ d_g}{360\ \eta_{TR}}\ (f_R \pm i) \tag{A.13}$$

And the fuel consumption per ton moved and km ran (in g/t×km) is:

$$C_g = \frac{c_l\ g\ d_g}{360\ \eta_{TR}}\ (f_R \pm i) \tag{A.14}$$

If d_g= 833 g/l, g= 9.82 m/s^2, $\eta_{TR} \approx$ 0.80, c_l= 0.25 l/(kWh), the following simplified formula is deduced:

$$C_g \approx 7\ \ (f_R \pm i) \tag{A.15}$$

A typical value for the friction coefficient in a civil work road is f_R= 3.5%.

Trucks

To calculate the emissions due to the transportation from the production factories to the construction site we will use an approach based on López and Sánchez (2008) results. The consumption, in grams, will be given using the following formula:

$$C_g \approx 15 - \frac{v}{20} \tag{A.16}$$

Where C_g is the amount of diesel consumed (grams) per ton transported and km driven and v is the speed of the truck.

A.3. Formulae to assess the electrical energy consumption

Ventilation system

The electrical power P_v (in kW) needed by a fan which supplies an air flow rate of Q_V (m^3/s) with a total pressure of H_V (Pa) is:

$$P_V = \frac{H_V\, Q_V}{1000\, \eta_F} \qquad \text{(A.17)}$$

Where η_F is the overall performance of the fan.

The pressure loss in a duct with a length L (in m) and diameter d (in m) when an air flow rate of Q_a (m^3/s) passes through it can be estimated by:

$$H_a = 0.992\ \frac{\lambda}{d^5}\ L\ Q_V^2 \qquad \text{(A.18)}$$

Where λ is the friction factor and the coefficient 0.992 evolves the density of the air, the gravity acceleration and the number □. By substitution in the formula of the power:

$$P_V = 10^{-3}\ \frac{\lambda\, Q_V^3}{d^5\ \eta_F}\ L \qquad \text{(A.19)}$$

Assuming now a typical values $\lambda = 0.024$, $\eta_F = 0.80$, and taking into account that the airflow rate at the face under acceptable conditions is $Q_F = 0.85\ Q_V$, the electrical power demanded by the fan as a function of the length and the necessary airflow rate at the face will be:

$$P_V = 5 \times 10^{-3}\ \frac{Q_F^3}{d^5}\ L \qquad \text{(A.20)}$$

Nevertheless, there is a relationship between the typical values of Q_F required in the tunnel, the diameter of the duct used and the maximum length of the tunnel (typical values of d= 1.6 to 2.5 m for tunnel lengths of L_{max} = 1000 to10000 m). Consequently, it can be observed empirically that the necessary electrical power at a given moment is proportional to the length of the tunnel L:

$$P_V = c_v\ L \qquad \text{(A.21)}$$

From our experience we have found that advancing by drilling and blasting up to 3000-4000 m from one of the portals, this coefficient is of about $c_V \approx 0.100$.

$$P_V = 0.100\ L \qquad \text{(A.22)}$$

When a tunnel advances from L_o to L_f, the average electrical power demanded is in kW:

$$P_V = 0.100\ \frac{L_o + L_f}{2} \qquad \text{(A.23)}$$

Due to the fan works practically 24 hours a day the energy consumed is (in kWh):

$$E_{CV} = 24\ T\ P_V \qquad \text{(A.24)}$$

Where T is the time, in days, spent for the excavation from L_o to L_f. Let us assume a tunnel through a rock mass characterized by its RMR; the advancing per round or advancing per blast a_{Bl}, in m/round, can be estimated approximately as follows:

$$a_{Bl} = \frac{RMR}{10} \tag{A.25}$$

If the number of rounds or number of blasts a day is n_{Bl}, in rounds/day, the total time to excavate the tunnel from L_o to L_f is, in days:

