ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

IRF Greenhouse Gas calculator
- Analysis and validation-

International Road Federation - IRF

N. Bueche

Prof. A.-G. Dumont

September 2009

ENAC – Faculté de l'environnement naturel, architectural et construit

LAVOC - Laboratoire des voies de circulation

IRF Calculator for Harmonised Assessment and Normalisation of Greenhouse gas Emission for Roads

CHANGER

Analysis and validation

Excerpt of Full Report

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[...]

1. Objectives of the study

The study of the Traffic Facilities Laboratory (Laboratoire des Voies de Circulation - LAVOC) of the Swiss Federal Institute of Technology (Ecole Polytechnique Fédérale de Lausanne - EPFL) consists of a global analysis and partial validation of the IRF greenhouse gas calculator. This calculator is currently under development. Thus, the considerations made in the present report concern only pre-construction and pavement modules that have been developed so far. Security barriers and road signs modules will not be considered in this report.

The detailed methodology followed and the fundamental basis of the calculator will not be treated here, the mandate consisting in an analysis and validation of databases and calculations procedure for greenhouse gases.

Indeed the major objective consists, in a first step, in an analysis of the calculation procedure. This permits to have a better understanding of the whole procedure that has to be followed and also identifying the databases that have to be considered for the different calculation steps. Based on this analysis, a study and validation will be conducted for following databases:

- Energy sources
- Construction materials
- Material transport
- Construction machines

The validation procedure consists at assessing the references, quality and reliability of the data used. The consistency of the various databases will also be assessed and if possible alternative data proposed for further calculations or sensitivity analyses.

Besides, it has been asked to put an emphasis on the emission standards and greenhouse gases. Different greenhouse gases to be considered and the calculation procedure has consequently been analysed and some recommendations provided.

Note that the Traffic Facilities Laboratory cannot be considered as responsible for the product (IRF GHG calculator) and its use. [...]

2. IRF – Greenhouse gas (GHG) Calculator

A. Calculator architecture

The IRF greenhouse gas calculator is divided into four main modules (Figure 1):

- Pre-construction;
- Pavement;
- Security barriers;
- Road signs.

As already mentioned, the present work considers only the first two modules; the other modules have not yet been developed.

Every single module follow the same structure as developed in Figure 1. Firstly, input data are entered by the user of the calculator. Then, a first calculation is carried out in order to obtain the material quantities, material transport, electricity used… These quantities are finally compiled with emissions factors in order to calculate the total emissions related to every step of the road construction process.

It is especially in this third phase involving standards and databases that the major contribution has to be performed through a detailed analysis of the dedicated database and standards used. Beforehand, the phase 1 and 2 will be analysed in order to have a better understanding of the whole process.

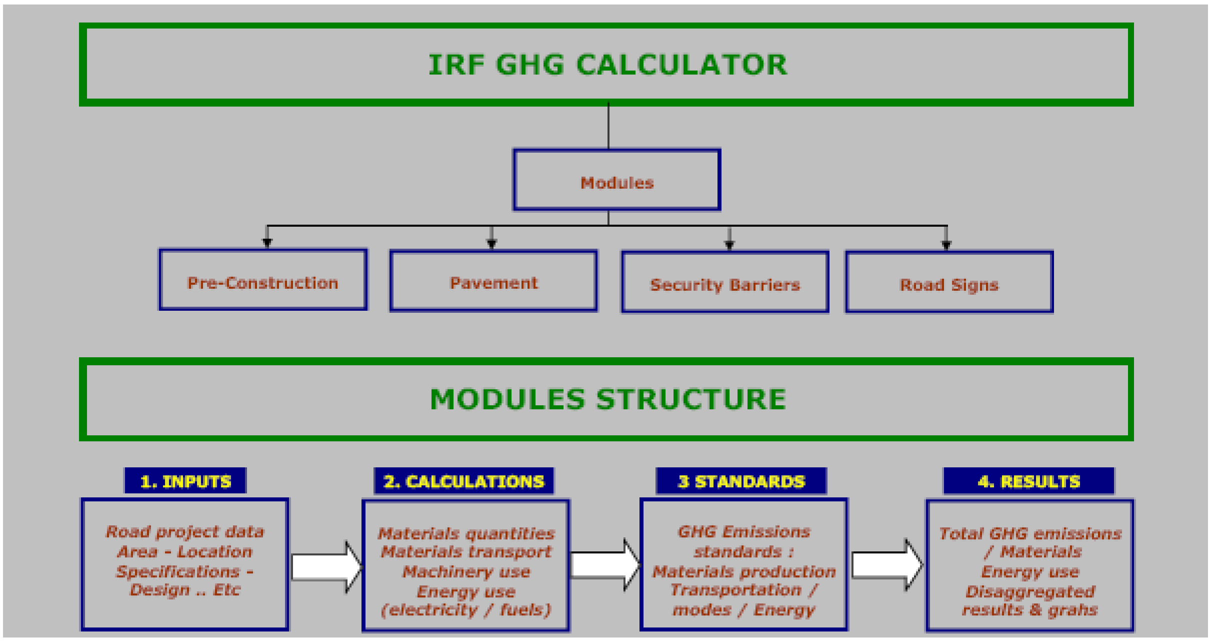

Figure 1: General overview of the IRF GHG calculator (Source: GHG_Module1_Validation_Final.xls)

[...]

D. General comments related to the methodology

In this initial phase, the general architecture of the IRF GHG calculator has been analysed. The general way of proceeding is very clear and performed in a logical way i.e. the various components are first identified and then the associated emissions calculated using emission database. The various emissions databases will be further analysed in section "database analysis". The different emission categories considered in this calculator can be discussed. For instance, according to IVL reports [2] [3] one could suggest considering the emissions related to the extraction of salt used for winter maintenance or snow clearance. This is another reason to consider separately the construction and maintenance phases. Indeed maintenance phases induce some specific actions that would need to be considered or mentioned such as trench digging for maintenance, sawing and sealing of joints in concrete road construction, foundation reinforcement...

Finally, it is crucial to clearly state the boundaries of the system by identifying the relevant topics. This has to be done in the beginning of the analysis. If it is planned to consider road lighting, road panels and the maintenance work of the road, it is also important to define a time period. This will affect the number of maintenance work and also the energy consumption related to the road system.

