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Micro and Macro modelling approaches for the evaluation of the carbon impacts of transportation

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Abstract

To quantify CO_2 emissions from road transport, literature suggests the adoption of several alternative methods, based on transport modelling and carbon modules. Some of these methods are labelled as a micro approach and others as a macro approach. Their distinction is made according to the temporal and spatial horizons, the aim of the study and the degree of accuracy required. This paper presents these methods and discusses their appropriateness, whereby special focus is laid on the potential of the micro approach on ICT, based on a literature review of several European projects. We conclude that the adoption of the micro approach, is quite promising – mostly at the urban level, despite the computational efforts required and the technical difficulties to model driver behaviors. Thus, further research is required to overcome the numerous sources of scientific uncertainties.

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1. Introduction

Europe is particularly sensitive to environmental issues, not only limiting its commitment to GHG reduction fixed at the international level but also elaborating its own continental strategy. The program "20-20-20" (EU, 2012) imposes a decrease of emissions by 20% by 2020. It has been integrated with the "2030 initiative", which aims at reducing the GHG production by 40% within 2030 (EC, 2015). Results of these policies are encouraging: many sectors (e.g., agriculture, industry, buildings) have obtained relevant results, with an almost generalized reduction of GHG. However, this reduction is not visible in transport, which is the only sector in countertrend, showing a GHG emission increase by about 22% in comparison to 1990 (EU, 2014).

This growth is mostly due to the road sector, which accounts for approximately 93% of the total transport GHG emissions (Eurostat, 2009). Huge policy efforts are addressed at minimizing the environmental impacts of the majority of emissions from road transport, particularly carbon dioxide (CO_2), one of the biggest by-products of engine combustion. Different factors affect pollutant emissions from motor vehicles, including travel, driver, facility, vehicle, fuel and overall environmental characteristics (Sinha and Labi, 2007). Travel-related factors include vehicle engine

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operating modes or temperatures (cold and hot starts, hot stabilized periods), speeds, accelerations and decelerations. Significant impacts on emission levels are also influenced by those driver behaviors causing speed variations in response to specific traffic conditions, vehicle and fuel types, thus imposing heavy loads on the engine. Facility-related factors, which include infrastructure engineering features and traffic signals, are supposed to encourage low-emitting speeds or operating modes. Emission rates further depend on vehicle-related factors such as vehicle ages, mileages, maintenance conditions, weights, sizes, engine powers, fuel delivery systems, emission control systems. Furthermore, environmental factors (air temperature, altitude, humidity) play an important role in affecting the emissions.

Based on the previously described elements, a number of analytical approaches for evaluating emissions have been developed for the "macro" and the "micro" scale. The choice between different models raises formidable methodological tasks, as the scale affects the appropriateness of the results. To analyze the distributional impact of macro modelling it is necessary to understand how changes at the macro level affect carbon production. However, microeconomic evidence suggests that this approach may fail for the importance of individual heterogeneity and decisions taken at the individual level for traffic and modal split outcomes (the so-called "individual behavior").

This paper describes the two methodologies that can be adopted to quantify CO_2 emissions, highlighting their area of application as well as their pros and cons. Our intention is to demonstrate that both appraoches face inherent limitation, including some assumptions (car ownership model, administrative policies, transit performance, etc.) that have not necessarily been adjusted. Only when such an approach is further developed, it may be effectively used for choosing the right perspective on the analysis of CO_2 and for obtaining right policy decisions. This analysis could integrate the results of our previous works, where a methodology to deal with the theme of CO_2 emissions and its quantification (Cavallaro et al., 2013), its economic valuation (Nocera and Tonin, 2014; Nocera and Cavallaro, 2014a; Nocera et al., 2015a) and its inclusion into mobility plans (Nocera et al., 2015b) have been provided at the macro scale. A thorough analysis of both approaches contributes to the reduction of the vast scientific uncertainties found in the literature.

The paper is structured as follows: section two provides a description of the macro and micro approaches adopted to determine transport demand and CO_2 emissions. Section three shows the implications of a micro evaluation applied to a specific field (ICT road technology). Finally, section four ends the contribution with a discussion about the transport implications, as well as the pros and cons deriving from the adoption of the two approaches.

