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CO_2 emissions calculation models for green supply chain management

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Green logistics is a new concept launched by several logistics companies. It means reducing carbon emissions caused by transport. A particular attention is to be paid to trucks, which play an important role in transport logistics. The quantification of CO_2 emissions linked to transport is a complex exercise due to the high number of parameters that influence these emissions. Still, at the moment, existing measurement and calculation methods do not take account of all these parameters.

The aim of this paper is to give an overview of the current measurement and calculation models that compute CO_2 emissions due to truck transportation. In this respect, journal articles and reports mainly published the last decade are reviewed and analyzed. This work aims at being able to calculate for a given route and a given heavy duty vehicle the overall amount of CO_2 of a given shipment.

Keywords: CO_2 emissions models, green SCM.

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1) Introduction

Freight transport has been worldwide a key factor in economic prosperity and it is likely that it will continue growing to meet the growing transport needs. However, in most countries, the transport sector is a significant contributor to energy consumption and GHG emissions, representing 23% of CO_2 worldwide emissions from fossil fuel combustion in 2005. The sector as a whole is also exceedingly vulnerable to oil production: since it is 98% dependent on this energy. Therefore our countries will have to envisage a significant behavioral change in transport sector and especially in freight transport to account for shortage in oil and for climate change (Zumkeller et al. 2008).

It is in this context that the concept of green logistics has been launched by several logistics companies (Abukhader et al. 2004). It means reducing carbon emissions caused by transport. A particular attention is to be paid to trucks which play an important role in transport logistics, even when it is well known that other transport modes are less polluting (EEA 2007).

This paper attempts to give an overview of the state of the art of research with respect to the CO_2 emissions calculation models and especially the emissions from road freight. Articles and reports mainly published the last decade in reputable journals are reviewed and analyzed. Based on this analysis, suggestions for future research are provided.

The paper is organized as follows. We first present the motivation for the study and describe the article selection and literature search procedure. We provide background on the concepts of CO_2 emissions modeling regarding the various studies proposed in the literature. In the next section, we present our main findings from the review. In particular, we show that even if many CO_2 emissions models are available in general, there still remains a weakness in the precise computation of the overall amount of CO_2 emissions of a given shipment. The final section concludes the paper and provides some directions for future research.

2) Background and motivation of the study

2.1) Context

In 2005, 73% of the EU-27 freight inland transport (in tonne.km) was done by road (Eurostat 2007). Between 1995 and 2005, goods transport in the EU grew by 31.3% and this growth is predicted to continue. CO_2 emissions from the road sector are 30% higher than in 1990 and transport is the only sector of the economy where emissions are predicted to increase in the future (WEO, 2008).

Rising transport demand is likely to be the biggest hurdle to overcome in order to reduce our greenhouse gas emissions. Transport is consuming an ever increasing proportion of our total energy use. Furthermore, the bulk of energy comes from burning petroleum products.

In January 2005 the European-wide CO_2 greenhouse gas (GHG) emissions trading system (EU ETS) has formally entered into operation. Under the Kyoto protocol the EU has committed to reduce GHG emissions by 8% as compared to the 1990 level by the years 2008-2012. The system regulates an annual allocation of the allowances and the right to emit a particular amount of CO_2 becomes a tradable commodity. 2008 corresponds to the Second commitment period which implies that it is the turn of the trucking companies, as well as the industry sector to pay credits for their CO_2 over-emissions. In this respect these companies have to define their strategy in order to reduce their overall emissions.

It is in this context that the concept of green logistics has been launched. Moreover, interest in the efficiency of logistical operations has increased during the 1990's (Samuelsson et al. 1997) and in particular in one subset of the supply chain efficiency, namely transport efficiency, (Ang-Olson et al. 2002), (Simons et al. 2004), (Lattemann et al. 2004), (McKinnon 2004), (McKinnon et al. 2005), (Baumgartner et al. 2008). To increase fuel efficiency of road transportation, the idea is to enhance transport performance for the same amount of energy consumed, see (Léonardi et al. 2004), (Ericsson et al. 2006) and (Lee et al. 2008).

The question that has to be addressed is how a haulage company can define herself as green ? At least the footprint of their activities on the environment has to be measured before being managed. Our study focuses on the calculation of the overall amount of CO_2 emitted by heavy duty vehicles. We first aimed at knowing the different emissions models currently available in order to calculate these CO_2 emissions.

2.2) Article selection and literature search procedure

The research method adopted in this study is a content analysis approach. It consists in a systematic, qualitative and quantitative description of the manifest content of literature. As mentioned by (Seuring et al. 2005), the procedure for conducting content analysis is centered on two major steps that are the definition of sources and procedures for the search of articles to be analyzed, and the definition of categories instrumental to the classification of the collected articles. Both issues are simultaneously addressed in the present review and described in detail in what follows.