3. Greenhouse gases

The IRF calculator aims at providing the GHG emissions for a complete road construction process including pavement, security barriers and road signs as well. In order to have a better understanding, it has to be clarified the gases to be considered and how these various elements should be taken in account within the calculation process.

This chapter will firstly describe the major GHG that have to be considered for an analysis and also the calculation method in order to convert gases in CO_2 equivalent that is the common unit used. Finally, some considerations will be drawn concerning standards related to emissions.

A. Major GHG and considerations related to road sector

Before starting with a complete calculation and analysis, it is essential to have a clear definition of greenhouse gases. Greenhouse gases are gases in an atmosphere that absorb and emit radiations within the thermal infrared range. This causes the so-called greenhouse effect that is the earth rise in temperature. Note that without the greenhouse effect, earth would be too cold for human to live; but on the other hand a too strong greenhouse effect would make the earth warmer and cause severe problems for human, plants and animals. It is well known that human activities have an effect upon the level of GHG in the atmosphere. Thus, considerable developments are performed in various domains in order to decrease this environmental load.

Most greenhouse gases have sources from both the nature in general and from human activities (anthropogenic). It is mainly through the burning of fossil fuels (mainly solid fuel, liquid fuel, gaseous fuels) and forest clearing that human activity has added greenhouse gases (mainly CO_2) to the atmosphere. One can also highlight the use of fertilizer in agriculture or the use of chlorofluorocarbons in refrigeration systems that lead to increases of nitrous oxide concentration. Another important GHG source is the volcanic activity. The major naturally occurring greenhouse gases are, in order of abundance:

- Water vapour: gas phase of water than can be produced by boiling water or water evaporation. Basically, water vapour level will increase with any warming associated to an increased concentration of other GHG.
- Carbon dioxide (CO_2): Most important gas in climate context. Enters the atmosphere through the burning of fossil fuels (oil, natural gas and coal), solid waste, trees and wood products and also as a result of other chemical reactions. It is also removed from atmosphere when absorbed by plants for the carbon cycle.
- Methane (CH_4): Emitted during the production and transport of coal, natural gas and oil. It also results from agricultural practices and the decay of organic waste.
- Nitrous oxide (N_2O): Atmospheric pollutant produced by combustion of fossil fuel and solid waste. It is also emitted during agricultural and industrial activities.
- Ozone (O_3).
- Chlorofluorocarbons (CFCs).

The major direct GHG (CO_2, CH_4, N_2O) occur naturally on earth. However, human activity increases the concentration of these gases and consequently produced a global earth warming. There are several other gases that do not have a direct global warming effect, but they do influence the formation or destruction of GHG. Thus, they indirectly affect the global warming. One can mention:

- Carbon monoxide (CO)
- Oxides of nitrogen (NO_x)

- Non methane volatile organic compounds (NMVOCs)
- Aerosols
- ...

The UNFCCC[1] Kyoto protocol [4] adopted in Kyoto (Japan) in December 1997 and which came into force in February 2005 mentions in article 3 that "*The Parties included in Annex I shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A do not exceed their assigned amounts ... with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012*". Thus, the protocol put an emphasis on the following direct greenhouse gases mentioned in Annex A of the protocol: carbon dioxide, methane, nitrous oxide and three CFCs that are potent greenhouse gases (hydrofluorocarbons HFCs, perfluorocarbons PFCs and sulfur hexafluoride SF_6). These gases contribute directly to climate change owing to their positive radiative forcing effect. The Kyoto protocol focuses on the major greenhouse gases emitting sectors i.e. energy, transport, industry sector, agriculture, forestry and waste management.

Since Kyoto protocol came into force, 184 counties ratified, accessed, approved or accepted the Kyoto Protocol and these countries represent 63.7% of worldwide emissions (as of 1st June 2009, according to UNFCCC website). The countries that signed Kyoto protocol perform for a specific time period (e.g. one year) a greenhouse gas emission and sink inventory. This consists in an accounting of the amount of gas emitted or removed from the atmosphere. It is essential to have a regular assessment of the situation in order to address climate changes issues by having an updated situation and fulfil the UNFCCC protocol. Such inventory permits also to identify the most emitting sectors, analyse trends, assess progress and improve the situation for the next time period.

Note that most CFCs are not regulated by Kyoto protocol but by the UNEP[2] "Montreal Protocol on Substances that Deplete the Ozone Layer" and ozone depletion plays a minor role in global warming. Moreover, water vapour is also not taken into account in these protocols and it does not seem necessary to be considered within a GHG calculator of road construction emissions, this because human activity does not significantly affect this water vapour gas emission.

In a road construction process, a major contributor to the emissions is the asphalt production. Stripple [3] showed that the major emissions can be attributed to the road construction phase while road maintenance and operation represent only a small percentage.

EAPA [5] produced an environmental guideline document for the production of asphalt paving mixes. In this document, it is mentioned that gaseous emissions are one among the other possible environmental impacts of an asphalt plant. One can also mention the particulates, noise, odour, water preservation or waste. Considering the gaseous emissions, leading emissions of asphalt plants are:

Inorganic emissions such as:

- SO_2: caused mainly by burning process in the dryer and influenced by fuel sulphur content.
- NO_x: mainly originates from the burner in the drying drum and influenced mainly by the nitrogen content of the fuel. Nitrogen oxides also contribute to the formation of acid rain.
- CO: mainly associated with the combustion process in the dryer. The carbon monoxide emissions influenced by the mineral composition (moisture, use of RAP, fines...) and its contact with the flame.

[1] UNFCCC: United Nations Framework Convention on Climate Change
[2] UNEP: United Nations Environment Program

- CO_2: emissions directly linked to the type of fuel used and heating process of bitumen and aggregates. Note that CO_2 emissions level depends on the type of fuel used.

Organic emissions:

- Total Organic Compound (TOC): most important source of these hydrocarbons emissions is the incomplete combustion of fuel and bitumen heating process.
- Polycyclic Aromatic Hydrocarbons (PAH): most important hydrocarbons category with respect to their toxicity.

Considering the vehicle or machines emissions, the major emissions can be related to the burning fuel. The major exhaust pollutants are (unburned) hydrocarbons, nitrogen oxides, carbon monoxide and carbon dioxide.

