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A Review of Recent Research on Green Road Freight Transportation

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Abstract

Road freight transportation is a major contributor to carbon dioxide equivalent emissions. Reducing these emissions in transportation route planning requires an understanding of vehicle emission models and their inclusion into the existing optimization methods. This paper provides a review of recent research on green road freight transportation.

Keywords: road freight transportation, green logistics, CO_2e emissions, operations research

1. Introduction

Road freight transportation system is essential for the economic development, but it is also harmful to the environment and to human health. Until recently, the planning of freight transportation activities has mainly focused on cost minimization (see, e.g., Crainic, 2000; Forkenbrock, 1999, 2001). With an increasing worldwide concern for the environment, logistics providers and freight

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carriers have started paying more attention to the negative externalities of their operations. These include pollution, accidents, noise, resource consumption, land use deterioration, and climate change risk (Schreyer et al., 2004).

At the local and regional levels, a significant portion of freight transportation is carried out by trucks, which emit a large amount of pollutants. While transportation technologies and fuels have improved over the years, most trucks run on diesel engines, which are major sources of emissions of nitrogen oxides (N_2O), particulate matter (PM) and carbon dioxide (CO_2). Repeated exposure to N_2O-based smog and PM has been linked to a wide range of health problems. At the global level, greenhouse gases (GHGs) significantly contribute to global warming. In the transportation sector, GHG emissions are dominated by CO_2 emissions from burning fossil fuels. These cause atmospheric changes and climate disruptions which are harmful to the natural and built environments and pose health risks. Until recently, GHGs were not classified as a pollutant in the classical sense. However, the United States Environmental Protection Agency (EPA) has recognized in 2009 that GHGs pose a danger to human health and welfare. GHGs absorb and emit radiations within the thermal infra-red range in the atmosphere and significantly raise the Earth's temperature. As of July 2013, the level of GHGs is estimated to be equal to 398.6 ppvm, and is still increasing (ESRL, 2013).

The carbon dioxide equivalent (CO_2e) measures how much global warming a given type and amount of GHG may cause, using the functionally equivalent amount or concentration of CO_2 as the reference. The selection of GHGs to include in the carbon footprint is an important issue. Wright et al. (2011) suggest that a significant proportion of emissions can be captured through the measurement of CO_2 and CH_4, which are the most prominent anthropogenic GHGs. The emissions of CO_2 are directly proportional to the amount of fuel consumed by a vehicle, which is in turn dependent on a variety of vehicle, environment and traffic-related parameters, such as vehicle speed, load and acceleration (Demir et al., 2011). On the other hand, CH_4 emissions are a function of many complex aspects of combustion dynamics and of the type of emission control systems used.

Freight transportation planning has many facets, particularly when viewed from the multiple levels of decision making. Arguably the most famous problem at this level is the well-known Vehicle Routing Problem (VRP), which consists of determining least cost routes for a fleet of vehicles to satisfy the demands of a set of customers, subject to side constraints. The traditional objective in the standard VRP is to minimize the total distance traveled by all vehicles, but this objective can be enriched through the inclusion of terms related to fuel consumption (Bektaş and Laporte, 2011; Demir et al., 2012).

Recent developments in green road freight transportation have heightened the importance of operations research techniques in this area (see, e.g., Dekker et al., 2012; Touati and Jost, 2012; Salimifard et al., 2012; Dobers et al., 2013; Lin et al., 2013). In the last decade, the body of knowledge on the reduction of CO_2e emissions from road transportation has grown notably. As of August 2013, we are aware of at least 59 papers on this topic.

In this study we focus on the green logistics literature related to total energy consumption.

The scientific contribution of this study is three-fold: *i*) to analyze the factors affecting fuel consumption, *ii*) to extensively survey the available vehicle emission models, *iii*) to review the scientific literature on green logistics. The remainder of this paper is organized as follows. Section 2 reviews the factors affecting fuel consumption. Section 3 lists the available tools to estimate CO_2e. In Section 4, we investigate routing problems with regard to fuel consumption. Section 5 presents an extensive body of literature of CO_2e emissions in routing and scheduling. Conclusions are stated in Section 6.

2. Factors affecting fuel consumption

The factors influencing fuel consumption have been studied by Ardekani et al. (1996); Bigazzi and Bertini (2009); Demir et al. (2011) and Alwakiel (2011). A summary of these works is provided in Figure 1. These factors can be divided into five categories: vehicle, environment, traffic, driver and operations. Most fuel consumption models concentrate on vehicle, traffic, and environmental influences, but do not capture driver related issues which are relatively difficult to measure. Moreover, operations related factors are often seen as an externalities affecting fuel consumption.

One important work by Eglese and Black (2010) studies the emissions arising in routing and lists some of the factors affecting fuel consumption. In contrast to the existing literature, the authors argue that speed is more important than distance traveled when estimating emissions. In another study, Demir et al. (2011) have compared several emissions models, and mentioned other relevant factors such as load weight and distribution, engine type and size, vehicle design, and road gradient.

Road freight is mostly carried by internal combustion vehicles. In order to move a vehicle, an engine must provide power to overcome the effects of inertia, rolling resistance, wind resistance, road slope, drive train losses and accessories. Other factors which affect engine efficiency, such as air-fuel-ratio, engine speed and compression ratio, etc. Here we focus on the scientific literature related to fuel reduction in road freight transportation by means of operations research techniques. It considers several areas separately.

- *Speed*: Fuel consumption depends on several factors, but speed is the most important one because it affects inertia, rolling resistance, air resistance and road slope. Most studies focus on distance traveled but as Van Woensel et al. (2001) have shown, applying an average emission value per kilometer is inaccurate. According to Demir et al. (2011), a rule of thumb for medium-duty vehicle (MDV) is that fuel consumption increases approximately by 0.001 liter/km for every km/h increase above 55 km/h. Decreasing the vehicle speed from 100 km/h to 90 km/h can reduce fuel consumption by approximately 0.02 liter per km. Demir et al. (2012) have derived an optimum driving speed and have shown that reductions in

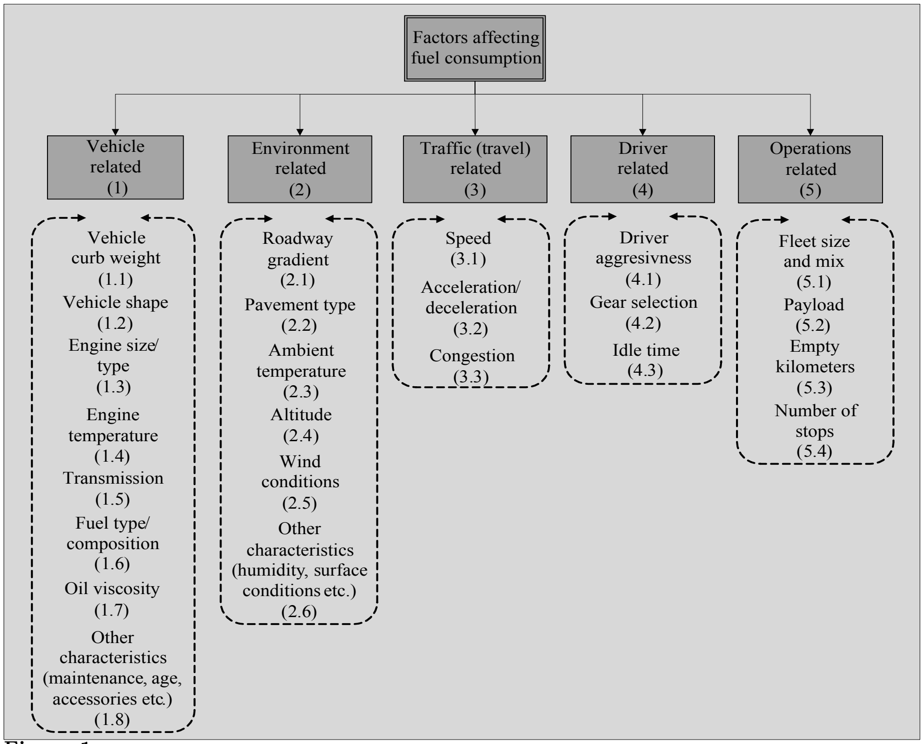

Figure 1
Factors affecting fuel consumption

emissions could be achieved by varying speed over a network. It should be noted that the optimum driving speed varies to a certain degree between geographical areas due to speed limits and traffic density.

- *Road gradient*: On a slope, wheel horsepower demand increases significantly with vehicle weight because of road slope force. In some regions, road gradient plays an important role and can result higher CO_2e emissions. In the study of Demir et al. (2011), fuel consumption of an MDV on a 1% road slope may increase by up to six liters on a 100 km segment. The reverse is also true: traveling on a negative slope surface reduces fuel consumption. With the help of an advanced GIS software, one can change speed on a portion of a road segment in order to reduce fuel consumption.

- *Congestion*: Driving in congested areas increases fuel consumption because of lower than optimal speeds. This is supported by Van Woensel et al. (2001) who have assessed the differences in CO_2 emissions between using constant speeds and flow dependent speeds. Based on a survey of cars on a motorway, they have shown that flow-dependent emissions of CO_2 are on average 11% higher than CO_2 emissions calculated using a constant speed. A peak increase of 40% was also observed during the congested rush hour period. In a manual of truck's engine (CAT, 2006), traveling 15% of the total kilometers on congested roads results approximately in an 8% increase in fuel consumption. Traveling 25% of the total kilometers on congested roads approximately results in a 15% increase in fuel consumption.

- *Driver*: One of the most significant factors affecting fuel consumption is the driver who controls vehicle speed, acceleration rate, brake usage, shifting technique, trailer gap setting, idle time, tire inflation pressure, and more. CAT (2006) shows that the difference in fuel consumption between the best and worst drivers can be as much as 25% (42.2 to 56.5 liters over a 100 km road segment). Idling the engine can also be seen as driver-related consumption.