2. Micro and Macro Approaches in transport demand and CO_2 emissions

Dealing with the modelling of CO_2 from transport requires the adoption of a two-step process, based on the provision of the travel demand and the calculation of its related fuel consumptions and emissions. The link between these two modules could be obtained by adopting different approaches, according to the geographical scale, the temporal horizon, the drivers' behavior and the simplifications decided by the modelers. Samaras et al. (2012) propose a division of the methods into the macro and micro scale. In the next sub-sections, the characteristics of the two approaches are presented for both transport modelling (section 2.1) and for CO_2 emission modules (section 2.2).

2.1 Transport models

Transport models aim at providing policy-makers with the adequate tools to solve planning issues by determining the travel demand, origins and destinations of the journeys. According to the temporal and the spatial scale considered, several models can be used. Linton et al. (2015) propose to include each model into one of six main groups, namely: traffic network models, behavioral models, agent-based modelling, system dynamics modelling, techno-economic and integrated assessment models (see also table 1). They are ordered ascending from the micro to the macro scale and descending according to the degree of accuracy.

Traffic network models, *behavioral models*, *agent-based models* can be considered as micro approaches, as they disaggregate travel demand according to the individual movements and choices. These methods are based on microsimulations that determine how the vehicles interact in a predefined traffic condition and predict traffic flows. In some cases, they even include travel behaviors. They present a high degree of accuracy: in many cases, the road network and traffic condition are modelled starting from the real condition, without adopting simplifications.

Particularly, in activity-based models (e.g., MATSim; Balmer et al., 2008) travel is seen as a result of activities and all agents. Their movements have to be considered accordingly. This requires a high degree of detail, making the computation in many cases complex and their use mostly suitable for short temporal horizons and limited areas (from the single intersection to the urban scale), even if broader temporal and spatial analyses are also provided. Behavioral models (Cappelli and Nocera, 2006; UK DfT, 2011) include an analysis of the travel behaviors, which consider the motivations and the constraints affecting the decisions of the single user.

System dynamic model is at an intermediate scale, which adopts both qualitative and quantitative techniques to assess the future transport demand (Shepherd, 2014). These methods are based on a general condition modelled through a macroeconomic module, which is further specified by a regional economic and a transport module. ASTRA (Rothengatter et al., 2000) is an example of this method, which works well at the regional scale and can be integrated into a specific environmental module that allows the calculation of GHG emissions. The details of these models are often overlooked, even if attempts to include them in a more accurate way are under development.

Finally, *Techno-economic* and *Impact Assessment Models* (IAMs) are representative for the macro approach. These models take into consideration the relationship between technology, economy and society and are used as a support for the formulation of global, national and international policies, with a temporal horizon up to the year 2100 (Ortiz and Markandya, 2009). Transport is considered as one of the subsectors of the economy and is not modelled directly. Indeed, aggregate projections are provided, as well as an economic assessment of impacts caused by CO_2 emissions.

2.2 CO_2 emission models

The factors that affect fuel consumption can be grouped into four main categories: vehicle (total vehicle mass, engine size, engine temperature, oil viscosity, gasoline type, vehicle shape, degree of use of auxiliary electric devices), environmental conditions (roadway gradient, wind conditions, ambient temperature, altitude, pavement type, surface conditions), traffic conditions (speed and acceleration), driver behaviour. According to the considered factors, it is possible to distinguish between the micro and the macro approaches. The former uses average emission factors, kilometres travelled per average speed and average slope gradient of a series of different vehicle types to calculate the amount of emission per link unit (Coelho et al., 2014). The latter considers the fuel consumption, stops, speed, acceleration, deceleration and engine power of the individual vehicle to model the instantaneous consumptions.

Several authors (Esteves-Booth et al., 2002; Boulter et al., 2007; Demir et al., 2011) classify the emission models according to the variables considered. Esteves-Booth et al. (2002) divide existing types of vehicular emission models for hot, cold start and evaporative emissions into three main groups, namely: emission factors models, average speed models and modal models. Due to the high level of complexity, the first two groups can be associated with the macro approach, whereas the third group belongs to the micro approach.

Boulter et al. (2007) provide an alternative and more detailed classification, valid mostly for Light Duty Vehicles (LDVs) but extendable also to Heavy Goods Vehicles (HGVs). At the **macro level**, several methods can be adopted. The simplest approach is based on *aggregated emission factors*, which provide a value (usually expressed in g/km) for a vehicle type according to the different conditions (urban, rural, highways). Due to the large oversimplifications, this approach can be suitable for the (inter)national and regional scale.