In this section, the major greenhouse gases and also the greenhouse gases taken in account by Kyoto protocol have been discussed. For the framework of IRF GHG calculator, it is important to consider the emissions that will be relevant for a road infrastructure project. It is obvious that carbon dioxide (CO_2) has to be considered in such a GHG calculator. Indeed, CO_2 is the most emitted gas and also the common unit used. For instance, Colas Ecologiciel® [IRF-1] considers that CO_2 represents approximately 80% of the total CO_2-equivalent emissions. In addition, it would be advisable to consider other greenhouse gases such as CH_4 and N_2O. This will be further discussed in the last part of this section, this because the choice of the GHG might depend on the effect of the gas on earth (section B) and limit values (section C).

B. How to calculate and convert GHG into CO_2-equivalent?

The contribution to greenhouse effect of a dedicated gas depends on the gas itself and also its abundance. Thus, a simple calculation methodology has been developed by IPCC[3] and widely accepted in order to compare the gases contribution. This methodology will be detailed below.

EPA[4] [6] explains that gases in the atmosphere can contribute to greenhouse effect both directly and indirectly. Indirect radiative forcing occurs when a chemical transformation produce other greenhouse gases, when a gas influences the atmospheric lifetime of other gases, and/or when a gas affect atmospheric processes that alter the radiative balance of the earth. Thus, to compare each greenhouse gases, IPCC has developed the Global Warming Potential (GWP) concept that is based on radiative properties. GWP is defined as *"the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas"* [7]. The reference gas used is CO_2 over all time periods. Therefore emissions are measured in CO_2 equivalent. The unit for weighted emissions is teragrams[5] (or million metric tons[6]) and as mentioned, GWP refers to a specific time scale that characterizes the removal of the substance from the atmosphere. It is important to consider the time horizon because the various gases have different lifetimes in the atmosphere. Thus, a molecule can have a high GWP on a short time scale (e.g. 20 years) and a small GWP on a long time scale (e.g. 100 years) depending on its own lifetime. The, GWP will decrease in function of the lifetime of the chemical element considered. The GWP values are indicated in the IPCC reports that are regularly updated. Many reports are based on the IPCC Second Assessment Report (SAR) [8] as it consists of a well known common basis. Updated values can be found in IPCC Third

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[3] IPCC: Intergovernmental Panel on Climate Change
[4] EPA: US Environmental Protection Agency
[5] 1 Tg=10^{12} grams=10^9 kg=10^6 metric tons
[6] 1 metric ton = 1000 kg according to SI

Assessment Report (TAR) [9] and IPCC Fourth Assessment Report (AR-4) [10]. ***Table 1*** indicates a summary of the emission values for the major GHG considered in this study, according to SAR, TAR and FAR, for a 100 years time horizon. Note that all values are in CO_2 equivalent and unweighted units. Detailed information and background considerations can be found in section 6.12 of TAR or section 2.10 of FAR.

Gas	GWP (SAR)	GWP (TAR)	GWP (FAR)
CO_2	1	1	1
CH_4	21	23	25
N_2O	310	296	298

Table 1: Global Warming Potential (100-Year time horizon) according to SAR, TAR and FAR

Table 1 means for instance that emissions of one million metric tons of methane are equivalent to emissions of 23 million metric tons of carbon dioxide (TAR). Finally, Carbon dioxide equivalents are commonly expressed as "million metric tons of carbon dioxide equivalents ($MMTCO_2Eq$)."

MMTCO2Eq = (million metric tons of a gas) · (GWP of the gas)

Despite the bigger GWP for methane and nitrous oxide, the global effect of carbon dioxide is much more important because of the quantities produced. For instance, in US and for year 2007, CO_2 originates 85% of the total CO_2-equivalent emissions while CH_4 and N_2O represent respectively 8% and 4% [6]. The largest source of CO_2, and of overall GHG emissions, was fossil fuel combustion for this case. It can also be highlighted that the conversion in CO_2-equivalent might have a negative effect. Indeed, methane or nitrous oxide are very important and harmful gases that could be underestimated through the simplification of CO_2-equivalent calculation. The stakeholder might have the impression that only carbon dioxide has to be considered that is far from reality. This has to be taken in account in IRF GHG calculator.

It can be emphasis that Kyoto protocol consider the "*aggregate anthropogenic carbon dioxide equivalent emissions*" that means to calculate in CO_2-equivalent. Note that IPCC does not provide GWP values for CO, NO_x, NMVOCs, SO_2 and aerosols because there is no consensus for the method to estimate the gas contribution. Indeed, these gases are short-lived in atmosphere, spatially variable or have only indirect effects. Besides, some other greenhouse gases are not often listed because of the very small quantities, but they do present an important global warming potential (e.g. nitrogen trifluoride).

Finally, it is also recommended by IPCC [11] to recalculate emissions when the methods have been changed or improved in order to have updated values.

C. Emissions standards

As mentioned above, there are various greenhouse gases that might be considered. The choice will depend on the type of analysis and degree of accuracy needed. A GHG calculation can have various objectives but the comparison of various solutions and the respect of standards are obviously very common ones. Thus, it could be imagined to compare the calculated results with standards or emissions objectives previously defined. The use of national or international standards can also help for a first assessment of the results, this on order to verify the coherence and order of magnitude. Besides, standards or emissions limit values could also be used in a database for instance concerning the vehicle emissions. This will be further discussed in the databases analysis.

In this chapter, a few examples of international and then national policy examples and emissions standards that could be considered for a greenhouse gas calculator of a road project are mentioned. These non-exhaustive emission standards do not aim at giving limit value for the various items in the calculator but rather at offering a possibility to improve the GHG calculation or results assessment. Some additional considerations would be advisable for a further complete international standards comparison.

<u>International emissions standards</u>

A key element in emissions comparisons is the measurement method and procedure. This can lead to completely different results according to the measurement method applied. Different ISO and CEN standards exist that describe these measurement methods. Considering the emissions limit values for gaseous emissions that could be applied to a road construction process, some typical values are provided by European Asphalt Pavement Association [5]. Note that these values highly depend on type of fuel used, use of RAP and, as already mentioned, measurement methods[7]:

- SO_x and NO_x: Typical limit values are between 350 and 500 mg/Nm^3.
- CO and CO_2: Typical limit values are between 350 and 1000 mg/Nm^3. There are no limits for CO_2 emissions in European countries, but some national rules and recommendations.
- TOC: Typical limit values are between 50 and 150 mg/Nm^3.