$$T = \frac{L_f - L_o}{n_{Bl}\ a_{Bl}} \tag{A.26}$$

Tunnel dewatering system and water treatment plant

When a tunnel with a slope i (%) is excavating downhill, the water must be taken off the tunnel by a pumping system. The electrical power P_w (in kW) needed by a hydraulic pump pumping a water flow rate of Q_w (m^3/s) under a total pressure of H_w (Pa) is:

$$P_w = \frac{H_w\, Q_w}{1000\, \eta_P} \tag{A.27}$$

Where η_P is the overall performance of the pump. If the specific water flow rate is q_L, in m^3/s per m of tunnel, the water flow rate for all the tunnel is:

$$Q_w = q_L\ L \tag{A.28}$$

Water inflow becomes in a problem for high water flow rates. Based on our experience, a value of q_L between 2×10^{-5} y 5×10^{-5} m^3/s per m of tunnel can be used in this case.

H_w has two contributions. The first is the geometric height H_G or difference between the pump and the water exit point. For the case of a tunnel with a length L with moderate slope i (%) and assuming that there is a pump at the advancing face, H_G can be calculated, in m, as follows:

$$H_G = \frac{i}{100}\ L \tag{A.29}$$

The other contribution of the total pressure is the pressure losses due to the circulation of water within a pipe J which can be estimated, in m, by classical formulae as the follows:

$$J = 10.34\ \frac{n^2\ L}{d^{16/3}}\ Q_w^2 \tag{A.30}$$

Where d is the pipe diameter, in m, and n the friction factor which depends on the pipe material. The total pressure is, in Pa, is:

$$H_w = 1000\ g\ (H_G + J) \tag{A.31}$$

Where g is the gravity acceleration. Then, the electrical power is in kW:

$$P_w = \frac{g\, L\, Q_w}{\eta_P} \left(\frac{i}{100} + \frac{10.34\, n^2\, Q_w^2}{d^{16/3}}\right) \tag{A.32}$$

For the case of very long tunnels in which the quantity of water flow is very high, it is common to use several pipes N_p in parallel and the water flow rate for each one is:

$$Q_{wp} = \frac{Q_w}{N_p} \tag{A.33}$$

The total power corresponding to this fraction of the flow rate is:

$$P_T = N_p \, \frac{g \, L \, Q_{wp}}{\eta_P} \left(\frac{i}{100} + \frac{10.34 \, n^2 \, Q_{wp}^2}{d^{16/3}}\right) \tag{A.34}$$

Pipes and pumps are selected as a function of the maximum length of the tunnel L_{max} and then the power required for a given length L is approximately proportional to this length:

$$P_w = c_w \; L \tag{A.35}$$

From the analysed tunnels, typical values are $c_w \approx 0.25$ for tunnels with i= 1%-5% and $c_w \approx 0.50$ for tunnels with i= 5%-15%.

Once the power is known, the energy can be estimated by using the formulae A.24 to A.26.

Finally, the power necessary in the treatment plant is approximately proportional to the water flow rate to be treated:

$$P_t = c_t \; q_L \; L \tag{A.34}$$

From data of different tunnels, we have found that the average installed power in the water treatment plant is of about 1000 kW per m^3/s of water to be treated c_t= 1000.

External services and tunnel illumination

The tunnel is illuminated by means of lamps with two 36 W fluorescent tubes each 5 m of tunnel. On the other hand, each working face is illuminated with four lamps 1000 W each one. Assuming that there are two working faces (one the advancing face and another in an intermediate point) the electrical power for the lighting of a tunnel is in kW:

$$P_L = 8 + \; 0.015 \; L \tag{A.35}$$

The average electric power necessary for the lighting while the tunnel advances from the length L_o to the length L_f is:

$$P_L = 8 + \; 0.015 \; \frac{L_0 + L_f}{2} \tag{A.36}$$

If the power demanded by external services (offices, workshops…etc) is P_{ext}, then the total electric power for auxiliary systems P_{aux} is:

$$P_{aux} = P_{ext} + \; P_L \tag{A.37}$$

Assuming that in the worst conditions both external services and lighting have to work 24 hours a day, the energy demanded in a day is, in kWh/day:

$$E_{aux} = 24 \, P_{aux} \tag{A.38}$$