Based on a similar approach, *traffic situation models* express the estimations by the use of emission factors related to one vehicle type and a specific driving mode, as for instance urban, rural or motorway. Emission factors are extracted from real-life situations, derived from the mean values of repeated measurements over a particular driving cycle and expressed in mass of pollutant per-unit-distance. These models provide different values according to a set of factors, from which the modellers can choose. For example, the Handbook Emission Factors for Road Transport (HBEFA; INFRAS, 2014) is one of the models belonging to this group. Different types of vehicle are considered: cars, LDVs, HGVs, coaches, busses and motorcycles. Each of them is characterised according to its size, load, fuelling (petrol and diesel) and Euro class (from Euro 0 to Euro 6). Emissions vary according to the area (urban, rural), the type of road (motorway, primary, secondary, local, access), the level of service (free flow, heavy, saturated, stop and go) and road gradient (classes between -6% and +6%). This method is particularly suitable for the macro scale (Nocera and Cavallaro, 2016a), such as the development of national and regional emission inventories, but it also could be used at the local level (Nocera and Cavallaro, 2016b).

Average speed models are based on speed-related emission functions, generated by the measurement of the emission rates over a variety of trips at different speed levels. Similarly to the previous models, their use at a macro scale is preferable. In fact, they do not include changes in operational modes or multimodal evaluations. These models are among the most adopted due to the easy use, yet they entail some problems: the same average speed can be obtained through very different vehicle operations (mostly at low speeds) and the spatial resolution is not adequately taken into account. An example of a program belonging to this group is the computer programme to calculate emissions from road transportation (COPERT; Ntziachristos and Samaras, 2000). COPERT provides an estimation of emissions for all major air pollutants as well as GHGs produced by various vehicle categories ranging from passenger cars to HGVs. Differently from the emission factor models, COPERT includes two speed ranges in its analysis. However, road gradient and acceleration are not considered.

Adjusted average speed models are similar, but they include a correction factor that is a function of the congestion.

Finally, *multiple linear regression models* calculate emissions through a weighted-least-squares multiple regression of tests with different driving cycles, characterized by several parameters. However, this method is only used in a limited number of studies due to the large preliminary information required as input.

The **micro-level** models operate at a higher level of complexity. They provide a more accurate fuel consumption and emission estimation, for a particular vehicle type for any given driving cycle. Such models include different levels of speed and various operational modes or driving cycles (acceleration, deceleration, steady-speed cruise and idle), but also significant variables such as the engine power and the road gradient.

Simple modal models are the less accurate among the micro approaches as they are based on a subdivision of the journey according to the different transport modes. For each of them, the time on board is calculated and multiplied by the specific emissions.

The main group of micro models is composed by the *instantaneous models*, which assess the fuel consumption and emissions according to short time steps (typically one second) and to a large operation profiles. Referring to the fuel consumption, Demir et al. (2011) further divide this group into *instantaneous fuel consumption models*, *four-mode elemental fuel consumption models*, *running speed fuel consumption models* and *comprehensive modal emission models*. Subsequently, CO_2 emissions can be calculated by considering the specific emission factors of the different fuels. *Instantaneous fuel consumption models* consider the power required or the fuel consumption per second by a vehicle. They take into account vehicle characteristics such as mass, energy, efficiency parameters, drag force, rolling resistance, acceleration, deceleration, cruise, idle phase and fuel consumptions components. They are better suited for short trip emission estimations of individual vehicles, but they should be extremely accurate in providing second-by-second results, otherwise the benefits of this approach are lost. The problem related to this method lies in the expensiveness of data collection, which makes its adoption limited. *Four-mode elemental fuel consumption models* predict the amount of fuel consumption for idle, cruise, acceleration and deceleration modes, which are specifically assessed by independent functions. The model considers an independent function for each phase and considers several parameters such as initial speed, final speed, energy, distance, cruise speed, idle time and average road grade. For this reason, the computation is rather complex and accurate data is required. *Running speed fuel consumption models* represent an aggregated form in order to estimate fuel consumption during periods when a vehicle is running and is in an idle mode. These models are regarded as being more suitable for estimations in long distance trips. Finally, *comprehensive modal emission models* take specifically into account engine power, engine speed and fuel rate. Similar to instantaneous fuel consumption models, they are nevertheless based on detailed vehicle-specific parameters, as for instance the engine friction coefficient.