These values provide a first global order of magnitude for the emissions. Then, each country has its own national policy that will be further applied.

In the United States, the Environmental Protection Agency has the mission to protect human health and environment. The "Clean Air Act" [12] is a law, established by the American Congress, which defined EPA's responsibilities for protecting and improving the nation's air quality and the stratospheric ozone layer. This document explains in particular that EPA has to fix air quality standards for pollutants that might endanger human health. Basically, two different standards level has been established for the six major pollutants, this including following greenhouse gases: carbon monoxide, dioxide of nitrogen and ozone.

<u>International vehicles emission standards</u>

Since 1995, international standards (called "Euro") are used to set up the maximal emissions values for vehicles. These standards are applied to new vehicles (since 1988 for first circulation in Euro 0) and aim at decreasing the environmental pollution due to road traffic. The major vehicle emissions are considered for the Euro standards in particular, hydrocarbons, nitrogen oxides and carbon oxides. Particulate matters are also measured. Carbon dioxide is emitted in important quantity by vehicle, it is however not directly considered in the Euro standards as it does not represent a danger for human and animal being. CO_2 emissions are however controlled by other international standards.

Concerning diesel vehicles, the particle weight is currently considered, but not the particle size. This currently leads to discussions and probably further standards modifications by introducing a criteria related to the number of particle in addition to the weight. Indeed it is now recognized that the finest particle size are the most dangerous for health. Thus the current standard that considers only the particle weight favour the elimination of the heaviest particles that are less dangerous.

[7] N term is an abbreviation of norm or normal. In pollution engineering N means a temperature of 0 °C and a pressure of 1.013 bar, the conditions at which one mole of an ideal gas has a volume of 22.413837 liters.

Table 4 indicates the limit emission values for passenger cars (category M1) according to the Euro standards. Note that diesel vehicles have more strict CO standards but allow higher NO_x emissions.

Standards	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
	After 1993	After 1996	After 2000	After 2005	After Sept. 2009	After Sept. 2014
NO_x [g/km]	-	-	0.15	0.08	0.06	0.06
CO [g/km]	2.72	2.2	2.2	1	1	1
HC [g/km]	-	-	0.2	0.1	0.1	0.1
PM_{10} [g/km]	-	-	-	-	0.005	0.005

Table 2: Euro emissions standards for petrol (gasoline) vehicles in function of year of production

The standards for heavy-duty diesel trucks and bus engines (mass > 3'500 kg) are commonly known under Euro I ... VI while arabic numerals are usually reserved for light vehicle standards. Whereas for passenger cars, the standards are defined in g/km, for lorries (trucks) they are defined by engine power, g/kWh, and are therefore in no way comparable.

The Euro standards are not only applied in the European Union but also in many Asian countries for instance such as China, India, Indonesia, Malaysia and Vietnam. United States have their own standards regarding vehicles (so-called "US Tier").

In the framework of a GHG calculator, these standards could for instance help in assessing the vehicle emissions used. On the other hand, if no information is available, one could imagine proposing the emissions limit values as default values for the database related to vehicle emissions.

Swiss political policies related to CO_2

The Swiss law [13] and Swiss recommendations [14] related to CO_2 consider only the CO_2 emissions related to energetically use of fossil fuel and combustible. No other GHG are considered in these documents. This can be explained by the fact that in Switzerland, CO_2 emissions represent about 80% of total GHG emissions considered in Kyoto protocol. Thus, The Swiss CO_2 law is a crucial tool in order to respect the Kyoto protocol commitments. Note that CO_2 law applies a correction factor on the total emissions in order to take in account the fuel consumption used for heating. This correction factor is not used in the Kyoto protocol and consequently data cannot be directly compared. Besides, a tax for the emission of CO_2 on fossil fuel is also perceived in Switzerland. The amount of this tax varies in particular in function of the global national results and other countries policy, but this tax might reach the amount of 36 CHF/to_{CO2} for the year 2010. The maximal amount foreseen is 210 CHF/to_{CO2} and by doing sufficient efforts and reducing its emissions, a company can be tax exhausted.

Swiss CNA standards

Some other national policies deal with the limit emissions values on a working place. In Switzerland, this is for instance standardized by SUVA. This organism provides limit values for emissions in order to respect workers health. Thus, this does not concern GHG in first priority but all potentially dangerous substances. These guidelines has to be respected for instance in an asphalt plant chimney or during the laying phase of an asphalt mixture. In the SUVA document, average emission values (VME) as well as limit emission values (VLE) are indicated for the considered substances. CO_2 is not considered in such a document, but some average and/or limit values can be obtained for greenhouse gases such as ozone, methane or carbon monoxide. Standards providing emission limit values as mentioned here could also be used in order to assess the results of the calculation and, if necessary, highlight potential health danger in function of the calculation results.

Kyoto Protocol

Finally, the well known Kyoto protocol, worldwide ratified by many countries can be mentioned. This protocol does not contain any emission standards or limit values. However, the countries that ratified this protocol have a commitment for emissions reduction or limitation. In order to achieve this, some national policies have then been developed.

For instance, Switzerland ratified the Kyoto Protocol in 2003 and consequently decided to decrease CO_2 and other GHG emissions by 8% between 2008 and 2012, in comparison with the situation in 1990. Following this objective of emissions reduction, some other national political policies have been decided: CO_2 imposition for fossil fuel emissions, tax for most emitting vehicles (heavy vehicles)…

In UK, the Climate Change Programme published in March 2006 [15] describes measures to ensure that the UK delivers its legally binding target under the Kyoto Protocol to reduce emissions of the six greenhouse gases to 12.5% below base year levels over the first commitment period 2008-2012, and to move the UK towards its domestic goal of a 20% reduction in carbon dioxide emissions below 1990 levels by 2010. In addition, UK has an additionally long-term goal of putting itself on a path to cut CO_2 emissions by 60% by 2050, with real progress by 2020. This is further detailed in the Energy White Paper published in February 2003 [16].

Thus, Kyoto protocol cannot be considered as a basis for emissions standards, but it has to be highlighted that such decisions originated national and international policies and/or standards.