The research started with the searching for articles relevant to the purpose of this study. We considered articles mainly published the last decade in academic journals. The search for related publications was mainly conducted as a structured keyword search. Major databases were used, such as those provided by major publishers, Elsevier (www.sciencedirect.com), Springer (www.springerlink.com), Wiley (www.wiley.com), or library services (e.g. Scopus www.scopus.com or Ebsco www.ebsco.com) .

We did not take account of the social dimension induced by sustainability (Seuring et al. 2008), and focused on green logistics that is why we used “road transportation”; “road freight”, “environment”, “CO_2 emissions models”, “emissions from transport” “CO_2 emissions from road transportation” and “green supply chain” as the main key words in the literature search procedure. Abstracts and when necessary full texts were considered to confirm the relevance of the papers.

Due to the relatively small number of found articles, we also performed a direct search in journals (web sites) in the areas of logistics, environment and transportation.

Journals were selected according to their contribution to the environmental footprint of the road freight. As a result of this search, additional articles were identified. Reading the collected papers, cited references were used as a secondary source but did not yield many additional papers which can be taken as an indication of the validity of the search.

At the first step of the search, we noticed that many more results were provided when professional/specialized websites were included to the research procedure. These non-(peer)- reviewed references were also considered. In fact they provide details on the methodologies used in the emissions calculation which are really usefull.

All the analyzed report and articles appear in the reference list of this paper. Although this search may not be exhaustive, it is believed that the journals selected and the references reviewed comprise a reasonably representative and comprehensive body of the research work being accomplished in the field of CO_2 emissions calculation.

3) Emission models

3.1) History

The first European initiative for developing emission inventory methods[†], beyond local initiative was the CORINAIR working group on emission factors for calculating emissions from road traffic, see (CITEPA). This working group began in 1987 with the aim of developing a methodology, including appropriate emission factors, for the estimation of vehicle emissions in the reference year 1985. The methodology was transformed into a computer program COPERT which was used by many European Union countries. In 1991, the same group of experts proposed an enhanced methodology which was translated into the

[†] Emission inventories are quantities of pollutants measured over time. Emission inventories can be compared with air pollutant levels in an area to determine if increased emissions decreases the air quality.

computer program COPERT90. A new version of the model was developed in 1997 which used result of the research program COST 319, see (Joumard et al. 1999). In 1989 Germany, joined later by Switzerland and Austria, initiated a project to provide a new and comprehensive data base of emission factors. For heavy duty vehicles, new measurements and an improved version of the emissions calculation model were achieved within the research program COST 346 (Strum et al. 2005) (INFRAS 2007).

The first model for highway vehicle emission factors developed in the USA by the "Environment Protection Agency" named MOBILE was developed in 1978. The MOBILE6.2 is EPA's most up-to-date MOBILE model for predicting gram per mile emissions CO_2 from trucks under various conditions (EPA 2004).

3.1) Emission Factors Assessment

An emission factor is the estimated average emission rate of a certain pollutant for a specific activity. For example an emission factor can be the amount of CO_2 emitted by the combustion of one liter of fuel. What we focus on in this section is the amount of CO_2 emitted for different classes of vehicles. Pollutants emitted from vehicles vary depending on vehicle characteristics; operating conditions; inspection and maintenance levels; fuel characteristics; devices (Roujol et al. 2009) and ambient conditions such as temperature, humidity, altitude (Froberg et al. 2006), and wind speed and direction. Emission factors are strongly influenced by vehicle driving patterns (André et al. 2009), average speed, and the degree of acceleration (Larsson et al. 2009) and deceleration in the driving cycle (INFRAS 2007)(Vermeulen 2006) (Ericsson 2001), (Smit et al. 2008).

The CO_2 emission models are developed to assess these emission factors.

3.2) Overview of the CO_2 emissions models

3.2.1) Average speed models

These are the most commonly used models and account for vehicle dynamics using the concept of average speed (. The total emissions are calculated as a product of activity data provided by the user and speed-dependent emission factors calculated by the software. They work on the basis of specific emission/consumption factors for vehicle/engine technologies for particular traffic conditions. They usually form the basis of local air quality calculations, and work characteristically on the scale of a town. For instance, the software application of COPERT 4 methodology (Gkatzoflias et al. 2007) has been developed for the compilation of national inventories on a yearly basis. However, it has been shown that the methodology can also be used with a sufficient degree of certainty at a higher resolution too, i.e. for the compilation of urban emission inventories with a spatial resolution of 1x1 km^2 and a temporal resolution of 1 hour. Another example is the EMFAC which is the latest version of the California mobile source emissions model. It is an officially approved regulatory model, which calculates emission inventories for motor vehicles operating on roads in California by combining vehicle emission rates with local specific activity data (EMFAC2007). The basic application is to generate emission factors for on-road motor vehicles at a county or at a state level. EMFAC is also capable of estimating regional emissions.