To sum up, measuring the emissions from road traffic is an operation that can be carried out according to both a macro and to a micro approach, by selecting the most appropriate transport and emission models (table 1). The differences among the two approaches usually refer to the geographical scale of application and the level of detail in data collection. Macro models are suitable for large spatial scales (i.e. national or regional), where little detail on flows and vehicle operations is needed. Although easier in terms of data collection and management, they are nonetheless characterized by a number of disadvantages when more details are required. For these reasons, micro models are preferred when predicting emissions at a smaller spatial scale. Specifically, they relate the modes of vehicle operation encountered on a given trip to the emissions produced during those modes, and may also take into account engine power, congestion, road gradient and travel behavior. However, the volume of data required and the level of complexity in data management is sometimes an obstacle to the use of such models and an accurate preliminary evaluation of the economic and modelling availability is required.

Table 1. Classification of traffic and CO_2 emission models. Source: own elaboration based on Esteves-Booth et al. (2002), Boulter et al. (2007), Demir et al. (2011), Linton et al. (2015).

Traffic models				
Scale	*Group*	*Description*	*Characteristics*	*Example*
Macro	Techno-economic models	Based on socio-economic, energy and environmental modules. Transport as one of the subsectors included, but not directly modelled.	Easy computation (based on vehicle-km). Top-down approach, integrated with other fields. Global and (inter)national long-term policies.	WEPS+
	Integrated Assessment Models	Based on GDP, population and socio-economic variables to determine the future travel demand. Transport is not directly modelled.	General approach, integrated with economic and environmental modules. Global, (inter)national and regional long-term policies.	PECE
	System dynamic models	Based on casual loop diagrams that simulate stocks and flows. Quantitative and qualitative approach.	Versatile, but alternatives are difficultly comparable. Regional and urban dimension, medium- and long-term scale taken into account.	ASTRA
Micro	Traffic network models	Different scales; among them, microsimulation of a specific network (from the single intersection to an urban area), based on a four-step model.	Good level of accuracy and versatile approach. Complexity of computation (real-world model). Multi-scale (macro and micro) and short-medium term taken into account.	VISSIM
	Behavioral models	Assessment of travel behaviors (motivations and constraints) to understand the mobility needs. Based on social psychology and behavioral economic.	Good level of accuracy (individual choices). Limited multi-scale and temporal analysis (short temporal horizon and limited area).	ARCHISIM
	Agent-based models	Definition of travel demand by tracing the daily schedule and the travelers' decisions. Modelling of the environment and interactions between agents.	Bottom-up approach with a high level of accuracy. High complexity of computation. Multi-scale -from local to (inter)national level- and multi-temporal analysis.	MATSim
CO_2 emission models				
Scale	*Group*	*Description*	*Characteristics*	*Example*
Macro	Aggregated emission factors	A unique value represents a type vehicle and a type of driving (urban, rural, motorways). Input: road type.	Easy computation, adoption in several contexts (e.g., inventory, environmental impact assessment). (Over)simplified approach.	NAEI
	Average speed models	Based on the principle that average emissions are a function of speed. Input: average speed.	Easy computation and adoption in several contexts (e.g., inventory, dispersion modelling). General approach.	COPERT
	Adjusted average speed models	Similar to average speed models, but considering also congestion as a correcting factor. Input: average speed, congestion.	Easy computation and adoption in several contexts (e.g., inventory, dispersion modelling). General approach.	TEE
	Traffic situation (emission factor) models	Based on national road measurements. Different type vehicles (according to the size, load, Euro classes), characteristics of the area, type of road, level of service, road gradient taken into account.	Good level of accuracy, national specifications. Adoption in several contexts (e.g., inventory, environmental impact assessment, dispersion modelling, urban traffic schemes).	HBEFA
	Multiple linear regression models	Emissions are calculated through a weighted-least-squares multiple regression of tests with different driving cycles. Input: driving pattern.	Good level of accuracy and adoption in several contexts (e.g., inventory, dispersion modelling). Complexity of computation.	VERSIT+
Micro	Simple modal models	Each transport mode has its own specific emission; total emissions are given as a sum of the different modes. Input: driving modes.	Easy computation. General approach (used for the evaluation of specific measures or urban traffic management).	UROPOL
	Instantaneous fuel consumption models	Emissions (derived from the fuel consumption per second) are measured from mass, energy, efficiency, fuel consumption, drag and rolling resistance. Input: driving pattern.	Good level of accuracy. Limited multi-scale and temporal analysis (mostly for short trip emission estimations of individual vehicles). Complexity of computation, expensive data collection.	DGV
	Four-mode elemental fuel consumption models	Model that includes acceleration, deceleration, cruise and idle phases. Difficultly implementable due to a large number of functions. Input: driving pattern.	Very good level of accuracy, both for short and long trips. Very high complexity of computation and expensive data collection.	SIDRA-TRIP
	Running speed fuel consumption models	Acceleration, deceleration and cruise are considered together in a single function. Idle is not considered. Input: driving pattern.	Good level of accuracy (short and, mostly, long distance trips). Quite complexity of computation and expensive data collection.	MODEM