D. GHG consideration in the framework of the calculator

In this section, the major greenhouse gases have been detailed and the calculation procedure into equivalent CO2 explained. Besides, some considerations regarding current standards are provided. This could be used for assessing the calculation results and/or add additional information to the databases.

[...]
It is essential to be consistent and systematic by considering the same emissions for the whole process. However, to consider these various gases in the calculator needs to put a lot of effort in the literature research and analysis in order to get the necessary data. If some data are missing, it would be recommended to use a given factor in order to calculate the emissions of the missing gases. This is performed for some others GHG calculators. For instance, CO_2 emissions could be multiplied by 1.2 in order to have a rough idea of the equivalent CO_2.

4. Databases analysis

As mentioned in introduction, the first part of the work consisted in analyzing the calculation procedure. This has been performed [...] by following a complete calculation process. In this phase, the databases needed for each calculation step have been identified. In a second part, some considerations have been made in order to identify the major greenhouse gases, detail the calculation procedure that has to be followed and propose some emissions standards that could be considered.

Based on these elements, an analysis of following databases will be conducted:

- Electricity;

- Transport emissions;
- Utilities emissions;
- Material emissions;

The overall objective of this databases analysis is firstly to assess the coherence and then, if possible, propose some improvement possibilities or other related data / information. For every single database, a first summary of the insertion and influence in the IRF GHG calculator is conducted. Afterwards, the proposed are analysed before to suggest some modifications or provide additional information that might be useful. Note that lot of information and data related to life cycle inventory and life cycle analysis of road can be found in [2] and [3]. Some elements will be mentioned in this section. For more information it would be recommended consulting these documents.

The various elements mentioned in this section are LAVOC's consideration and advices. Their application is then up to the calculator developer. Note that machinery emissions are not considered in this section.

A. Utilities Emissions

This database concerns the sheet "Utilities - Emissions" in the Excel spreadsheet. It contains emissions related to the various fuels that are used for machines.

Role in IRF GHG calculator

The utilities emissions are used in order to provide CO_2 emissions for the following machines, in function of their individual fuel consumption:

- Pre-construction phase: clearing and pilling machines
- On site machines: transport fuel purchased during road construction process
- Machinery: paver, roller, emulsion applier and other machiner (reclaimer, compactor, wheel dozer, forestry machine …)

Database analysis

[…]

By considering the data, so called "emission factors" are needed for the various fuels. Emission factors can be defined as "the average emission rate of a given pollutant for a given source, relative to the intensity of a specific activity". For instance, they are commonly used to estimate GHG emissions based on the amount of combusted fuel. Emission factors assume a linear relation between the intensity of activity (fuel consumption) and the emissions. If carbon dioxide emissions from fuel combustion are considered, the emissions will then depend almost exclusively on the carbon content of the fuel which is generally known. Thus, the emissions can be calculated using the combustion equation of hydrocarbons. This will be detailed below.

Other available databases and information

As mentioned above utilities emissions [t_{CO2} /t_{mat}] can also be calculated through the combustion equation of alkanes $C_nH_{(2n+2)}$:

$$C_nH_{(2n+2)} + \frac{(3n+1)}{2}(O_2 + 3.76N_2) \rightarrow nCO_2 + (n+1)H_2O + \frac{(3n+1)}{2}3.76N_2$$

Carbon dioxide (CO_2) emissions from stationary combustion result from the release of the carbon in fuel during combustion. During the combustion process, most carbon is emitted as CO_2 immediately. CO_2 emission factors for fossil fuel combustion will depend upon the carbon content of the fuel that is an inherent chemical property and does not depend upon the combustion process or conditions. In the case of perfect and complete combustion, nitrogen can be neglected as there is no NO_x creation and no carbon monoxide as well. Considering the mass in the above equation, one finds that nCO_2 is obtained by combustion. Based on this, the amount of CO_2 emitted by combustion can be calculated for each fuel type. For instance, in the case of super gasoline following result is obtained:

- Super gasoline is usually a pure octane C_8H_{18}, with n=8
- According to combustion equation, the mass of CO_2, for 1 mol C_8H_{18} is 8·44=352 g
- The ratio between fuel consumption and CO_2 is: 352/114=3.09
- Finally, using the density of fuel, the emitted CO2 is calculated:
  0.755 $kgCO_2/l$ · 3.09=2.28 $kgCO_2/l$ of fuel

The same calculation can be performed for the other fuel types. Note that the results will depend on the chemical formula used for the chosen fuel. This is an important assumption that has to be discussed.

- For super gasoline C_8H_{18} can be taken as an average value. This is very close to the reality but it has to be kept in mind that super gasoline is in reality a mix of over 100 different molecules.
- Diesel is often considered as a hexadecane $C_{16}H_{34}$. However, common diesel fuel with a chemical composition from $C_{10}H_{20}$ to $C_{15}H_{28}$ could also be considered.
- LPG (liquefied petroleum gas) is usually considered as a mix of butane (C_4H_{10}) and propane (C_3H_8) and the averaged value n=3.5 can be applied.

IPCC "Good Practice" mentions that "*the energy content (i.e. calorific value or heating value) of fuels is an inherent chemical property. However, calorific values vary more widely between and within fuel types, as they are dependent upon the composition of chemical bonds in the fuel*". Thus, it is important for a calculation or database to clearly state which chemical composition is taken into account.
[...]
Based on the above combustion equation, different emission factors can be calculated (Table 3).

Fuel	**Chemical composition**	**Density Kg_{fuel}/l_{fuel}**	**Kg co_2 /l_{fuel}**	**t co_2 / t $_{fuel}$**
Diesel	$C_{16}H_{34}$	0.83	2.62	3.16
Super Gasoline	C_8H_{18}	0.755	2.33	3.09
LPG	C_4H_{10}/C_3H_8	0.509	1.54	3.02

Table 3: Calculation of emission factor through combustion equation

The results above are rather consistent with the database proposed in the IRF GHG calculator. [...]

The differences between ***Table 3*** and IRF database might be explained by the different chemical compositions taken into account. Thus, it is recommended to precisely indicate the chemical composition of the fuel used to the user of the calculator. It could also be useful to let the opportunity to the user to enter specified density or emission values. Concerning the densities, it would also be advisable to indicate the dedicated references or measuring conditions.