- *Fleet size and mix*: Selecting the right type of vehicle has an important impact on fuel consumption. Small vehicles which have smaller engines consume less fuel than larger vehicles. However, using a large vehicle may lead to less fuel consumption than using two smaller vehicles. According to Demir et al. (2011), for a certain amount of payload, the difference between a medium and heavy-duty vehicle may be up to 14 liters of fuel on a 100 km road segment.

- *Payload*: Increasing the payload increases the engine demand horsepower, which leads to a higher fuel consumption. Vehicle payload affects the inertia force, rolling resistance and road slope force and can be an important part of routing decisions. Kara et al. (2007) and Bektaş and Laporte (2011) have studied the effect of payload on fuel consumption. Demir et al. (2011) show that, with an average load of one ton, fuel consumption increases by approximately three liters over a 100 km road segment. CAT (2006) shows that a 4,500 kg reduction in payload reduces fuel consumption by about 4.4%. Moreover, a reduction in gross weight from 36,000 kg to 27,000 kg generates an 8.8% improvement in fuel savings. In a study of DEFRA (2012), the change in CO_2 emissions is shown to be up to 25% for an articulated heavy-duty vehicle (HDV) with a gross weight of more than 33 tons.

- *Empty kilometers*: Empty kilometers are kilometers driven by empty vehicles and should be avoided as much as possible. Reducing them always results in a lesser fuel consumption. Most of the routing operations start or end at a depot with an empty load. According to EC (2010), in 2010, almost a quarter (23.9%) of all vehicle-km of HDVs in the EU involved an empty vehicle. In inbound transport, the share of empty vehicle-km is usually higher than in outbound transportation. Empty kilometers cause environmental pollution and place an unnecessary strain on the transportation infrastructures. Empty kilometer driving is often caused by a lack of information. For example, if a transportation company does not have the information that goods are waiting to be transported close to where a driver has just dropped off a previous load, the driver will simply be asked to return to the depot with an empty truck.

- *Green freight corridors*: The concept of green corridors was developed in recent years to minimize the environmental related factors affecting fuel consumption. The use of green corridors enables reductions in fuel consumption and CO_2e emissions, and should improve the environmental performance of road freight transport in the future. Green corridors can be structured based on several environmental and traffic-related factors. For example, CAT (2006) shows that the impact of climate is as important as vehicle speed and aerodynamics. Cold air increases the aerodynamic drag on the vehicle. Compared to 21 C°, fuel consumption can go up by 5% if the temperature reduces to 10 C° and it can go up to 10% at 0 C°. Wind and road surface are other factors that must be considered while creating green corridors.

3. Fuel consumption models

This section reviews fuel consumption (vehicle emission) models. A short description of each model is provided, along with a discussion pertaining to its development and applicability. In order to get a full picture of these models, the reader is referred to the classification of Williams et al. (2012) which classifies the models based on their simplicity and parameter uncertainty (Figure 2). In this study, we focus on the way of estimating fuel consumption more accurately.

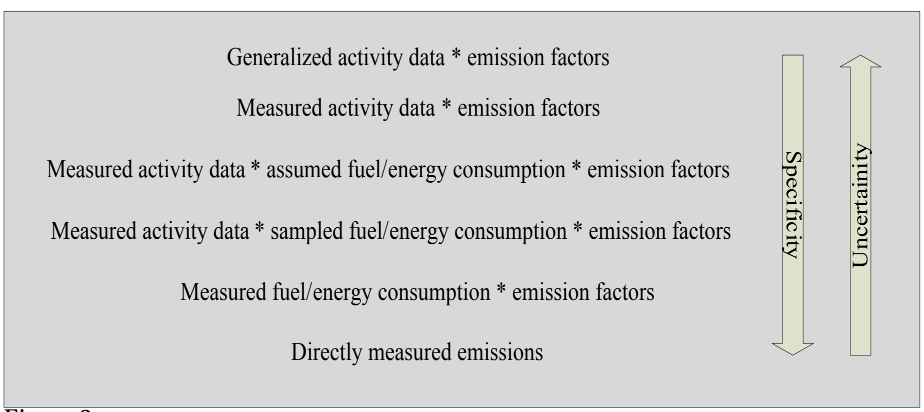

Figure 2
Examples of several methods for quantifying emissions (Williams et al., 2012)

The average fuel consumption of vehicles is provided by manufacturers, but the information provided does not make it possible to derive CO_2e emissions. For freight trucks, these measurements are based on engine test benches or from a standard test cycle using a chassis dynamometer, rather than on real-life driving cycles. These emission certification tests have been shown to differ significantly from real driving conditions (Pelkmans and Debal, 2006).

Rakha et al. (2003) mention that numerous energy and emission models are available and differ in their modeling approaches, modeling structures, and data requirements. Here, we categorize fuel consumption models into three main groups of increasing levels of complexity: factor models, microscopic models and macroscopic models. Factor models include simple fuel consumption methods. Macroscopic models use average aggregate network parameters to estimate network-wide emission rates. Microscopic models estimate the instantaneous vehicle fuel consumption and emission rates at a more detailed level. Models can also be grouped into the load (power)-based and the regression-based emissions models. These definitions also refer to micro- and macro-emission modeling, respectively.

Emissions can be approximated through the use of an emission factor related to one type of vehicle and a specific driving mode (Esteves-Booth et al., 2002). Furthermore, the emission factors are derived from the mean values of repeated measurements over a particular driving cycle. This type of model is particularly useful on a macro-scale, when the information on traffic flows and operational modes is insufficient. An example of a distance based factor model can be found in Protocol (2013). Another example of factor calculation can be found in DEFRA (2012), which provides information on how to calculate the GHG emissions. It is concerned with calculating and reporting the direct emissions resulting from burning fuel when driving in freight transport operations.

3.1. Macroscopic models

This section reviews 13 macroscopic (average speed) emission models, which are important tools in a wide-area emission assessment. These models can be used to calculate and develop a national or regional emission inventory, especially in green supply chain management studies. Generally, emission rates are measured for a variety of trips, each with a different average speed.

3.1.1. Methodology for calculating transportation emissions and energy consumption (MEET)

A publication of the European Commission by Hickman et al. (1999) on emission factors for road transportation (INFRAS, 1995) describes a methodology called MEET, used for calculating transportation emissions and energy consumption for heavy goods vehicles. MEET is based on on-road measurements and all its parameters are extracted from real-life experiments. It covers all current vehicle technologies for different classes of vehicles. For vehicles weighing less than 3.5 tonnes, the fuel consumption is estimated using a speed-dependent regression function of the form $\epsilon = 0.0617v^2 - 7.8227v + 429.51$. For other classes, MEET suggests the use a function the form $\epsilon = K + av + bv^2 + cv^3 + d/v + e/v^2 + f/v^3$, where ϵ is the rate of emissions (g/km) for an unloaded goods vehicle on a road with a zero gradient, and v denotes the average speed of the vehicle (km/h). The parameters K and a to f are predefined coefficients whose values can be found in Hickman et al. (1999).

The emission factors and functions of MEET refer to standard testing conditions (i.e., zero road gradient, empty vehicle, etc.) and are typically calculated as a function of the average vehicle speed. Depending on the vehicle type, a number of corrections may be needed to account for the effects of road gradient and vehicle load on the emissions once a rough estimate has been produced. The following road gradient correction factor is used to take the effect of road gradient into account: $GC = A_6v^6 + A_5v^5 + A_4v^4 + A_3v^3 + A_2v^2 + A_1v + A_0$. The coefficients A_0 to A_6 used to compute GC are given by Hickman et al. (1999). The following load correction factor is used to take the load factor into account: $LC = k + n\gamma + p\gamma^2 + q\gamma^3 + r/v + s/v^2 + t/v^3 + u/v$, k and n to u are coefficients whose values can be found in Hickman et al. (1999). MEET suggests estimating CO_2 emissions (g) as

$$F = \epsilon \cdot GC \cdot LC \cdot D, \tag{1}$$

where D is the distance traveled. It is noted that the parameters of MEET model were calibrated in 1999. The new engine technology and aerodynamics design of vehicles would require updates version of these parameters.

3.1.2. Network for transport and environment (NTM)

The NTM is a non-profit Swedish organization created in 1993 (Road, 2008). Its aim is to establish a common way to calculate the environmental performances from different transportation modes. The calculation pertains to the usage of natural resources and other external effects from freight transport. The method was mainly developed for market actors of transport services, making it possible to evaluate their own individual carbon footprint. The NTM considers distance, load factors, type of transport mode, positioning, empty return trips, topography and type of road (urban, rural or motorway). The fuel consumption at the specified load factor $F_t(lf)$ can be calculated as

$$F_t(lf) = F_t(empty) + (F_t(full) - F_t(empty)) \cdot lf,$$

where $F_t(empty)$ is the fuel consumption of the empty vehicle (L/km), $F_t(full)$ is the fuel consumption of the fully loaded vehicle (L/km) and lf is the specified load factor. The total carbon dioxide E can then be calculated as

$$E = F_t(lf) \cdot D \cdot e_{CO_2}, \tag{2}$$

where D is the distance (in km) and e_{CO_2} is the emission factor. The NTM provides a default database if no vehicle-specific data are available.

3.1.3. Computer programme to calculate emissions from road transportation (COPERT)

The COPERT is an European Economic Area funded emissions model (Kouridis et al., 2010), which estimates vehicle emissions for a range of vehicles by engine classification and vehicle type. It is driven by a database of emissions by vehicle class, engine technology and speed. It estimates emissions for all major air pollutants, as well as GHGs produced by different vehicle categories. Similar to MEET, COPERT uses a number of regression functions to estimate fuel consumption, which are specific to vehicles of different weights. An example of total fuel consumption function (g/km) with different load and gradient factor is given by

$$F_t = (e + (a \exp(-b\, v)) + (c \exp(-d\, v))) \cdot D, \tag{3}$$

where a to e are the coefficient and D is the distance (in km). The latest emission factor parameters of the COPERT 4 methodology have been updated for HDV on the basis of the latest HBEFA, version 3.1.