	Comprehensive modal emission models	Models considering engine power, engine speed and fuel rate. Similar to instantaneous fuel consumption models, but with vehicle-specific parameters. Input: driving pattern.	Good level of accuracy. High complexity of computation (specific parameters of each vehicle are required).	MOVES

3. A field of application of Micro Modelling Approaches: ICT measures

Due to the global scale of CO_2 emissions, the use of the macro modelling approach is well established. However, micro modelling can represent an adequate scale for specific topics, such as the information and communications technologies (ICTs) and the Intelligent Transport Systems (ITS; EU, 2010). Micro models can be applied to road traffic, in addition to a set of integrated measures such as the introduction of fuel-efficient technologies or new fuels, thus determining significant impacts on the energy consumption and the reduction of CO_2 emissions (EC, 2009).

A full assessment of ICT related impacts is a challenging task, because the mechanisms through which ICT solutions affect CO_2 emissions depend on the vehicle fleet and technology, the mean speed and the speed variation. Any evaluation has to take into account the real-world driving patterns of the single vehicles and the drivers' behaviors and decisions, which affect the nature of the transport demand itself, the modal split, the route choice, the trip timing, the quantities and types of vehicles using the overall transport network (Samaras et al., 2012).

Klunder et al. (2009) reviewed the models that are suitable to evaluate the impacts of three classes of ICT-related measures (eco-solutions, traffic management, Advanced Driver Assistance Systems, ADAS) on road traffic CO_2 emissions. At the macro level, CO_2 emission models based on traffic situations are used to assess the effects of traffic management measures on traffic intensity. An example is the ARTEMIS model (Andrè et al., 2008), adopted for the evaluation of the Stockholm congestion charge. A sufficiently large variety of traffic situations –necessary to ensure a proper validation– is still lacking, although the extension of micro models might provide the possibility to import different traffic situations. The evaluation of the effects deriving from the traffic management measures is also possible with instantaneous emission models combined with microscopic traffic simulations.

A number of studies have been launched simultaneously over the last years in Europe with the aim to develop standardized micro-scale methodologies to evaluate the impacts of the ITSs on traffic, vehicle energy saving and CO_2 emissions. EC-METI (2009) and Klunder et al. (2009) state the importance of micro modelling approaches in the assessment of these measures. Indeed, generic parameters typical of macro simulations –the composition of the vehicle stock, traffic flow (vehicles per hour), traffic density (vehicles per kilometer), average speed and predefined trip assignment rules, trip times and standard driving cycles– are in most cases inadequate. Compared to macro models, microsimulations take into consideration the movements and operations of individual vehicles (speed and acceleration), which are dynamically predicted in real-time using models of driver behavior such as car-following, gap acceptance, lane-changing and signal behavior theories, the prime focus of most ICT measures.