3.2.2) Micro-scale models

This kind of models uses detailed speed profiles (second by second) of a vehicle to calculate fuel consumption and emissions for the individual vehicles at specific trips (Frey et al. 2007). One of this emission model is the PHEM (Passenger car and Heavy duty Emission Model) developed at Graz University (Hausberger et al. 2003).

These models take into account vehicle kinematics through detailed parameters such as speed and acceleration. They allow calculations on a local scale (down to traffic intersections) (Smit et al. 2008) (Silva et al. 2006), but can also be integrated for regional or national inventories.

They allow vehicle characteristics to be altered individually and thereby to expected future trends.

The different form of applications of an emission model are :

Emission forecasts: These are applications where fine spatial and temporal resolution is not required, and trends are generally more important than absolute emission levels. Thus, speed-dependent emission factors can adequately simulate reality. In order to come up with reliable emission factors, for each driving mode (e.g. urban driving) the corresponding average speed should be derived using appropriate measurements and assumptions.

Air quality models : Applications for a urban region, which are comparatively detailed, require emission inventories with a spatial resolution of 500x500m or 1x1m (Wang et al. 2009). On such a scale, emissions in individual streets are not of great interest since emissions are averaged over a number of similar streets. Hence, speed-dependent emission factors seem to be sufficient. What is of particular importance in such simulations is an accurate knowledge of the distance travelled with cold engines in each part of the simulated area and for each hour of the day, as well as the impact of these cold starts on emissions. Attention should therefore focus on these issues in addition to effect of the altitude of the region and the gradient of streets in specific parts of the area.

Small-scale applications : the calculation of emissions on the level of a single street is associated with a high degree of uncertainty . The representativity of all input data (driving profile, emissions, etc) is crucial, and the outcome for some individual streets may be considerably different from the average simulated emissions in streets of the same type. In such cases, in addition to the average speed, the vehicle kinematics on that street may have a significant influence, and simple speed-dependent emission factors may therefore be inadequate. Where driving behavior and dynamics are of major interest (e.g. the impacts of changes in the driving behavior have to be assessed) disaggregated approaches are recommended. However, instantaneous models do not predict consistent trends. Furthermore, what should be noted is that models based on modal emission measurements indicate that speed fluctuation is indeed relevant, but average speed itself is still an important influencing factor (Smit et al. 2008). Moreover the dispersion of emission results should not be overlooked since if applied to a particular case, there is a wide variation of different driving profiles – even in the same street, creating a wide dispersion of emission results.

All the previous emission models provide emission factors that can be used with the emission calculation tools.

4) Emissions calculation tools

At the moment, several existing tools permit to compute the effective overall CO_2 emissions of a truck. These tools have been mainly developed in the more general framework of Life Cycle Assessment Inventories. One can cite for instance, the "ecoinvent data version 2.0" which contains international industrial life cycle inventory data on transport services and is included in the leading Life Cycle Assessment software tools developed by the Ecoinvent Centre (a Swiss Centre for Life Cycle Inventories), see (Althaus et al. 2007). Another tool named GEMIS (Global Emission Model for Integrated Systems version 4.5) has been developed by the Öko-Institut (Institut for applied ecology) in Germany, see (Fritsche et al. 2007).

Another tool named the "GHG Transport Module-Calculation of emissions" spreadsheet program is used to calculate the greenhouse gas emissions corresponding to the transportation of goods linked to an activity of an entity. It represents the application of the quantification method developed jointly by the ADEME and EpE (Entreprises Pour l'Environnement which is an association of french companies which have committed themselves to voluntarily reduce their GHG emissions), described in the document “Protocol for the quantification, reporting and verification of the GHG emissions resulting from the activities of an entity” (EPE 2007).

In a same way as the other tools, it consists in several worksheets associated with a transport mode. It is named ‘Module GES Transports-Calcul des emissions’ and is completed with a user’s manual.

Each emissions calculation sheet contains several tables for entering data and calculations. The calculations are made using the emission factors linked to the consumption of the different energies used in transport, which can be either the fuel emission factors from France, Europe or the CO_2 content of the electrical kWh consumed. One can distinguish two types of methods for the calculations : the direct method and the indirect methods.

For a better accuracy, it is recommended to use in priority, when possible, the GHG emissions calculation method based on fuel consumption, since the characteristics of the vehicles, the conditions for their use and the way they are driven (Ericsson et al. 2006),(Af Wälberg 2002), (Van der Vort et al. 2001) are different and influence the fuel consumptions.