3.1.4. Ecological transport information tool (ECOTRANSIT)

The ECOTRANSIT was developed in 2003 with a regional scope limited to Europe. The recent version EcoTransIT World published in 2010 allows the estimation of environmental impacts of worldwide transports (Knörr et al., 2011), including the environmental impact of freight transport for any route and any transport mode. It covers energy consumption, GHG emissions and air pollutants. The model can take into account of upstream energy consumption, which is beyond the scope of this survey. The full calculation can be performed in three steps. The first step is to calculate the final energy consumption per net tonne km as $ECF_{tkm} = ECF_{km}/(CP \cdot CU)$, where ECF_{km} is the final energy consumption per net tonne km, CP is the payload capacity, and CU is the capacity utilization. The second step is to calculate the combustion related emissions per net tonne km as $EMV_{tkm} = EMV_{km}/(CP \cdot CU)$, where EMV_{km} is the combustion related vehicle emission factor of vehicle per km. The third step is to measure total emissions (kg) and energy consumption (MJ) as

$$E = D \cdot M \cdot EMV_{tkm}; F = D \cdot M \cdot ECF_{tkm}, \tag{4}$$

where D is the distance traveled, and M is the mass of freight transported. Energy consumption and emissions also depend on road category, gradient, and driving pattern. The influence of the load factor is modeled according to the HBEFA. For example, the fuel consumption of an empty vehicle can be one third below that of a fully loaded vehicle. This influence can be even stronger depending on driving characteristics and road gradient. The gradient takes into account region-specific factors and fuel consumption also depend on the driving pattern.

3.1.5. Emission factors (EMFAC)

The EMFAC is an emission model developed by the California Air Resources Board. The current version of the EMFAC model is EMFAC2011 (CARB, 2011). The EMFAC emission rates are a function of vehicle average travel speed. Adjustments are made for different temperatures, gasoline types, humidity, etc. Basic emission rates are derived from emissions tests conducted under standard conditions such as temperature, fuel, and driving cycle. The following equation is used to calculate the running emission rate for a vehicle category:

$$RE(vc) = VMT(vc) \cdot TVMT \sum_{v=5}^{70} \{SF(v, vc) \cdot REF(v, vc)\}, \tag{5}$$

where $TVMT$ is the total vehicle miles traveled, $VMTF(vc)$ is the fraction of vehicle miles traveled for vehicle category vc and can be calculated as $VMTF(vc) = VMT(vc)/TVMT$. Moreover, $SF(v, vc)$ is the speed fraction for vehicle category at speed v (in mph) and can be calculated as $SF(v, vc) = VMT(v, vc)/TVMT(vc)$. In addition, $REF(v, vc)$ (g/mile) is the running emission factor for vehicle category vc at speed v and can be calculated as $REF(v, vc) = DRE(vc, v)/(TVMT(vc)$. $DRE(v, vc)$ is the default running emissions.

3.1.6. National atmospheric emissions inventory (NAEI)

The NAEI model was developed for a large range of sectors including agriculture, domestic activity, industry and transport (NAEI, 2012). Emissions from road transportation are calculated either from a combination of total fuel consumption data and fuel properties, or from a combination of driving-related emission factors and road traffic data. For each vehicle category, the emission rate with average speed functions for hot exhaust in the NAEI can be calculated as (in g/km)

$$E = (a + bv + cv^2 + dv^e + f\ln(v) + gv^3 + h/v + i/v^2 + j/v^3) \cdot x, \tag{6}$$

where v is the average vehicle speed (in km/h) and a to j, and x are coefficients. These parameters can be found in NAEI (2012).

3.1.7. Other macroscopic models

In this section, we summarize seven macroscopic fuel consumption models we have identified. The reason why we separate these seven models from those presented above is that the sources describing them are either similar to those of earlier models, or there does not exist sufficient information on their methodology to provide a detailed description.

- *MOBILE*: The model was developed by the Environment Protection Agency (EPA) Office of Transportation and Air Quality and published in 1978. The last version MOBILE 6.2 was developed using recent vehicle-emission testing data collected by the EPA, CARB, and automobile manufacturers, as well as inspection and maintenance tests conducted in various places (EPA, 2003). The descriptive and spreadsheet outputs from MOBILE report emission rates in grams of pollutant per vehicle-mile traveled. In 2010, the MOBILE series of models was replaced by Motor Vehicle Emission Simulator (MOVES) as EPA's official model for estimating emissions.

- *MOVES*: The MOVES was developed by EPA (EPA, 2012). The purpose of the tool is to provide an accurate estimate of emissions from mobile sources under a wide range of user-defined conditions. The model performs a series of calculations which were carefully developed to accurately reflect vehicle operating processes, such as cold start or extended idling, and provide estimates of bulk emissions or emission rates.

- *HBEFA*: The handbook emission factors for road transport is the database for vehicle emission factors in Europe. It was introduced in 1995 by Hausberger et al. (2009), and the current version HBEFA 3.1 was published in 2009. It provides emission factors for all current vehicle categories of road transport, all EU emission standards and a wide variety of traffic situations. Besides hot emission factors, it also provides cold start and evaporation emission factors.

- *GREET*: The greenhouse gases, regulated emissions, and energy use in transportation model was developed as a full life-cycle model by the Argonne National laboratory (Wang, 1999). It is used to evaluate energy and emission impacts of various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis. The first version of GREET was released in 1996. Since then, GREET model has continued to updated and expanded, and is now called GREET2 2012. For a given vehicle and fuel system, GREET2 2012 separately calculates consumption of total energy and CO_2e emissions.

- *LEM*: The lifecycle emissions model of Delucchi (2003) estimates energy use, criteria pollutant emissions, and CO_2e emissions from a variety of transportation and energy life cycles. It includes a wide range of modes of passenger and freight transport.

- *VERSIT-LD*: The model was developed to predict traffic stream emissions for light-duty vehicles in any particular traffic situation (Smit et al., 2007). It predicts traffic stream emissions for any particular traffic situation by using accurate mean emission factors, expressed in grams per kilometer.

- *IVE*: The international vehicle emissions model was designed to estimate emissions from motor vehicles (ISSRC, 2008). It predicts local air pollutants, toxic pollutants and GHGs emissions. The emission prediction process of the IVE model starts with a base emission rate, and a series of correction factors are then applied to estimate the amount of pollution from a variety of vehicle types. These main factors refer to temperature, humidity, fuel quality and driving behavior.

3.2. Microscopic models

This section reviews instantaneous emission models (at time t) for the estimation of hot-stabilized vehicle emissions. Instantaneous models are necessary to predict traffic emissions more accurately. These are based on instantaneous vehicle kinematic variables, such as speed and acceleration, or on more aggregated modal variables, such as time spent in each traffic mode, cruise and acceleration.

In order to increase the readability and understandability of the models, we use similar notations for specific definitions. The standardized notations are the following: v is the speed of the vehicle (m/s), M is the total weight of the vehicle (kg), a is the instantaneous acceleration (m/s^2), ω is the gradient (%), and g is the gravitational constant (m/s^2), ρ is the air density (in kg/m^3), A is the frontal surface area (in m^2), C_d is the coefficient of aerodynamic drag, and C_r is the coefficient of rolling resistance.

3.2.1. An instantaneous fuel consumption model (IFCM)

An energy-related emissions estimation model was described by Bowyer et al. (1985). The IFCM uses vehicle characteristics such as mass, energy, efficiency parameters, drag force and fuel consumption components associated with aerodynamic drag and rolling resistance, and approximates the fuel consumption per second. The fuel consumption with an IFCM can be calculated as

$$f_t = \begin{cases} \alpha + \beta_1 R_t v + (\beta_2 M a^2 v/1000) & \text{for } R_t > 0 \\ \alpha & \text{for } R_t \leq 0, \end{cases}$$

where f_t is the fuel consumption per unit time (mL/s), R_t is the total tractive force (kN) required to move the vehicle and calculated as the sum of drag force, inertia force and grade force as $R_t = b_1 + b_2 v^2 + Ma/1000 + gM\omega/100000$. Furthermore, α is the constant idle fuel rate, β_1 is the fuel consumption per unit of energy (in mL/kJ), β_2 is the fuel consumption per unit of energy-acceleration (in mL/(kJ·m/s^2)), b_1 is the rolling drag force (in kN), and b_2 is the rolling aerodynamic force (in kN/(m/s)^2). Using the IFCM, the total amount of fuel consumption F_t (mL) for a journey of duration t_0 can be calculated as

$$F_t = \int_0^{t_0} f_t dt. \quad (7)$$

The IFCM works best at a micro-scale level and is better suited for short trip emission estimations.

3.2.2. A four-mode elemental fuel consumption model (FMEFCM)

The FMEFCM was introduced by Bowyer et al. (1985). It estimates fuel consumption for each of the four following modes of driving: acceleration, deceleration, cruise, and idle. This model includes the same parameters as the IFCM but also introduces new parameters, such as initial speed, final speed and energy-related parameters. The model consists of four functions, F_a, F_d, F_c and F_i, which correspond to fuel consumption estimations (mL) for each mode of driving.