Some other references for emission factors can be proposed. One could mention for instance the US Environment Protection Agency that provides emission factors of fuel combustion [17]. In this document, VOC, CO, NO_x, PM_{10}, SO_x, CH_4, N_2O and CO_2 emissions are indicated for the different fuels. Note that units used are g/10^6 Btu of fuel input. Btu, British Thermal Unit, is a traditional unit of energy that can be easily converted:

10^6 Btu = 1 MMBtu = 1 million Btu = 1.054615 GJ

Thus, emissions factor scan be obtained in kg CO_2/GJ. This type of unit is very common for emission factors and can if necessary be converted in kg CO_2/kg material using the fuel energy content. CO_2 emissions can also be indicated in kg CO_2/kWh.

IVL report [3] regarding life cycle assessment of road also provides interesting information and data. In this research, it has been decided not to calculate the fuel consumption, but the emissions of every vehicle type. This can lead to more accurate emission data but on the other hand the various vehicles have to be considered separately. For instance, this report indicates emissions for:

- Diesel driven maintenance vehicles: maintenance vehicles are often equipped with diesel engines for power source. However, there are many types of vehicles with various fuel consumption and emission factors. Besides, it is hard to estimate the fuel consumption variation in function of vehicle ageing. In this study, it has been decided to consider only low-emission engines. Thus, these data could be used in IRF GHG calculator, but it would not be advisable to take it as a reference value. Indeed, IRF calculator aims at being used worldwide while IVL report concerns only the Swedish case.
- Wheel loaders: production data and energy consumption for different wheel loaders. Based on this, the emissions have been calculated.
- Excavators.
- Dumper: for this calculation the direct fuel consumption (energy) and the production of the corresponding amount of fuel have been taken into account. So, the machine production is not considered. The same assumption has been made for the other machines.
- Road rollers: for this calculation the direct fuel consumption (energy) and the production of the corresponding amount of fuel have been taken into account.
- Asphalt pavers: the calculations for asphalt pavers have been based on Dynapac's product program. As an illustration, ***Figure 1*** presents the typical emission table proposed for two different asphalt pavers.

In or outflow	Unit	Total per MJ used diesel	Total per m^2, Dynapac F12	Total per m^2, Dynapac F16
Diesel oil	MJ	1.1	7.72E-01	6.53E-01
CO_2	g	79	5.55E+01	4.69E+01
SO_2	g	0.038	2.67E-02	2.26E-02
NO_x	g	0.71	5.01E-01	4.24E-01
Dust	g	0.028	2.00E-02	1.69E-02
CO	g	0.085	5.98E-02	5.06E-02
N_2O	g	0.0016	1.12E-03	9.50E-04
HC	g	0.051	3.61E-02	3.05E-02
CH_4	g	0.00005	3.51E-05	2.97E-05
Oil (aq)	g	0.0004	2.81E-04	2.38E-04
Phenol(aq)	g	0.00057	4.00E-04	3.39E-04
COD	g	0.0012	8.42E-04	7.13E-04
Tot-N(aq)	g	0.00019	1.33E-04	1.13E-04

Figure 1: Emissions for two different asphalt pavers (3)

Basically, the methodology followed by the Swedish Environmental Research Institute is rather comparable to IRF methodology. However, it is important to notice that in IVL report energy units (MJ) are commonly used and then emissions deduced from this. This is slightly different from IRF calculator that considers the fuel consumption, but not the energy. Besides, the emissions considered in IVL report are rather broad as not only $C0_2$, CH_4 and N_20 are considered, but also SO_2, NO_x, CO, HC, dust … All these emissions are taken into account for the different vehicles. Then, for the calculation, the emissions are considered separately without equivalent CO_2 calculations.

B. Transport Emissions

This database concerns the sheet "Transport_Emissions" in the Excel spreadsheet. It contains emissions related to the type of vehicles considered.

Role in IRF GHG calculator
The emissions indicated in this database are used to evaluate the material transport emissions for:

- Pre-construction: Transportation of material for export off site and import to site
- Material transport: Emission assessment for the transport of construction material

Database analysis
This database is used for the transportation of material using road vehicles, rails or waterways. As mentioned, it provides emissions in function of the kilometres and vehicle type used. This is different than for other vehicles database for which a calculation of the fuel consumption has been performed before to calculate the emissions using emission factors. In order to be consistent the same methodology should be used for the whole calculator and the different databases.

Following comments can be made regarding the material transport database:

[...]

- The obtained values for vehicles could be compared to standards in order to assess the pollution level of the vehicles used.

[…]

- It might be useful to make a distinction between full and empty vehicles. In the calculator, this can be done by varying the load in the input data.

[...]

Other available databases and information

Some other information can be found in IVL report [3]. For transportation by truck, two different types of lorries have been considered in two different driving conditions: distribution trucks outside of urban areas (14 tones loading) and long distance truck with a 32 tones loading. It is assumed that this permits to represent the transport during a road construction and maintenance phase. As mentioned, only the fuel consumption and related energy are considered.

Truck production is not included. Assuming that a truck is fully loaded and empty on return, following emissions are proposed by IVL:

Emissions	**Total flow, distribution truck (14 t.) [g/vhc km]**	**Total flow, long-distance truck (32 t.) [g/vhc km]**
CO_2	943	1050
NO_x	6.02	8.06
CO	0.956	1.34

Table 4: Emissions for distribution truck and long distance truck [2]

Comparing these emissions to the emissions proposed in IRF GHG calculator, rather important deviation can be observed. Indeed, according to the calculator, a 14 tones road truck produce 3094 g. CO_2 that is much more than 943 g. proposed by IVL. For a 32 tones truck, IRF GHG calculator proposes 6272 g. CO_2 emissions that is about 6 times more than the values proposed by IVL report. This difference might be explained by the calculations hypothesis. However, this would need to be further investigated. In the mentioned IVL report, sea freight shipment is also considered. The data have been calculated based on emission and fuel data from Lloyd's register of shipping (0.13 MJ/tone assumed). The CO_2 emissions for cargo shipping proposed are 10 g/t km. As for road truck transport, IRF GHG calculator proposes to use higher emission values with 38 g/ t km.