As measures such as ADAS or eco-driving influence the driving dynamics of the single vehicle, more detailed emission models are suitable to evaluate their consequences effectively. Recalling the taxonomy of section 2, traffic micro simulations and real-world driving data (GPS) provide datasets of emission fields from single vehicles – based on speed and acceleration – on which these emission models are based. For example, the VERSIT+ micro model has been adopted for the assessment of Adaptive Cruise Control's effects (ACC) on the fuel consumption in the TRANSUMO IV project, with real-world time speed transients recorded through GPS data. VETO and VeTESS models have been used in Lund (Sweden) for the assessment of the effects of a fuel-optimized navigation tool on the fuel consumption. In this case, time-speed transients of single vehicles are derived from digitalized routes from the navigation system, extracted from a database of real traffic driving patterns connected to the street network. More detailed emission models, such as engine power demand and vehicle design models (PHEM, ADVISOR and ADVANCE) are needed for the assessment of eco-solutions, which are directly supposed to interfere with the drive-train characteristics of vehicles and/or the driving behavior. The ADVANCE model, for instance, was used to evaluate the power train derived from the conversion of a Volkswagen New Beetle into a hybrid vehicle.

Samaras et al. (2012) developed an integrated methodology that can be used to quantify the impacts of various ICT solutions for road transport CO_2 emissions at two inter-linked levels, thus combining benefits from both micro and macro modelling. Firstly, it designs and develops some new modules and interfaces to link existing traffic and emission models at the micro-scale (real-world driving pattern and traffic behavior of passenger cars and instantaneous emission models). Secondly, it extrapolates these detailed results to a larger aggregated scale using a macro traffic approach, including all passenger road transport modes. The total CO_2 emissions from road transport are then calculated by all vehicles using traffic situation and/or average speed specific emission factors for other road transport vehicles. In addition, such methodology intends to develop vehicle simulators to calculate the energy and CO_2 emissions of vehicles when operating in ICT regimes, also considering advanced vehicle technologies.

4. Conclusions and future research patterns

The purpose of this paper was to discuss the effectiveness of the micro and macro modelling approaches in dealing with CO_2 emission in different transport conditions. A number of methods have been presented, regarding traffic, fuel consumption and CO_2 modules. On the one hand, the macro-scale approach allows to understand the decisions necessary to mitigate CO_2 emissions at the global scale, yet the specific contribution of each field is not accurately provided. On the other hand, micro-scale tools model vehicle interactions. Here, the potential of CO_2 emission scheming is not univocal, as greater disaggregation generates more data, and the huge uncertainty affecting carbon decisions in transport may make this approach tricky. Despite their theoretical soundness, only a few of them are up-to-date and based on a reasonably large dataset (Samaras et al., 2012), thus requiring a constant revision of the input values deriving from the technological development. Furthermore, according to the current knowledge, traffic behavior (including detailed changes in driving style and conditions) can be simulated only partially.

The main challenges of the traffic models that still need to be addressed are the following:

- The uncertainty in estimating the driver's behavior and the decisions relating to the choice of mode, route and transport time in response to ICT measures, traffic management, infrastructure and external characteristics;
- The uncertainty caused by engines in response to driver behaviors and infrastructure characteristics;
- The need to simulate accurate time-speed profiles in order to ensure accurate input for the emission models;
- The sensitivity by which models can address the impact of ICT measures;
- The extrapolation of results from the micro to the macro scale.

As for the energy consumption and emission models, challenging factors to be addressed are the following:

- The rather limited number of vehicles and technologies on which models are often based (lack of experimental data on real-world emissions and representative results for certain vehicle categories);
- The consideration of few average driving cycles, which represent traffic conditions and driving behavior;
- The difficulty in determining a validated link between driver behavior and engine/vehicle response;
- The lack of a consolidated interface (appropriate scales and parameters) between traffic and emission models.

Finally, it has to be considered that the application of the two models is performed in a "sequential" logic, with the traffic models simulating the driving condition subsequently introduced in the emission models.

Further developments are important for the validation of the models: on the one hand, to understand driving patterns from micro simulations or real-world measurements; on the other hand, to extrapolate the results to a higher scale without losing too much accuracy. In this sense, mixed-techniques are promising (Maheshwari et al., 2015; Zhou et al., 2015), even if the transition between the two modelling forms should be defined more precisely.