- Acceleration fuel consumption (F_a): This function computes the amount of fuel consumption over the acceleration phase of a vehicle from an initial speed v_i to a final speed v_f. It is defined as

$$F_a = \max\{\alpha t_a + (\Gamma + k_1 B(v_i^2 + v_f^2) + \beta_1 M E_k + k_2 \beta_2 M E_k^2 + 0.0981\beta_1 M\omega)x_a, \alpha t_a\},$$

where, E_k denotes the change in kinetic energy per unit distance during acceleration and is calculated as $E_k = 0.3858\,10^{-4}(v_f^2 - v_i^2)/x_a$. Furthermore, the integration coefficients are $k_1 = 0.616 + 0.000544v_f - 0.0171\sqrt{v_i}$ and $k_2 = 1.376 + 0.00205v_f - 0.00538v_i$. When the travel distance x_a and the travel time t_a are not known, they can be estimated as $x_a = m_a(v_i + v_f)t_a/3600$, where $m_a = 0.467 + 0.00200v_f - 0.00210v_i$ and $t_a = (v_f - v_i)/(2.08 + 0.127\sqrt{v_f - v_i} - 0.0182v_i)$. In addition, Γ is the function parameter (in mL/km), and B is the function parameter (in (mL/km)/(km/h)^2).

- Deceleration fuel consumption (F_d): The amount of fuel consumption during the deceleration phase from an initial speed v_i to a final speed v_f is calculated as

$$F_d = \max\{\alpha t_d + (k_x\Gamma + k_y k_1 B(v_i^2 + v_f^2) + k_a\beta_1 M E_k + k_x\beta_1 M E_k^2 + 0.0981\beta_1 M\omega)x_d, \alpha t_d\},$$

where $k_x = 0.046 + 100/M + 0.00421v_i + 0.00260v_f + 0.05444\omega$, $k_y = k_x^{0.75}$, $k_a = k_x^{3.81}(2 - k_x^{3.81})$ and $k_1 = 0.621 + 0.000777v_i - 0.0189\sqrt{v_f}$. If the travel distance x_d and travel time t_d are not known, they can be estimated as above, although in this case the coefficients change slightly. In addition, k_x, k_y and k_a are the energy related parameters.

- Cruise fuel consumption (F_c): The following function can be used to calculate the total amount of fuel consumption by a vehicle during a cruise phase:

$$F_c = \max\{f_i/v_c + \Gamma + Bv_c^2 + k_{E1}\beta_1 M E_{k+} + k_{E2}\beta_2 M E_{k+}^2 + 0.0981k_G\beta_1 M\omega, f_i/v_c\}x_c,$$

where f_i denotes the idle fuel rate (in mL/h), v_c is the average cruise speed (km/h), and x_c denotes the travel distance (km). The change in total positive kinetic energy per unit distance during the cruise mode is calculated as $E_{k+} = \max\{0.258 - 0.0018v_c, 0.10\}$ and the other parameters are set to $k_{E1} = \max\{12.5/v_c + 0.000013v_c^2, 0.63\}$, $k_{E2} = 3.17$, and $k_G = 1 - 2.1E_{k+}$ for $\omega < 0$, and $1 - 0.3E_{k+}$ for $\omega > 0$. Furthermore, k_{E1}, k_{E2} and k_G are the calibration parameters.

- Fuel consumption while idle (F_i): The following function can be used to calculate the total amount of fuel consumption when the vehicle is idle:

$$F_i = \alpha t_i,$$

where t_i is the idle time (s), and α is the idle fuel rate (mL/s).

The total fuel consumption F_t (mL) using the elemental model can be calculated as

$$F_t = \int_0^{t_a} F_a dt + \int_0^{t_d} F_d dt + \int_0^{t_c} F_c dt + \int_0^{t_i} F_i dt. \tag{8}$$

The model requires data in detail for each driving mode, such as the total distance, speed, time and average road grade. If the data are available, the estimation of fuel consumption can be very accurate.

3.2.3. A running speed fuel consumption model (RSFCM)

The RSFCM is an aggregated form of the FMEFCM and was also introduced by Bowyer et al. (1985). The model calculates fuel consumption separately during driving modes when a vehicle is running on idle. Acceleration, deceleration and cruise modes are considered together within a single function. The model is as follows:

$$\begin{aligned} F_t = \max \{ & \alpha t_i + (f_i/v_r + A + B v_r^2 + k_{E1}\beta_1 M E_{k+} + k_{E2}\beta_2 M E_{k+}^2 + \\ & 0.0981 k_G \beta_1 M \omega) x_s, \alpha t_s \}, \end{aligned} \tag{9}$$

where F_t is the total fuel consumption (mL), x_s is the total distance, v_r denotes the average running speed (km/h), t_s and t_i the travel and idle time, respectively. The average speed is calculated as $v_r = 3600 x_s/(t_s - t_i)$. Furthermore, $E_{k+} = \max \{0.35 - 0.0025 v_r, 0.15\}$, $k_{E1} = \max \{0.675 - 1.22/v_r, 0.5\}$, $k_{E2} = 2.78 + 0.0178 v_r$. The model needs fewer data than of FMEFCM but it is less accurate for measuring fuel consumption.

3.2.4. Average speed fuel consumption model (ASFCM)

This model is an another extension of the IFCM and was also proposed by Bowyer et al. (1985). The model relates fuel consumption per unit distance to average speed. In this model, the total fuel consumption (mL) can be estimated as $F_s = f_x x_s$, where the fuel consumption per unit distance is $f_x = f_i/v_s + cK$, and v_s denotes the average travel speed (km/h). Furthermore, $K = 1 - K_1(1 - M/1200) - K_2(1 - \beta_1/0.090) - K_3(1 - \beta_2/0.045 - K_4(1 - b_1/0.000278M) - K_5(1 - b_2/0.00108)$, K is the adjustment factor for different types of vehicles, c is the regression coefficient, K_1–K_5 are parameters based on the analysis of real on-road data.

3.2.5. Vehicle specific power (VSP)

The VSP was introduced by Jimenez-Palacios (1998) to estimate instantaneous vehicle fuel consumption and emission rates. It is highly correlated with variability in second-by-second emissions of pollutants from diesel vehicles. The

VSP is a measure of the road load on a vehicle and is defined as the power per unit mass to overcome road grade, rolling and aerodynamic resistance, and inertial acceleration. It can be calculated using an equation given by EPA (kW/ton):

$$VSP = v(a(1+\epsilon) + g\omega + gC_r) + 0.5\rho C_d A v^3/M,$$

where ϵ is the mass factor accounting for the rational masses. The fuel consumption (g) is

$$F_t = (VSP \cdot M)/\eta, \tag{10}$$

where η is the efficiency rate. The VSP is also used as a base model to measure power demand in different emission models.

3.2.6. Emissions from traffic mode (EMIT)

The EMIT model was introduced by Cappiello et al. (2002). It is a statistical model with a basis in the physical system for fuel consumption of light duty vehicles. The fuel rate (g/s) can be calculated as

$$fr = \begin{cases} \alpha_{fr} + \beta_{fr} v + \gamma_{fr} v^2 + \delta_{fr} v^3 + \zeta_{fr} av & \text{if } P_{tract} > 0 \\ \alpha'_{fr} & \text{if } P_{tract} = 0, \end{cases}$$

where $P_{tract} = A_{fr}\mathrm{v} + B_{fr}\mathrm{v}^2 + C_{fr}\mathrm{v}^3 + Ma\mathrm{v} + Mg\sin\omega(\theta)\mathrm{v}$, A_{fr} is the rolling resistance coefficient $(\mathrm{kW}/(\mathrm{m/s})^2)$, B_{fr} is the speed correction to rolling resistance coefficient (in $\mathrm{kW}/(\mathrm{m/s})^2$),and C_{fr} is the air drag resistance coefficient (in $\mathrm{kW}/(\mathrm{m/s})^3$). More information on coefficients $\alpha_{fr}, \alpha'_{fr}, \beta_{fr}, \gamma_{fr}, \delta_{fr}$ and ζ_{fr} can be found in Cappiello et al. (2002). The total fuel consumption (g) is

$$F_t = \int_0^{t_0} fr dt. \tag{11}$$

The EMIT model was calibrated based on the two light-duty vehicle categories. It provides reasonable results compared to actual measurements. We also note that EMIT was developed and calibrated for hot-stabilized conditions with zero road grade, and without accessory usage, and does not correspond to cold-start emissions.

3.2.7. Virginia tech microscopic (VT-Micro)

This model was developed by Ahn et al. (2002) from experimentations with numerous polynomial combinations of speed and acceleration levels using chassis dynamometer data on light duty vehicles. The CO_2 emissions were estimated using the carbon balance equation in conjunction with the fuel consumption measurements. The fuel consumption rate for a cruising speed equal to the free-flow speed and on a grade of ω can be computed as

$$f_r = \exp\left(\sum_{i=1}^{3}\sum_{j=1}^{3} L_{i,j} v_f^i (g\,\omega)^j\right),$$

where $L_{i,j}$ is the model regression coefficients at speed exponent i and acceleration exponent j. The total fuel consumption (L) can be calculated as

$$F_t = 3600 f_r d_l/(v_f)_l, \tag{12}$$

where d_1 is the length of link l (km) and $(v_f)_l$ is the free-flow speed on link l (km/h).

3.2.8. The Oguchi et al. (2002) fuel consumption model (OFCM)

The OFCM was developed by Oguchi et al. (2002). The function consists of five components, which are idle consumption, friction loss, altitude change loss, air drag loss, and acceleration loss. The total fuel consumption F_t (mL) using the OFCM can be calculated as

$$\begin{aligned} F_t = f_{idle}T + E\sum_{j=1}^{J}\{\mu Mg\int_{t_{js}}^{t_{je}} vdt + \sin\theta Mg\int_{t_{js}}^{t_{je}} vdt+ \\ C_d\int_{t_{js}}^{t_{je}} v^3 dt + (M+m)(0.5v_{je}^2 - 0.5v_{js}^2)\}, \end{aligned} \tag{13}$$

where $f_{(idle)}$ is the base consumption, T is the travel time, E is the fuel-energy equivalent, μ is the friction coefficient, and J is the number of interval. The parameters j_s and j_e are the start and end of interval, and m is the internal resistance equivalent. The idle fuel consumption is the fuel used for the inertia resistance of the engine and transmission, air conditioner, and some other electric components. The other components estimate the energy loss by the vehicle's movement.