4.1) Direct methods

If the actual energy consumptions are known (consumption of petrol, diesel, etc.), the direct method must be used. It is particularly suitable for a “transport professional” type entity, which owns all or some of the vehicles used for the service. For each fuel used, the annual consumption must be entered in the corresponding line of a table named “Road freight : calculation based on the fuel purchases”. Then the emission factor corresponding to the fuel used permits to calculate the overall amount of CO_2 emitted.

4.2) Indirect methods

For cases in which fuel consumption is not known, three other methods for quantifying GHG emission are proposed, according to the information accessible to the entity. The data which have to be available are :

- either the average fuel consumption for each vehicle and the corresponding vehicles.km, which are the overall kilometers driven by a certain type of vehicle.
- or the vehicles.km for each lorry category.
- or the tons.km for each lorry category.

In the latter two cases, default average data (based on national statistics in France) are used as parameters to calculate the results. They concern the conditions for using the vehicle : loading percentage (in weight), and journeys when empty. The average data can be replaced by more accurate data as long as the validity of the customized data can be demonstrated. The following table corresponds to the vehicle.km method :

24 – Road freight: calculation based on vehicles.km and authorised gross weight (AGW)	kg CO2-e per vehicle.km when empty	kg CO2-e per vehicle.km when full	% of journey made while empty	average tonnage per vehicle when loaded	average payload (tons)	vehicles.km: methods owned, controlled or operated	vehicles.km: transportation of materials or products purchased or incoming	vehicles.km: transportation of materials or products sold or outgoing	vehicles.km: internal transportation (on site or between sites)	vehicles.km: externalised activity for transportation of goods	$kg\ CO_2$-e per vehicle.km
AGW 1.5 to 2.5 t (diesel)											0.224
AGW 2.6 to 3.4 t (diesel)											0.287
AGW 3.5 tons											0.330
AGW 6.1 to 10.9 tons	0.518	0.746	19%	1.65	4.69						0.583
AGW 11 to 19 tons	0.674	0.971	18%	4.24	9.10						0.788
AGW 19.1 to 21 tons	0.776	1.117	15%	4.93	10.64						0.910
AGW 21 to 32.6 tons	0.982	1.414	30%	8.27	15.91						1.139
Road tractors	0.824	1.196	21%	14.31	25.00						0.998
Total											

Calculation of the amount of CO_2 with the vehicle.km method

The emission factor per vehicle.km (E_v) relies on the following equation :

$$E_v = E_{fab} + E_{vv} + (E_{vpc} - E_{vv}) * (1 - T_{dv}) * T_{rm}$$

where E_{fab}, E_{vv} and E_{vpc} stand respectively for the emissions linked to the manufacturing of the truck, the emissions when the truck is empty and the emissions when the truck is full. T_{dv} is the rate of distance made when empty and T_{rm} is the average tonnage per vehicle when loaded divided by the average payload , see (ADEME 2007) for more details.

Nevertheless, these indirect methods show weaknesses since they rely on statistical data. For example, let us consider a truck and trailer combination with a gross vehicle mass of 40 tons, a vehicle model typically used in long-distance transport. If we have a journey from Hambourg to Barcelona which represents a distance of 1806 km, and a shipped weight of one tonne, we obtain a shipment characteristic of 1806 ton.km. The three methods give then the three following results 1669 kg, 1784 kg or 53kg CO_2equivalent which shows huge discrepancies. These differences are less spectacular and can be lightened when considering shipments corresponding to the national average data. Still, the uncertainties tied to the calculation methods are not negligible because many parameters are to be taken into account and the uncertainties linked to these parameters are added during the CO_2 emissions calculation.

5) Conclusions and perspectives

We have attempted in this work to give an overview of the current measurement and calculation models that compute CO_2 emissions due to truck transportation.

Any model is based on assumptions and simplifications and therefore is debatable and uncertain. Nevertheless many models are used in practice since emissions cannot always be measured in reality.

Still, the quantification of greenhouse gases emissions linked to transport is a complex exercise due to the high number of parameters that influence these emissions (Facanha et al. 2006). At the moment, existing measurement and calculation methods do not allow a calculation to be made that takes account of all these parameters. Moreover, the main parameters influencing carbon emissions due to truck transportation are difficult to enter into pure analytical models. A lot of parameters are dependent and absolute quantifications are not always obvious. This means that the emission model is a complex composite of different components arising from different modelling methodologies. In fact there are many variables like weather, human behaviour, traffic density, road sinuousness and so on that could be best introduced into a model through rules rather than equations. That is exactly what fuzzy logic enables one to do. There is no model in the Life Cycle Assessment Inventory literature that is based on fuzzy logic. So a perspective of this work is to create a robust model based on this logic to always choose a transportation mode minimizing CO_2 emissions for a given logistics route. It could also help designing and optimizing future distribution networks.

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