Policymakers must be aware that each modelling approach implies some initial assumptions and limitations. The accuracy in capturing the emissions depends on the correct representation of the transport system and the scale of the analysis. Section 2 has highlighted where the micro-scale simulation may outperform a purely macro-scale approach, and how the latter can be adjusted to improve its effectiveness. Since the travel demand can vary and the technology patterns may not be forecasted effectively, knowing advantages and disadvantages of both schemes in advance is imperative to optimally choose if and how one technique can best simulate emissions while minimizing operator costs. This is mostly valid at the urban level, where the transport sector accounts for about 40% of the overall CO_2 emissions (Glaeser and Kahn, 2010). In such context, policymakers have to address global warming issues operatively, through the most adequate forms of modelling that support their decisions. Coherently, transport modelling is often adopted as a support tool in the definition of mobility plans. However, this approach is rarely extended to the evaluation of CO_2 emissions, thus determining an ancillary role of the carbon issues, which may affect the appropriateness of the decisions made (Nocera and Cavallaro, 2014b). To reach this aim, both the micro and the macro methods can provide transport planners with some insights on the precise details of traffic demand and CO_2 emissions, according to the nature and the scale of the study. The potential of these results has to be better understood by policy makers, making it a cultural rather than a technical challenge, and developing the idea that the consequences of a worldwide issue like global warming are manageable also through local decisions.

References

Andrè, M., Keller, M., Sjödin, Å, Gadrat, M., Mc Crae, I., Dilara, P., 2008. The Artemis European tools for estimating the transport pollutant emissions. Online at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.523.4881&rep=rep1&type=pdf [14.02.2016].

Balmer, M., Meister, K., Rieser, M., Nagel, K., Axhausen, K.W., 2008. Agent-based simulation of travel demand: Structure and computational performance of MATSim-T, 2nd TRB Conference on Innovations in Travel Modeling, Portland, June 2008.

Boulter, P.G., Mc Crae, I.S., Barlow, T.J., 2007. A review of instantaneous emission models for road vehicles. Online at: http://docs.niwa.co.nz/library/public/PPR267.pdf [14.02.2016].

Cappelli, A., Nocera, S., 2006. Freight modal split models: Data base, calibration problem and urban application (2006), WIT Transactions on the Built Environment, 89, pp. 369-375.

Cavallaro, F., Maino, F., Morelli, V., 2013. A new method for forecasting CO_2 operation emissions along an infrastructure corridor. European Transport \ Trasporti Europei, Issue 55, Paper n° 4, ISSN 1825-3997.

Coelho, M.C., Fontes, T., Bandeira, J.M., Pereira, S.R., Tchepel, O., Dias, D., Sá, E., Amorim, J.H., Borrego, C., 2014. Assessment of potential improvements on regional air quality modelling related with implementation of a detailed methodology for traffic emission estimation. Science of the Total Environment 470-471, 127-137.

Demir, E., Bektaş, T., Lavorate, G., 2011. A comparative analysis of several vehicle emission models for road freight transportation. Transportation Research Part D, 16, 347-357.

EC, European Commission, 2009. Mobilising Information and Communications Technologies to facilitate the transition to an energy-efficient, low-carbon economy. Online at: http://ec.europa.eu/information_society/activities/sustainable_growth/docs/recommendation_d_vista.pdf [26.02.2016].

EC, European Commission, 2015. 2030 framework for climate and energy policies. Online at: http://ec.europa.eu/clima/policies/2030/index_en.htm [26.02.2016].

EC-METI task force, 2009. Methodologies for assessing the impact of ITS applications on CO_2 emissions. Online at: http://www.transport-intelligent.net/IMG/pdf/ecmetiMethodologiesImpactITSApplications.pdf. [26.02.2016].

Esteves-Booth, A., Muneer, T., Kubie, J., Kirby, H., 2002. A review of vehicular emission models and driving cycles. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, vol. 216 n. 8, 777-797.

EU, European Union, 2010. Directive 2010/40/EU of the European Parliament and of the Council. Online at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010L0040 [26.02.2016].

EU, European Union, 2012. Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage. Online at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:0265:FIN:EN:PDF [26.02.2016].

EU, European Union, 2014. EU energy in figures, Statistical Pocketbook 2014. Luxembourg: Publications Office of the European Union.

Eurostat, 2009. Panorama of Transport. Online at:http://ec.europa.eu/Eurostat/documents/3217494/5711595/KS-DA-09-001-EN.PDF/9c90d489-5009-4acc-9810-ae39612897d3?version=1.0. [26.02.2016].

Glaeser, E. L., Kahn, M. E., 2010. The greenness of cities: Carbon dioxide emissions and urban development. Journal of Urban Economics, 67(3), 404-418.