3.2.9. Physical emission rate estimator (PERE) model

The PERE was designed by Nam and Giannelli (2005) to measure vehicle emissions. It was developed to support the new EPA energy and emissions inventory model, namely MOVES. The PERE consists of a series of stand-alone spreadsheets, which can be run and modified by an user. The model performs well: in most cases the predictions are within 10% of observed values. The fuel consumption rate (kg/s) can be formulated as

$$fr = \varphi\{kNV + (P_b/\eta_t + P_{acc})/\eta)\}LHV, \tag{14}$$

where φ is the fuel air equivalence ratio, k is the engine friction, N is the engine speed, V is the engine displacement volume, η_t is a transmission and final drive efficiency, P_{acc} is the power draw of accessories, and LHV is the factor lowering heating value. The power demand (W) can be calculated as $P_b = C_r v + Bv^2 + C_d v^3 + Mv(a + g\omega)$, where B is a rotating resistance coefficient.

3.2.10. Comprehensive power-based fuel consumption models (CPFMs)

Two power-based second-order polynomial models were introduced by Rakha et al. (2011). These models were inspired from one of the base models which can be found in the mechanical engineering literature (Wong, 2001). The first model does not require any engine data given that the power used by a vehicle is a function of the vehicle speed and acceleration level. The second model requires engine data in addition to external data and therefore can be used to model eco-drive with gear-shifting strategies. The two models can be formulated as

$$\begin{aligned} &F_t(1) = \alpha_0 + \alpha_1 P(t) + \alpha_2 P(t)^2, \\ &and\, F_t(2) = \beta_0 \omega(t) + \beta_1 P(t) + \beta_2 P(t)^2, \end{aligned} \tag{15}$$

where $\alpha_0, \alpha_1, \alpha_2, \beta_0, \beta_1$ and β_2 are vehicle-specific constants given for each type of vehicle. The function $P(t) = ((R(t) + 1.04ma(t))/3600\eta_d)v(t)$ measures the total power exerted by the vehicle driveline (kW) at time t, $R(t)$ is the total resistance force (N), and η_d is the the driveline efficiency. In addition, the total resistance force can be calculated as $R(t) = (\rho/25.92)C_d C_h A v^2(t) + 9.8066mC_r\{c_1 v(t) + c_2\} + 9.8066mG(t)$. The detailed calculation of each coefficient is shown in Rakha et al. (2011). The CPFM-1 and CPFM-2 can be easily calibrated using publicly available data, for example using the European Environmental Agency's city and highway fuel economy ratings. The models are also proved to be consistent with in-field measurements.

3.2.11. Passenger car and heavy duty emission model (PHEM)

The microscopic emission model PHEM was designed for simulating fuel consumption. Due to the cooperation between ARTEMIS (Boulter and McCrae, 2009), COST 346 (Rexeis et al., 2005) and HBEFA (Hausberger et al., 2009), the measurement program covered different engines and vehicles. The PHEM interpolates the fuel consumption from the engine maps according to the course of engine power demand and engine speed in the driving cycles. The actual engine power (P) can be calculated as $P = P_{rr} + P_{ar} + P_{acc} + P_{gr} + P_{au} + P_{tl}$, where $P_{rr} = Mg(fr_0 + fr_1 v + fr_2 v^2 + fr_3 v^3 + fr_4 v^4)v$ is the rolling resistance, $P_{ar} = 0.5C_d A\rho v^3$ is the air resistance, and $P_{acc} = (M + m_{rot})av$ is the acceleration. Moreover, $P_{gr} = Mg\omega 0.01v$ is the gradient resistance, $P_{au} = P_0 P_{rated}$ is the power demand for auxiliaries and $P_{tl} = P_{dr}/\eta_t - P_{dr}$ is the transmission losses, where fr_0 to fr_4 are the rolling resistance coefficients, m_{rot} is the reduced mass for rational accelerated part, P_0 is the power demand of the auxiliaries as ratio to the rated power P_{rated}, and P_{dr} is the power to overcome the driving resistances. The total emission value can be calculated under the transient conditions

$$E_{trans} = E_{qs} + P_{rated} + F_{trans}, \tag{16}$$

where E_{qs} is the quasi-steady-state emission value interpolated from steady-state emission map (in g/h), P_{rated} is the rated engine power (kW) (since emission values are normalized to the rated power), F_{trans} is the dynamic correction function ((g/h)/kW rated power). More information can be found in Boulter and McCrae (2009).

3.2.12. A comprehensive modal emission model (CMEM)

The CMEM for heavy-goods vehicles was developed and presented by Scora and Barth (2006), Barth et al. (2005) and Barth and Boriboonsomsin (2008). It is based upon second-by-second tailpipe emissions data collected from 343 light-duty vehicles (LDVs) tested under a variety of laboratory driving cycles. The CMEM is similar to the IFCM. However, to produce accurate estimations, it requires detailed vehicle specific parameters for the estimations such as the engine friction coefficient, and the vehicle engine speed. The CMEM follows to some extent the model of Ross (1994) and is composed of three modules, namely engine power, engine speed and fuel rate.

- The engine power module: The power demand function for a vehicle is obtained from the total tractive power requirements P_{tract} (kW) placed on the vehicle at the wheels:

  $$P_{tract} = (Ma + Mg \sin \omega(\theta) + 0.5 C_d \rho A v^2 + MgC_r \cos \omega(\theta))v/1000. \quad (17)$$

  To translate the tractive requirement into engine power requirement, the following relationship is used:

  $$P = P_{tract}/\eta_{tf} + P_{acc},$$

  where P is the second-by-second engine power output (kW), and η_{tf} is the vehicle drive train efficiency.

- The engine speed module: Engine speed is approximated in terms of vehicle speed as

  $$N = S(R(L)/R(L_g))v,$$

  where N is the engine speed (in rpm), S is the engine-speed/vehicle-speed ratio in top gear L_g, $R(L)$ is the gear ratio in gear $L = 1,\ldots,L_g$, and η is the efficiency parameter for diesel engines.

- The fuel rate module: The fuel rate (g/s) is given by the expression

  $$FR = \phi(kNV + P/\eta)/43.2, \quad (18)$$

  where ϕ is the fuel-to-air mass ratio, k is the engine friction factor, and V is the engine displacement (in liters). The CMEM can be seen as a state-of-the-art microscopic emission model because of its easy applicability.

3.3. A tabulated comparison of the models

As discussed earlier, fuel consumption depends on a number of factors which can be grouped into five categories: vehicle, environment, traffic, driver, and operations related factors. Considering these five categories, we present in Table 1 a tabulated comparison of the 25 models reviewed so far.

This comparison shows that most of the models consider vehicle load and speed, although the way in which they incorporate these factors into the ap-

Table 1
A detailed comparison of macroscopic and microscopic models

	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	2.1	2.2	2.3	2.4	2.5	3.1	3.2	4.1	4.2	4.3	5.1	5.2	5.3	5.4
Macroscopic models																						
MEET	✓		✓	✓		✓		✓	✓	✓	✓		✓	✓				✓	✓	✓		
NTM	✓					✓													✓	✓		
COPERT	✓	✓	✓	✓	✓	✓		✓	✓					✓					✓	✓		
ECOTRANSIT	✓	✓				✓			✓	✓			✓	✓	✓	✓			✓	✓	✓	✓
EMFAC	✓	✓				✓		✓	✓	✓	✓	✓	✓	✓				✓	✓	✓		
NAEI	✓			✓		✓					✓			✓		✓	✓		✓	✓		
MOBILE	✓				✓	✓		✓	✓		✓			✓					✓	✓		
MOVES	✓				✓	✓		✓	✓		✓			✓				✓	✓	✓		
HBEFA	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓			✓	✓	✓		
GREET	✓			✓		✓								✓					✓	✓		
LEM	✓					✓			✓					✓					✓	✓		✓
VERSIT-LD	✓	✓			✓	✓		✓	✓	✓				✓	✓				✓	✓		
IVE	✓	✓				✓			✓					✓		✓			✓	✓		
Microscopic models																						
IFCM	✓	✓							✓	✓	✓	✓		✓	✓			✓	✓	✓		
F-MEFCM	✓	✓							✓	✓	✓	✓		✓	✓			✓	✓	✓		
RSFCM	✓	✓							✓	✓	✓	✓		✓				✓	✓	✓		
ASFCM	✓	✓							✓	✓	✓	✓							✓	✓		
VSP	✓	✓	✓			✓		✓	✓	✓	✓	✓		✓	✓				✓	✓		
EMIT	✓	✓						✓	✓	✓	✓	✓		✓	✓				✓	✓		
VT-Micro	✓								✓					✓	✓				✓	✓		
OFCM	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓		✓	✓			✓	✓	✓		
PERE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓				✓	✓		
CPFM	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓				✓	✓		
PHEM	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓				✓	✓		
CMEM	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓				✓	✓		

proximations, in particular for load, varies highly. Microscopic models are similar in that they are able to react a certain level of detail so as to consider technical and vehicle-specific parameters such as vehicle shape (frontal area), and road conditions (e.g., gradient, surface resistance). This is not the case in macroscopic models which present mostly simpler ways of regression-based estimations through a predefined set of parameters for a certain vehicle class. It is worth mentioning that only a few of the models listed in Table 1 consider driver-related factors and none of the models considers congestion, since the inclusion of such detailed factors in the estimation process is rather difficult. None of the models included in Table 1 considers factors 2.6 and 3.3.

4. Fuel consumption modeling in road transportation planning

We now review emission models used at different levels of planning for road freight transportation. The planning levels in transportation are categorized based on three temporal dimensions: strategic, tactical and operational. Green road transportation studies can also be categorized according to these three dimensions.