In order to make another comparison and assess the proposed database, data from the research and consulting group INFRAS (http://www.infras.ch) have been also compared. This society took part to the establishment of the "Handbuch für Emissionsfaktoren (HBEFA)". This report is the result of a common research between the Federal Office for the Environment of Switzerland (BUWAL), Germany (UBA) and Austria (UBA). These offices worked together since many years in order to have a complete database emission for vehicles. This database is also regularly updated with a first version (1.1) in 1995 and different revision since that time. Version 2.1 is currently available online [18]. In this database, the following emission factors are proposed for the year 2005 in Switzerland:

HDV Heavy Duty Vehicles

LDV Light Duty Vehicles, light commercial vehicles

Country	Year	Vehicle category	Pollutant	Emission factor	Unit
Switzerland	2005	HDV	CO	1,543	[g/VehKm]
Switzerland	2005	HDV	CO2	753,895	[g/VehKm]
Switzerland	2005	HDV	HC	0,431	[g/VehKm]
Switzerland	2005	HDV	NOx	7,686	[g/VehKm]
Switzerland	2005	HDV	PM	0,194	[g/VehKm]
Switzerland	2005	LDV	CO	4,014	[g/VehKm]
Switzerland	2005	LDV	CO2	271,798	[g/VehKm]
Switzerland	2005	LDV	HC	0,275	[g/VehKm]
Switzerland	2005	LDV	NOx	1,113	[g/VehKm]
Switzerland	2005	LDV	PM	0,071	[g/VehKm]
Switzerland	2005	pass. car	CO	2,872	[g/VehKm]
Switzerland	2005	pass. car	CO2	209,36	[g/VehKm]
Switzerland	2005	pass. car	HC	0,214	[g/VehKm]
Switzerland	2005	pass. car	NOx	0,324	[g/VehKm]
Switzerland	2005	pass. car	PM	0,007	[g/VehKm]

Table 5: Emissions factors for different vehicles according to HBEFA [18]

As mentioned, this database also permits to vary the reference year and the country considered (Switzerland, Austria or Germany). Besides this database also permits to obtain fuel emission factors that might be useful comparison elements. For CO_2 emissions, the order of magnitude is around 680-750 g/vhc·km for HDV and 245-270 g/vhc·km for the emissions in 2005, in the considered countries. Considering the various hypothesis and different conditions between these countries and the Swedish case, the order of magnitude can be considered rather comparable between IVL report and HBEFA. However, these data are much lower than the proposed emission factors considered in the IRF GHG calculator. Thus, it is highly recommended reconsidering the proposed emissions for road truck. Besides, some consideration should be made regarding the different countries and related emissions factors. Indeed the emissions might be different from one continent to another for instance.

C. Electricity

This database concerns the sheet "Electricity" in the Excel spreadsheet. It indicates the emission inventory for the electricity production in different countries.

Role in IRF GHG calculator
The database is used in order to get the emissions for the electricity usage on the construction site. In this section a difference is made between the countries, this because the emissions related to electricity can be different.

Database analysis
Following comment can be made regarding the proposed database:

[...]

- A calculation using GWP is performed in order to provide equivalent CO_2 for the different countries. For this calculation, GWP potential from the SAR is used. This is consistent with the period considered 1999 – 2002. Besides, IPCC mention that "*GWPs of certain greenhouse gases have been updated in the IPCC Third Assessment Report (IPCC, 2001). However, it has been agreed internationally that these will not apply to the Kyoto targets under the first commitment period. All calculations and inventory submissions throughout this period will be based on the GWPs given in the Second Assessment Report (IPCC, 1996).*"

[...]

- The use of "metric tons" is correct and necessary
- It would be recommended to detail or indicate the production procedure for the energy that is considered in order to provide the emissions related to each country.

[...]

Concerning the reference, IEA is a reliable database that is to recommend. [...] The database and IEA database should be regularly checked in order to use updated emission factors.

Other available databases and information

As mentioned, the database proposed is reliable and detailed. More information can also be found in the IVL reports that provide emission factors for electricity production. It is however important to keep in mind that this concerns Sweden where electricity is primarily produced using hydropower and nuclear power. Note that emission factors proposed by IVL are in grams per mega joules. This report uses energy units for the whole process instead of KWh.

D. Materials emissions

This database concerns the sheet "Materials_Emissions" in the Excel spreadsheet. The database concerns the emissions related to various materials used in the construction process.

Role in IRF GHG calculator

This database is used in order to calculate the emissions related to the different materials used for the road construction in “Construction1” sheet. The various results are then reported in the “Results materials” sheet.

Database analysis

[...]

Various references have been used in order to create this database. These are well referenced and reliable documents.

Reference [IRF-1] concerns the Colas spreadsheet document that is not available for public use. Thus, no specific analysis of this reference can be performed.

Reference [IRF-2] that is an inventory of Carbon & Energy (ICE) from Bath University is widely used for the creation of the database. This document is the summary of a larger database created using data collected from various sources (journal articles, LCA, books, conference papers…). It is recommended checking for updates of this ICE and considering the mentioned limitations in data accuracy.

Reference [IRF-3] concerns “The CO_2 emissions estimator tool for the use of aggregates in construction” written by Centre for Sustainability (C4S) at TRL Limited. It would be recommended to pay special attention to this GHG calculator (Excel spreadsheet) as it contains interesting information regarding the methodology and data. This reference could also be used in order to check the data for other values proposed in the IRF GHG calculator.

[...]

Finally, it would be recommended to explain, at least in the user guide, the signification of the database used at this step of the calculation procedure. Indeed, this database indicates the embodied carbon of various construction material used in road domain. One can consider that the embodied carbon of a given material can be taken as the total carbon released over its life cycle. Ideally, the boundaries would be set from the extraction of the raw material until the end of the products lifetime. This has to be clearly stated and the title of the database could also be slightly modified in order to be clearer.

Other available databases and information

As already mentioned, some other databases can be found, for instance in the IVL reports which proposes values for cement production, crushed aggregated production... For cement, IVL uses a value of 0.8 kg·CO_2/kg·material that is slightly different than the value proposed in IRF GHG calculator (0.97 kg·CO_2/kg·material). Note that this database also proposes some emissions standards for other greenhouse gases.