INFRAS, 2014. The Handbook Emission Factors for Road Transport (HBEFA). Online at: http://www.hbefa.net [25.02.2015].

Klunder, G.A., Malone, K., Mak, J., Wilmink, I.R., Schirokoff, A., Sihvola, N., Holmén, C., Berger, A., De Lange, R., Roeterdink, W., Kosmatopoulos, E., 2009. Impact of Information and Communication Technologies on Energy Efficiency in Road Transport – Final Report. Online at: http://repository.tudelft.nl/view/tno/uuid%3A2a2c6c59-0ddd-4a93-91b2-0ca7d363918c/ [26.02.2016].

Linton, C., Grant-Muller, S., Gale, W., 2015. Approaches and Techniques for Modelling CO_2 Emissions from Road Transport. Transport Reviews, 35:4, 533-553.

Maheshwari, P., Kachroo, P., Paz, A., Khaddar, R., 2015. Development of control models for the planning of sustainable transportation systems. Transportation Research Part C: Emerging Technologies, 55, 474-485.

Nocera, S., Cavallaro, F., 2014a. A methodological framework for the economic evaluation of CO_2 emissions from Transportation. J. Adv. Transp., 48,138–164.

Nocera S., Cavallaro F., 2014b. The ancillary role of CO2reduction in Urban transport plans, Transportation Research Procedia, 3, pp. 760-769

Nocera, S., Cavallaro, F., 2016a. Economic Valuation of Well-to-Wheel CO2 Emissions from Freight Transport along the main Transalpine Corridors. Transportation Research Part D: Transport and Environment, 47, pp. 222-236. doi: 10.1016/j.trd.2016.06.004

Nocera, S., Cavallaro, F., 2016b. The competitiveness of alternative transport fuels for CO2 emissions. Transport Policy, Volume 50, August 2016, Pages 1–14. DOI: 10.1016/j.tranpol.2016.05.013

Nocera S., Tonin S., 2014. A joint probability density function for reducing the uncertainty of marginal social cost of carbon evaluation in transport planning (2014) Advances in Intelligent Systems and Computing, 262, pp. 113-126.

Nocera, S., Tonin, S., Cavallaro, F., 2015a. The Economic Impact of Greenhouse Gas Abatement through a Meta-Analysis: Valuation, Consequences and Implications in terms of Transport Policy. Transport Policy, Volume 37, January 2015, 31-43.

Nocera, S., Tonin, S., Cavallaro, F., 2015b. Carbon Estimation and Urban Mobility Plans: Opportunities in a Context of Austerity. Research in Transportation Economics, Volume 51, 71-82.

Ntziachristos, L., Samaras, Z., 2000. COPERT III Computer Programme to Calculate Emissions from Road Transport: Methodology and Emission Factors (Version 2.1). Technical Report. European Environment Agency, Copenhagen, Denmark.

Ortiz, R. A., Markandya, A., 2009. Integrated impact assessment models of climate change with an emphasis on damage functions: A literature review. BC3 Working Paper Series.

Rothengatter, W., Schede, W., Martino, A., Roda, M., Davies, A., Dovereux, L., Williams, I., 2000. ASTRA — assessment of transport strategies. Karlsruhe: Commission of the European Communities.
Samaras, Z., Ntziachristos, L., Burzio, G., Toffolo, S., Tatschl, R., Mertz, J., Monzon, A., 2012. Development of a methodology and tool to evaluate the impact of ICT measures on road transport emissions. Proc. Soc. Behav. Sci. 48, 3418-3427.
Shepherd, S. P., 2014. A review of system dynamics models applied in transportation. Transportmetrica B: Transport Dynamics, 2, 1–23.
Sinha, K.C., Labi, S., 2007. Transportation decision making. Principles of project evaluation and programming. John Wiley & Sons, New Jersey.
UK DfT, department for transport, 2011. Behavioural Insights Toolkit. Online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/3226/toolkit.pdf [25.02.2016].
Zhou, X., Tanvir, S., Lei, H., Taylor, J., Liu, B., Rouphail, N.M., Frey, H.C., 2015. Integrating a simplified emission estimation model and mesoscopic dynamic traffic simulator to efficiently evaluate emission impacts of traffic management strategies, Transportation Research Part D: Transport and Environment, Volume 37, 123-136.