The factors affecting fuel consumption should be considered within a specific time frame. For example, green freight corridors are long-term planning decisions. Fleet size and driver selection are medium-term planning problems. Other routing decisions are matters of short-term planning. Since, strategic planning is not directly related to routing and scheduling operations, it is not covered by this survey. Tactical and operational planning will be combined.

Freight transportation includes many facets, particularly when viewed from the multiple levels of decision making. Arguably the most important problem at the operational level is routing and scheduling. This section is concerned with vehicle routing studies which include an explicit consideration of environmental concerns, in particular CO_2e emissions. There exists an extensive mature body of research on vehicle routing. In contrast, the literature on the green routing is relatively young (Sbihi and Eglese, 2007), but the interest in environmental issues has grown in recent years. As for freight transportation, most of the published studies on routing are concerned with internal cost minimization. In the following sections, we review several applications with different emission modeling approaches at the operational planning level.

4.1. Applications of the IFCM

The IFCM (Eq. 7) was studied by Palmer (2007) who considered CO_2 emissions models in the context of the vehicle routing routing with time windows (VRPTW). The objective was to develop an effective method of constructing vehicle routes minimizing CO_2 emissions. Results indicate that there exists a potential for reducing CO_2 emissions by around 5% by minimizing this objective instead of travel time.

A second application was studied by Urquhart et al. (2010a), who used the IFCM to solve the VRPTW for low CO_2 solutions using evolutionary algorithms.

The authors looked at the trade-offs between CO_2 savings, distance and the required number of vehicles. Their results indicate that savings of up to 10% can be achieved, depending on the problem instance and the ranking criterion used in the evolutionary algorithm.

4.2. An application of the VSP

An eco-friendly routing problem was studied by Bandeira et al. (2012) who used a microscopic vehicle scheduling model (Eq. 10) to assess whether eco-friendly routes change during peak hours, based on three distinct case-studies on two continents. The authors collected more than 13,330 km of data using GPS equipped light diesel and gasoline duty vehicles, in the United States and Portugal. The authors demonstrated empirically that most eco-friendly route during off-peak hours is also the most eco-friendly during peak hours. Regarding intercity routes, tests conducted during both the peak and the off-peak hours have shown that the faster routes can reduce CO_2 emissions by up to 30%. In a related research, Bandeira et al. (2013) investigated a way to generate information about emissions for drivers faced with a choice of routes. According to their results, the choice of a route can substantially affect emission rates of the analyzed pollutants and that smoother driving styles can also result in considerable emissions reduction. For example, faster intercity routes are more desirable in terms of fuel use and CO_2 emissions. However, these same routes yielded more CO and N_2O emissions.

4.3. Applications of the OFCM

Using OFCM (Eq. 13), Kono et al. (2008) introduced an ecological route search system which minimizes fuel consumption by considering many factors such as traffic information, geographic information, and vehicle parameters. The authors collected an extensive data set in areas with different geographical features and in various traffic conditions. Their results suggest that the fuel consumption of the eco-routes is 9% lower than that of the time priority routes, even though the travel time of the ecological routes is 9% longer. They argue that ecological routes could be different from time-priority routes, contrary to the conclusions of the study by Bandeira et al. (2012).

In a similar study, Correia et al. (2010) have analyzed eco-routing in France, with the help of OFCM. The authors proposed an analysis method using geographical features for the needs of eco-route search. According to their results, the fuel savings could be between 1% and 36% compared to the fastest routes.

4.4. An application of the CPFEM

The CPFEM (Eq. 15) was studied by Minett et al. (2011) who investigated eco-routing to reduce fuel consumption considering motorways, local and provincial routes. The authors developed a tool in which historical link speed data were used as a basis for replicating vehicle speed profiles, thus enabling the calculation of fuel costs per link. These fuel costs and speed profiles were validated by field test data. According to the results, based on field tests, provincial route would offer an average time saving of 10.41 (25%) minutes over the local route, and an average fuel saving of 1.25 liter over the motorway route (45%).

4.5. Applications of the CMEM

A first application of the CMEM is that of Bektaş and Laporte (2011). The authors have introduced the pollution-routing problem (PRP), an extension of the classical VRPTW which consists of routing a number of vehicles to serve a set of customers, and determining their speed on each route segment, so as to minimize a function comprising fuel, emission and driver costs. In estimating pollution, the authors consider factors such as speed, load, and time windows, using the emissions function Eq. 17. They assume that in a vehicle trip all parameters will remain constant on a given arc, but load and speed may change from one arc to another. Their model approximates the total amount of energy consumed on the arc, which directly translates into fuel consumption and further into GHG emissions. Computational results reported by the authors suggest that by using the proposed approach, energy savings can be up to 10% when time windows are in place, and up to 4% when the demand variation is high.

The second application of the CMEM to the PRP is due to Demir et al. (2012), who computed the total fuel consumption per second via Eq. 18. The authors applied a heuristics to solve the PRP. The algorithm iterates between the solution of the VRPTW and of a speed optimization problem. The former problem was solved through adaptive large neighborhood search (ALNS) (Ropke and Pisinger, 2006) and the latter was solved through a polynomial time speed optimization procedure (SOP) as will be discussed later. The authors introduced new removal and insertion operators aimed at improving solution quality in terms of CO_2 emissions. In order to analyze the fuel consumption more accurately, the authors generated benchmark instances by randomly selecting cities from the United Kingdom and therefore using real geographical distances. All instances can be downloaded from http://www.apollo.management.soton.ac.uk/prplib.htm. According to their results, the reduction on CO_2 emissions were around 10%. In a related research, Demir et al. (2013) investigated the trade-offs between fuel consumption and driving time via CMEM. They showed that trucking companies need not compromise greatly in terms of driving time in order to achieve a significant reduction in fuel consumption and CO_2 emissions. The converse of this insight also holds, i.e., considerable reductions in driving time are achievable if one is willing to increase fuel consumption only slightly.

Using CMEM, Ramos et al. (2012) investigated the service areas and routes that minimize the CO_2 emissions of a transportation system with multiple products and depots. The authors proposed a decomposition solution approach and applied it to a case study in order to reshape the current system and create a more environmental-friendly routes. According to their results, by comparing the CO_2 emissions of the current system with the proposed one, a decrease of 23% can be achieved if the company reshapes both its service areas and vehicle routes. The total potential savings can be up to 20% if the company keeps its current service areas.

The last application of CMEM reviewed here is by Franceschetti et al. (2013) who investigated fuel consumption, CO_2 emissions and driver costs under traffic congestion. The authors identified the conditions under which it is optimal to wait idly at certain locations in order to avoid congestion and to reduce the cost of emissions. Their results suggest that a 20% reduction in the cost of fuel, CO_2 emissions and driver cost is achievable based on the instances generated by Demir et al. (2012).

4.6. Applications of the MEET

The MEET model (Eq. 1) has been widely used by several researchers. The very first application of MEET was done by Kim et al. (2009) who investigated the relationships between freight transport costs and CO_2 emissions in intermodal and truck only freight networks, as a part of multi-objective study. The CO_2 emissions were estimated as a function of cruising speed and distance traveled, and average values were used for other factors, such as cold-start emissions and ambient temperature.

The second application is due to Figliozzi (2010) who studied the minimization of emissions and fuel consumption. The author introduced the emissions vehicle routing problem (EVRP), an extension of the time-dependent vehicle routing problem (TDVRP). The author provides a formulation and an algorithm for the problem. The objective of the EVRP is the minimization of emission costs, which are proportional to the amount of GHG emitted, which in turn is a function of travel speed and distance traveled. In the proposed algorithm, a partial EVRP is first solved to minimize the number of vehicles by means of a TDVRP algorithm, and emissions are then optimized subject to a fleet size constraint. The departure times are also optimized using the proposed algorithm for any pair of customers. The author worked with three traffic classes: uncongested, somewhat congested, and congested traffic conditions. He solved the Solomon (1987) instances, and suggested that uncongested travel speeds tend to reduce emissions on average; however, this is not always the case, and the opposite trend is sometimes observed. The author suggests that a 20% reduction is possible by optimizing departure times. In another study (Figliozzi, 2011), the author focused on the analysis of CO_2 emissions for different levels of congestion and time-definitive customer demands. Travel time data from an extensive archive of freeway sensors, time-dependent vehicle routing algorithms, and instances with different types of binding constraints were used to analyze the impacts of congestion on commercial vehicle emissions.

Pan et al. (2010) have used MEET to analyze the effect of pooling supply chain networks on the reduction of transport-related CO_2 emissions. The authors have computed CO_2 emissions for two transport modes with real data. Their results show that reductions of 14% in CO_2 emissions for road transport only and of 52% for joint road and rail transport can be achieved.

Another application of MEET is due to Jabali et al. (2012) who have investigated travel times and CO_2 emissions in the context of the TDVRP by analyzing the effect of limiting vehicle speed. The authors also addressed the issue of congestion, where the vehicle is forced to drive slower and therefore emits more CO_2. The authors provided a formulation of the problem in which the costs of driving, fuel and CO_2 are included. Using tabu search algorithm, a reduction of 11.2% in CO_2 emissions on average requires increasing the travel time by 14.8% under a 90 km/h speed profile was achieved. Furthermore, the authors report that an increase of 4.7% in travel time yields a reduction of 3.7% in CO_2 emissions.

Omidvar and Tavakkoli-Moghaddam (2012) introduced a vehicle routing model for alternative fuel vehicles (AFV) (e.g., hybrid, electric and fuel cell vehicles) in order to minimize fuel consumption and CO_2 emissions. They have tested their model on the Solomon benchmark instances. Their results suggest that the importance of CO_2 emissions costs for these vehicle is around 3% of the total costs.

Another application of MEET is due by Saberi and Verbas (2012) who looked at emissions minimization in the context of the TDVRP. The authors have developed a continuous approximation model to analyze strategic planning of one-to-many distribution systems and have evaluated the effects of emissions costs. Their results suggest that a 50% reduction in emissions is possible.