The International Energy Agency (IEA) also provides emissions factors. For instance, it is mentioned for cement that “The average CO_2 intensity ranges from 0.65 to 0.92 tone of CO_2 per ton of cement across countries with a weighted average 0.83 t CO_2/t”. Considering the emissions related to the production of asphalt mixture, EAPA [5] provides some information. The CO_2 emissions are, among others, directly related to the energy consumption needed for the heating process of the aggregates and bitumen and the process efficiency. Thus, a distinction is made between different types of asphalt plants (light oil, natural gas, butane, brown coal). Figure 3 indicates the CO_2 emissions in function of asphalt plant power and fuel.

Specific heat requirement per metric ton of asphalt mixed (depending on humidity of mineral material, etc.)	Light Oil	Natural Gas	Butane	Coal	Brown Coal
	kg of CO_2 / metric ton of mixed asphalt				
70 kWh	18,65	11,63	15,27	23,05	23,61
85 kWh	22,65	14,13	18,54	27,99	28,67
100 kWh	26,64	16,62	21,81	32,93	33,73

Figure 2 : Gaseous emissions for the production of asphalt in function of fuel and heat requirement [5]

This highlights the effect of the asphalt plant type and efficiency on the total emissions. The data indicated above are rather consistent with the data used in IRF GHG calculator considering the fact that the calculator does not indicate the type of asphalt plant taken into account. For the production of hot mix asphalt, IVL reports propose a value of 0.0344 kg·CO_2/kg·asphalt that is comparable but slightly higher than EAPA and IRF databases. The difference between the different databases could be explained by the various assumptions concerning fuel type, burner efficiency, asphalt mixture temperature, bitumen content...

According to the references used in IRF GHG calculator and the other values obtained, it seems that the database proposed is rather consistent. However, it has to be highlighted that these values need to be regularly checked and/or updated. The boundaries of the method and the precision in the values and its influence must also be considered for instance through a sensitivity analysis. Finally, in the framework of a GHG calculator, it could be recommended to use the Ecoinvent database from the Swiss Centre for Life Cycle Inventories. This database of life cycle inventory data is provided by the Ecoinvent center. It contains among other international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, waste management services and transport services.

5. Conclusions and recommendations

In this study, a detailed analysis of the IRF greenhouse gases calculator has been carried out, with a special emphasis on databases. In order to achieve this, a preliminary analysis of the architecture has been conducted and the calculation procedure roughly analysed. Based on this initial analysis, a detailed study of the major greenhouse gases has been conducted and some preliminary recommendations drawn. Finally, a detailed analysis of the databases has been carried out in order to assess the quality and reliability of the various data proposed.

From a general point of view, the calculator is well established and the procedure very complete. In general, the analysed databases are consistent and contain comparable information than the other data used for the validation. However, some modifications and adjustments are proposed. [...] Thus, reference [IRF-17] should not be used and the "transport emissions" database modified with other references data suggested. It is also important that all the data entered by the user are used in order to perform the calculation. This permits to avoid misunderstandings and save time.

It is also important to clearly state to the potential user that this tool is not a complete Life Cycle Assessment and what are the limits. Indeed, the emissions considered are limited and some other important emissions to air, water or land are not taken in account. Thus, it is important to define, at the beginning of the analysis, the boundaries and limitations of the sustainability study that is proposed.

During the whole procedure, it is also important to keep in mind that the tool provides an estimation of the total emissions. It is illusory to have a too high accuracy in the various calculations and numbers. [...]

According to the study performed and the above comments, one could make following recommendations in order to improve the quality of the calculator:

- The calculator aims mainly at comparing different variants. At this step of the procedure, the user might not have all the needed information available. Thus, it could be useful to propose some default value that would be used for a preliminary calculation. These default values could be provided by the last calculation performed that could be downloaded. In addition, maximal and minimal values should be proposed to the user and a warning system applied in order to indicate if "non-realistic" values are entered.

- Before an extensive use of the calculator, it would be advisable to make some comparative study with other existing greenhouse gas calculator. This permits to assess and make a final validation of the calculator. Besides, the order of magnitude can be verified.

[...]

6. References

A. IRF references

Here are the references of the IRF-GHG calculator spreadsheet as indicated in the calculator.

(IRF-1) Colas Spreadsheet Document

(IRF-2) Hammond G and Jones C (2006) Inventory of Carbon and Energy (ICE) Version 1.5 Beta, Department of Mechanical Engineering, University of Bath (people.bath.ac.uk/cj219); Hammond & Jones (2008). Inventory of carbon and energy (ICE), University of Bath, http://www.bath.ac.uk/mech-eng/sert/embodied/

(IRF-3) AggRegain CO2 Estimator Tool (2006) Centre for Sustainability at TRL Limited, Taylor Woodrow Technology & Costain Limited - for WRAP (www.wrap.org.uk/document.rm?id=2910)

(IRF-4) Jacobs UK reasoned assumption based on similar materials

(IRF-5) Mortimer ND, Cormack P, Elsayed MD, & Horne RE (2003) Evaluation of the comparative energy, global warming, and socio-economic costs and benefits of biodiesel. Report by the Resources Research Unit, School of Environment and Development, Sheffield Hallam University, for DEFRA (www.defra.gov.uk/farm/crops/industrial/research/reports/nf0422.pdf)

(IRF-6) DTI Construction Industry Directorate, Project Report : Environmental Procurement of Aggregates, Project report number 206611, Prepared by BRE, 31 July 2002--- As Cited by co2_estimator.xls

[…]

(IRF-17) Module GES Transports - Calcul des émissions, EPE/ADEME, Octobre 2005 (http://www.rac-f.org/article.php3?id_article=443)

B. LAVOC references

Here are suggested additional references:

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[14.] Assemblée fédérale de la Confédération suisse (2007). Ordonnance sur la taxe sur le CO_2, Berne.

[15.] Department for Environment Food and Rural Affairs (2006). UK Climate change programme 2006

[16.] Department for Environment Food and Rural Affairs and Department for Transport (2003). Energy white paper.

[17.] U.S. Environmental Protection Agency (2007). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005, EPA 430-R-07-002, Annex 3.2, (April 2007), web site: http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

[18.] INFRAS (2004). Handbuch Emissionsfaktoren des Strassenverkehrs HBEFA, Bern.