4.7. Applications of the NAEI

The NAEI (Eq. 6) model was applied by Maden et al. (2010) who solved the vehicle routing and scheduling problem with the objective of minimizing the total travel time under congestion. The authors take into account regular congestion due to volume of traffic, and long-term road works, which can be predicted from historical data. Their results suggest that the proposed approach may yield CO_2 emissions savings of up to to 7%.

Urquhart et al. (2010b) have sought to identify traveling salesman tours with low CO_2 emissions. The authors examined two different fuel emission models: a power based instantaneous fuel consumption model (IFCM) and a simpler spreadsheet based model (NAEI). The authors have applied their algorithm to the latter model. Computational results on six randomly generated instances having between 10 and 30 delivery points suggest that only a small improvement can be achieved by using the fuel emission model because of the inadequacy of the emission model.

4.8. An application of the MOVES

The MOVES model was used by Wygonik and Goodchild (2011) who introduced the emissions minimization VRP (EVRPTW). The authors have modeled a specific case study involving a real fleet with specific operational characteristics and have analyzed different external policies and internal operational rules. Their results show a stable relationship between monetary cost and kilograms of CO_2 emissions: each kilogram of CO_2 yields a 3.5 dollars cost increase.

4.9. Applications of the COPERT

COPERT (Eq. 3) emission models have been widely used in different studies. The first study was conducted by Tavares et al. (2008), who looked at the optimization of routing networks for waste transportation. Their model takes into account both the road angle and the vehicle load. Their findings indicate that optimizing fuel consumption can yield savings of up to 52% in fuel when compared with minimizing distance. Another paper of Tavares et al. (2009) is concerned with the optimization of municipal solid waste collection routes to minimize fuel consumption using 3D GIS modeling. The results of this study suggest that the proposed approach reduces traveled distance by 29% and fuel consumption by 16%.

Scott et al. (2010) have studied the effect of topology and payload in the context of CO_2 optimized vehicle routing. They worked on two different data sets: delivery of groceries to households and delivery of paper from a central warehouse. They also worked on several traveling salesman instances randomly chosen from problem data sets, and assigned average speeds for each road category. Their results suggest that the effect of gradient and payload are highly dependent on the instances considered. The difference in CO_2 emissions between the instances was found to be less than 2.1% for the COPERT model.

Using COPERT models, Jovičić et al. (2010) have investigated the energy efficiency to estimate the potential for reduction of fuel consumption and thus CO_2 emissions through the optimization of solid waste collection. The authors show that in the City of Kragujevac in Serbia, savings of up to 20% can be achieved in costs and the associated emissions.

The PhD thesis of Qian (2012) studies fuel emission optimization in VRP with time-varying speeds. The author aims to generate routes and schedules for a fleet of heavy goods vehicles so as to minimize the emissions in a road network where travel speeds are time-dependent. Computational results obtained by the algorithm on a London case study suggest that 6–7% savings in fuel consumption may be achieved using the proposed approach.

4.10. An application of the IVE

Another eco-routing study was carried out by Kang et al. (2011) who used the IVE model to minimize fuel consumption and vehicle emissions. The authors sought to determine the vehicle specific power, which is derived from their vehicle routing and scheduling model. Their eco-routing approach may yield CO_2 emissions savings of up to to 18% compared to time minimization and by 8% compared to distance minimization.

4.11. Other applications

EMVRP: The energy-minimizing vehicle routing problem was introduced and formulated by Kara et al. (2007). The objective of the EMVRP is to minimize a weighted load function as a way of estimating fuel consumption. This function is based on a physics rule stating that on a flat surface work equals force times distance. The integer linear programming model proposed for the EMVRP is based on that of the capacitated VRP. Since the model minimizes the total work done on the road, the authors argue that this leads to minimizing the total energy requirements, at least in terms of total fuel consumption. They study the differences between distance-minimizing and energy-minimizing solutions on benchmark capacitated VRP instances from the literature and find that energy usage increases as total distance decreases. They conclude that there is a considerable difference between energy-minimizing and distance-minimizing solutions, and that the cost of routes minimizing total distance may be up to 13% less than those minimizing energy.

FCVRP: Xiao et al. (2012) studied the fuel consumption rate in the context of the capacitated VRP. To estimate fuel consumption, the authors use a regression model based on statistical data, proposed by the Ministry of Land, Infrastructure, Transport and Tourism of Japan. They present a mathematical model and apply a simulated annealing algorithm to solve the problem.

EVRP-VC: The emission minimization vehicle routing problem with vehicle classes were introduced by Kopfer et al. (2012). The model minimizes fuel consumption instead of driving distance by offering the possibility of using several types of vehicles. The authors compared their model to that of the traditional VRP. They replaced the distance minimizing objective function with an affine and piecewise linear fuel consumption function which considers payload. According to their results, a significant amount of reduction is possible through the use of a heterogeneous fleet of vehicles.

SOP: The speed optimization procedure (SOP) is a polynomial time exact algorithm and introduced by Demir et al. (2012). Given a vehicle route, the SOP consists of finding the optimal speed on each arc of the route between successive nodes so as to minimize an objective function comprising fuel consumption costs and driver wages. The objective of SOP is non-linear due to the function used to estimate the fuel consumption of a vehicle.

DSOP: The departure time and speed optimization procedure is an extension of SOP and was proposed by Franceschetti et al. (2013) to calculate the departure times from depot and customer sites while optimizing speeds on each arc of a given route.

5. Descriptive statistics

In this section, we present a statistical description of the growing body of literature on green transportation. The section is organized based on three indicators, namely the type of publication, the factors taken into account in estimating fuel consumption, and the reported savings.

5.1. Type of publication

We first analyze the number of manuscripts and categorize them according to publication type and year: journal articles (JA), conference proceedings (CP), technical reports (TR), and PhD theses (PT). The number of publications of each type is shown in Figure 3.

As can be seen from Figure 3, a total of 59 publications are associated with the reduction of fuel consumption in vehicle routing and scheduling. There is an indication of the increase of publications after 2009. The number of JA,

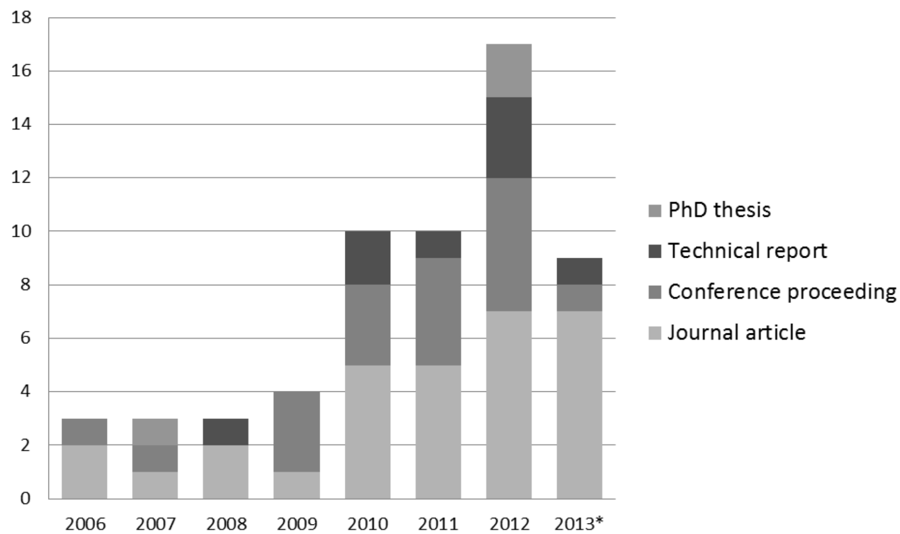

Figure 3
Number of papers per year until August 2013

CP, TR and PT publications are 30, 18, 8 and 3, respectively. The increase of publications is approximately 325% between 2009 and 2012.

5.2. Factors used in publications to estimate fuel consumption

In this section, we analyze publications based on the factors used in their research. Figure 4 illustrates the factors used in 50 publications reviewed in this paper. This figure is quite revealing in several ways. First, we see that most of the studies consider speed and load in their formulations. As discussed in Demir et al. (2012), speed has a significant effect in fuel consumption, and optimal speed could lead better reduction in terms of CO_2. Second, congestion is another important factor but only very few studies relate to congestion. Third, driver behavior and road gradient are mostly studied in eco-routing studies with the help of GIS softwares. Finally, fleet size and mix are attracting increasing attention due to the benefits of selecting the right type of vehicle. As discussed in Section 2, the total vehicle mass is directly related to the fuel consumption and any extra weight will lead more consumption.

5.3. CO_2e emissions savings

In this section, we analyze the CO_2e savings. These are grouped into four categories: Group I: 0–5,99%, Group II: 6–10.99%, Group III: 11-15.99%, and Group IV: higher than 16%. We provide a graph of savings in Figure 5. It is apparent from this figure that the actual savings are heavily dependent on the vehicle emission model used. To our knowledge, it is possible to achieve a 10%

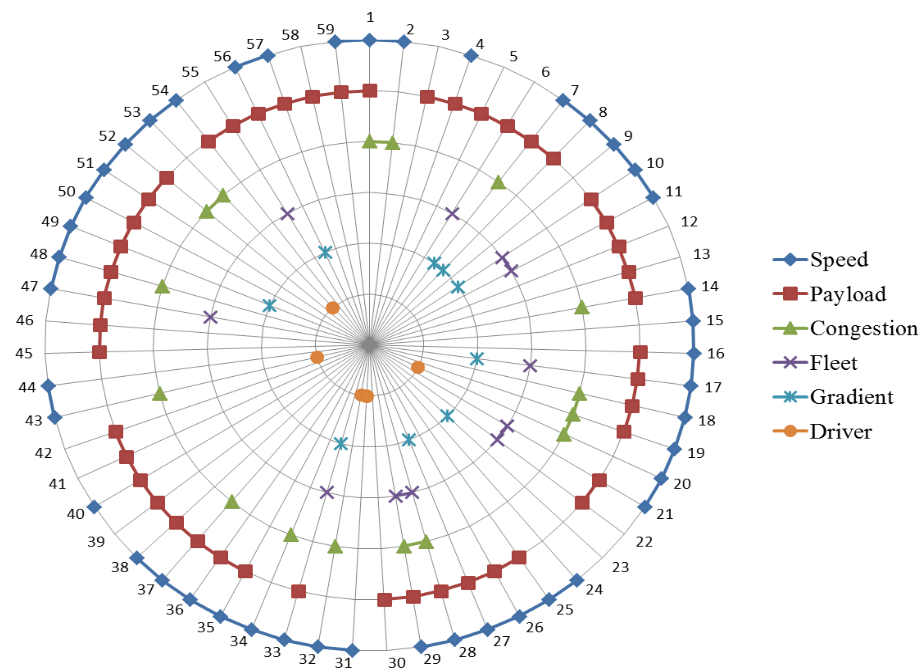

Figure 4
The analysis of publications

reduction in CO_2e emissions. However, the savings are related to the factors considered in the solution methodology.

Table 2 contains a summary of the publications reviewed in this paper. Since the topic has received attention from researchers of various backgrounds, this categorization can be very valuable to the research community. Most of the research on green road freight transportation has been carried in a relatively small number of areas. As can be seen from Table 2, most of the papers are supported by case studies, which indicates a well to ground the research in real-life applications. The most popular models are the COPERT at a macroscopic level and CMEM at a microscopic level.

6. Conclusions

There exists an increasing need for the use of fuel estimation models to reduce CO_2e emissions in vehicle routing and scheduling. In recent years, the number, quality and the availability of the available models have increased considerably. However, some gaps remain in the literature. Our research leads to the following four important conclusions:

- Most studies in the field of green road freight transportation have focused on a limited number of factors, mainly vehicle load and speed. We be-

Table 2
Literature on green road freight transportation

Reference	Publication type	Base problem	Mathematical model	Solution Approach	Case study	Emission model	CO_2e savings
1. Ando and Taniguchi (2006)	*JA*	$VRPTW-P$	✓	o, h		Factor	*II*
2. Ericsson et al. (2006)	*JA*	*Eco*		s		Factor	*II*
3. Christie and Satir (2006)	*CP*	*CVRP*		s		Factor	*IV*
4. Palmer (2007)	*PT*	*CVRP*		h	✓	IFCM	*I*
5. Kara et al. (2007)	*JA*	*CVRP*	✓	o		Factor	*III*
6. Faulin et al. (2007)	*CP*	*CVRP*		h	✓	Factor	*IV*
7. Kono et al. (2008)	*TR*	*Eco*		s		OFCM	*II*
8. Tavares et al. (2008)	*JA*	*Eco*		s	✓	COPERT	*IV*
9. Apaydin and Gonullu (2008)	*JA*	*Eco*		s	✓	Factor	*IV*
10. Tavares et al. (2009)	*JA*	*Eco*		s	✓	COPERT	*III*
11. Kim et al. (2009)	*CP*	*VRPTW*	✓	o	✓	MEET	*I*
12. Chalkias and Lasaridi (2009)	*CP*	*Eco*		s	✓	Factor	*I*
13. Yong and Xiaofeng (2009)	*CP*	*CVRP*	✓	h		Factor	*I*
14. Maden et al. (2010)	*JA*	*VRPTW*	✓	h	✓	NAEI	*II*
15. Urquhart et al. (2010a)	*TR*	*TSP*		h	✓	IFCM	*II*
16. Urquhart et al. (2010b)	*CP*	*CVRP*		h		NAEI	*I*
17. Scott et al. (2010)	*CP*	*Eco*		s	✓	COPERT	*III*
18. Kuo (2010)	*JA*	*VRPTW*		h	✓	Factor	*IV*
19. Figliozzi (2010)	*JA*	*CVRP*	✓	o	✓	MEET	*IV*
20. Correia et al. (2010)	*TR*	*Eco*		s	✓	OFCM	*IV*
21. Jovičić et al. (2010)	*JA*	*Eco*		s	✓	COPERT	*IV*
22. Pan et al. (2010)	*JA*	*SCD*	✓	o	✓	MEET	*IV*
23. Hao (2010)	*CP*	*VRP*	✓	o		Factor	*I*
24. Kuo and Wang (2011)	*JA*	*CVRP*		h	✓	Factor	*II*
25. Figliozzi (2011)	*JA*	*VRPTW*	✓	h	✓	MEET	*I*
26. Bektaş and Laporte (2011)	*JA*	*VRPTW*	✓	o		CMEM	*II*
27. Suzuki (2011)	*JA*	*TSPTW*	✓	o	✓	Factor	*II*
28. Pitera et al. (2011)	*CP*	*VRPTW*	✓	h	✓	Factor	*IV*
29. Goodchild (2011)	*TR*	*VRPB*	✓	h	✓	Factor	*IV*
30. Ubeda et al. (2011)	*JA*	*VRPB*	✓	o		Factor	*IV*
31. Kang et al. (2011)	*CP*	*Eco*		s	✓	IVE	*I*
32. Minett et al. (2011)	*CP*	*Eco*		s	✓	CPFEM	*IV*
33. Wygonik and Goodchild (2011)	*CP*	*VRPTW*		s	✓	MOVES	*I*
34. Qian (2012)	*PT*	*CVRP*		h	✓	COPERT	*II*
35. Demir (2012)	*PT*	*VRPTW*	✓	o, h		CMEM	*II*
36. Xiao et al. (2012)	*JA*	*CVRP*	✓	h	✓	Factor	*I*
37. Jabali et al. (2012)	*JA*	*VRPTW*	✓	h		MEET	*II*
38. Demir et al. (2012)	*JA*	*VRPTW*	✓	o, h		CMEM	*II*
39. Jemai et al. (2012)	*CP*	*CVRP*		h	✓	Factor	*I*
40. Treitl et al. (2012)	*JA*	*IRP*	✓	o	✓	Factor	*IV*
41. Aranda et al. (2012)	*JA*	*Eco*		s		Factor	*I*
42. Chen and Chen (2012)	*TR*	*VRPPD*		s		Factor	*IV*
43. Bandeira et al. (2012)	*CP*	*Eco*		s		VSP	*III*
44. Omidvar and Tavakkoli-Moghaddam (2012)	*CP*	*CVRP*	✓	h		MEET	*I*
45. Huang et al. (2012)	*CP*	*VRPPD*	✓	o		Factor	*I*
46. Ramos et al. (2012)	*TR*	*MDVRP*		o	✓	CMEM	*IV*
47. Kopfer et al. (2012)	*TR*	*HVRP*	✓	o, h	✓	Factor	*IV*
48. Saberi and Verbas (2012)	*JA*	*TDVRP*		h		MEET	*IV*
49. Rao et al. (2012)	*CP*	*CVRP*	✓	o, h		CMEM	*I*
50. Li (2012)	*JA*	*VRPTW*	✓	o,h		Factor	*IV*
51. Paksoy and Özceylan (2013)	*JA*	*SCD*	✓	o		Factor	*IV*
52. Franceschetti et al. (2013)	*TR*	*TDVRP*	✓	o		CMEM	*IV*
53. Bandeira et al. (2013)	*JA*	*Eco*		s	✓	VSP	*III*
54. Peiying et al. (2013)	*CP*	*VRPPD*	✓	s		CMEM	*I*
55. Kwon et al. (2013)	*JA*	*HVRP*	✓	h		Factor	*IV*
56. Oberscheider et al. (2013)	*JA*	*MDVRPPDTW*	✓	o,h	✓	Factor	*II*
57. Pradenas et al. (2013)	*JA*	*VRPBTW*	✓	o		CMEM	*II*
58. Gaur et al. (2013)	*JA*	*CumVRP*		o, h		Factor	
59. Demir et al. (2013)	*JA*	*VRPTW*	✓	h		CMEM	*II*

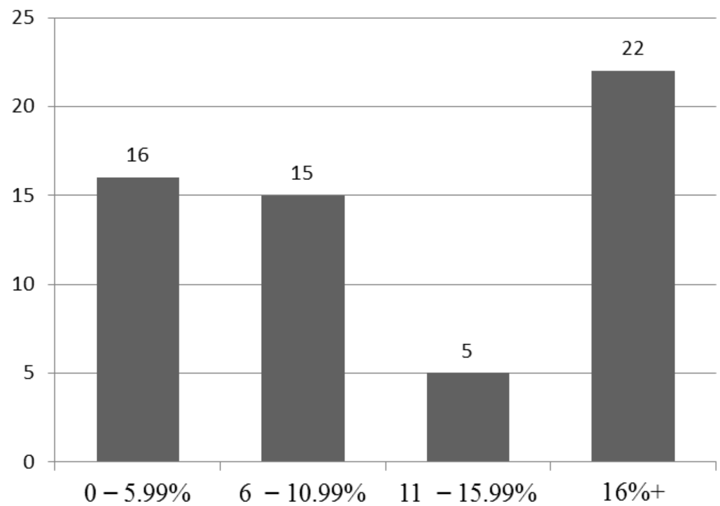

Figure 5
Savings in terms of CO_2e

lieve that other factors such as road gradient, and congestion could be incorporated in several models.

- The studies should focus on the selection of appropriate emission tools and standardize them. Our findings show that the COPERT and CMEM models serve different purposes and greatly depend on the availability of data.
- To our knowledge, CO_2e emissions can be reduced up to 10% under rather basic assumptions and using simple models. This could be achieved by controlling vehicle speed or sequence customers optimally in vehicle routes. Moreover, with the help of GPS more savings could be achieved by traveling in green corridors.
- Besides CO_2e emissions, other traffic externalities could be examined at the local and regional levels, such as other pollutants, noise, accidents, and environmental damage.

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