IMPACTS AND EVALUATION OF CO_2 EMISSIONS IN TRANSPORT PLANNING

Dissertation submitted for the degree of Doctor of Philosophy

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ABSTRACT

The theme of this thesis is the impact of the transport sector on CO_2 emissions and climate change. The thesis is based on a selection of seven peer-reviewed papers written during my three years of doctoral activities and published in international journals indexed in the Scopus database. The aim is to develop a replicable methodology able to help policy makers to understand the real carbon impact of transport policies, infrastructures, systems or measures and to include this aspect into their decisional process.

To this aim, the thesis identifies a three-step process, based on the quantification of CO_2 emissions, their economic valuation and their inclusion into the most suitable form of mobility plan. For each of these phases, a specific methodology has been proposed. The quantification of the emissions is founded on an energy and CO_2 balance between the do-nothing option and alternative(s) with the new project, policy or measure. The economic valuation relies mainly on a statistical meta-analysis that has assessed about 700 studies, determining the most important variables that influence the final price. In addition, the potentialities of an alternative approach such as the Multiple Agent Multi Criteria Decision Making have been discussed. Finally, the CO_2 inclusion into urban mobility plans adopts a cost benefit approach that assesses the carbon potentialities of alternative measures and selects the most efficient ones.

This method has been tested on different case studies, including the realization of a new transnational high-speed railway, the introduction of different European transport policies and the adoption of different measures at the urban level. The vast degree of scientific and economic uncertainties that affects the assessment has suggested keeping the models and formulas as simple as possible, focussing on an accurate data collection and on-site measurements. The method is adaptable in other contexts, provided that reliable data is available. With such premises and adequate political efforts, it should be finally possible to remove transport CO_2 emissions from the ancillary role currently assumed in mobility plans, making them one of the main variables that actively influence the decisions of policy makers.

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Co-Author: Federica Maino (Researcher at European Academy of Bolzano)
Journal: Ingegneria Ferroviaria, Volume **12**, 2015, pages 1045-1072
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Paper 2: A new method for forecasting CO_2 operation emissions along an infrastructure corridor

Co-Authors: Federica Maino (Researcher at European Academy of Bolzano), Vincenzo Morelli (Engineer, ATOS progetti srl)
Journal: *European Transport \ Trasporti Europei*, Issue **55**, 2013, paper n° 4
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Paper 3: A methodological framework for the economic evaluation of CO_2 emissions from Transportation

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Paper 4: The Economic Impact of Greenhouse Gas Abatement through a Meta-Analysis: Valuation, Consequences and Implications in terms of Transport Policy

Co-Authors: Silvio Nocera (Professor at University IUAV of Venice), Stefania Tonin (Professor at University IUAV of Venice)
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Co-Author: Silvio Nocera (Professor at University IUAV of Venice)
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1. INTRODUCTION: GREENHOUSE GASES AND TRANSPORT

Greenhouse gases (GHGs) are responsible for the greenhouse effect, a phenomenon through which atmosphere absorbs the infrared radiation emitted by the planet's surface as a result of exposure to solar radiation, thus increasing the mean temperature of the planet. GHGs, which constitute about 0.05% of the dry atmosphere, include carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O), ozone (O_3) and fluorinated gases (F-gases). Carbon dioxide counts for more than 78% of total anthropogenic emissions (IPCC, 2014a) and is considered as the main indicator of climate change. CO_2 is not considered detrimental if it does not exceed the threshold of 350 parts per million by volume (ppmv; Hansen et al., 2008). However, its concentration grew by 25% between 1850 and 2000, passing from 288 ppmv in 1850 to 369.5 ppmv in 2000 (CDIAC, 2011), with a further exponential growth in the last 15 years, which brought its value to 400 ppmv at the end of 2015 (NOAA/ESRL, 2015). At this concentration, CO_2 contributes actively to global warming and to climate change, with relevant social, environmental and economic consequences (Watkiss et al., 2005).

Despite some minority positions ("climate change counter-movement"), the international community largely agrees that human activities are actively responsible for climate change: the International Panel on Climate Change (IPCC), the most acknowledged international scientific body on GHG issues, defines climate change as *unequivocal,* and its causes as *extremely likely* linked to anthropogenic activities (IPCC, 2014b). Hence, a common international effort to deal with human emissions is unavoidable.

The potential strategies to cope with global warming include two main approaches: adaptation and mitigation. Adaptation is a direct response to the negative consequences caused by climate change: for example, a coastal airport affected by the sea level rise can be rebuilt in a more appropriate location. Since the effects of climate change happen in the long-term, adaptation implies an awareness about the issue and a wait-and-see strategy. This approach has some undoubtable advantages, as it solves practical issues and it does not require complex international agreements. However, it bases on an endemic lack of fairness towards those less developed countries that have contributed only marginally to GHG emissions and now pay the highest price (Dessler, 2012). Furthermore, adaptation is not an attempt to solve, but rather to minimize the social and economic impacts of global warming. For these reasons, adaptation is a valid support solution, but it is alone not decisive to address the issue of global warming. Mitigation is a more proactive strategy, which aims at preventing climate change and avoiding its consequences trough a reduction of GHG emissions and a limitation of their concentration in the atmosphere. The recent Paris agreement (UN, 2015) is founded on this approach: 195 countries have elaborated a document, whose main aim is "*holding the increase in the global average temperature to well below 2° C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5° C"*. This proposal is the last step of a long political process of mitigation, which began in 1997 with the adoption of the Kyoto protocol (UN, 1998).

Europe has been particularly sensitive to these environmental issues, not only limiting its commitment to GHG reduction fixed at the international level, but also elaborating its own continental strategy. The programme "20 20 20" (EU, 2012a) imposes a decrease of the emissions by 20% by 2020; recently it has been integrated with the "2030 initiative", which aims at reducing the emissions 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 (EC, 2009). However, this reduction is not visible in transport, which is the only sector in countertrend: GHG emissions have increased by about 22% in comparison to 1990 levels (EU, 2014). Transport is responsible for 24.3% of GHG emissions and it is the second emitting field after energy production. According to EU forecasts, the transport demand is expected to grow by 50% for freight transport and 35% for passengers by 2020 in comparison to 2000 levels (DGET, 2006). If not well managed, this growth could lead to a further increase in GHG emissions, which is incompatible with the European targets previously recalled and with the long-term expectations (year 2050), indicated in the White Paper of Transport (EC, 2011).

The problems related to the reduction of GHG transport emissions are not only due to political and stakeholders' interests. Indeed, they are also a consequence of scientific and technical issues that make the univocal adoption of a shared methodology difficult. This thesis provides a comprehensive framework to deal with GHG emissions and to allow policy makers to deal with this theme consciously. After this introduction, section 2 describes the main problems regarding the phases of quantification, evaluation and inclusion in mobility plans. Section 3, which consists of the seven scientific articles, proposes a possible solution to such issues. It is articulated as follows:

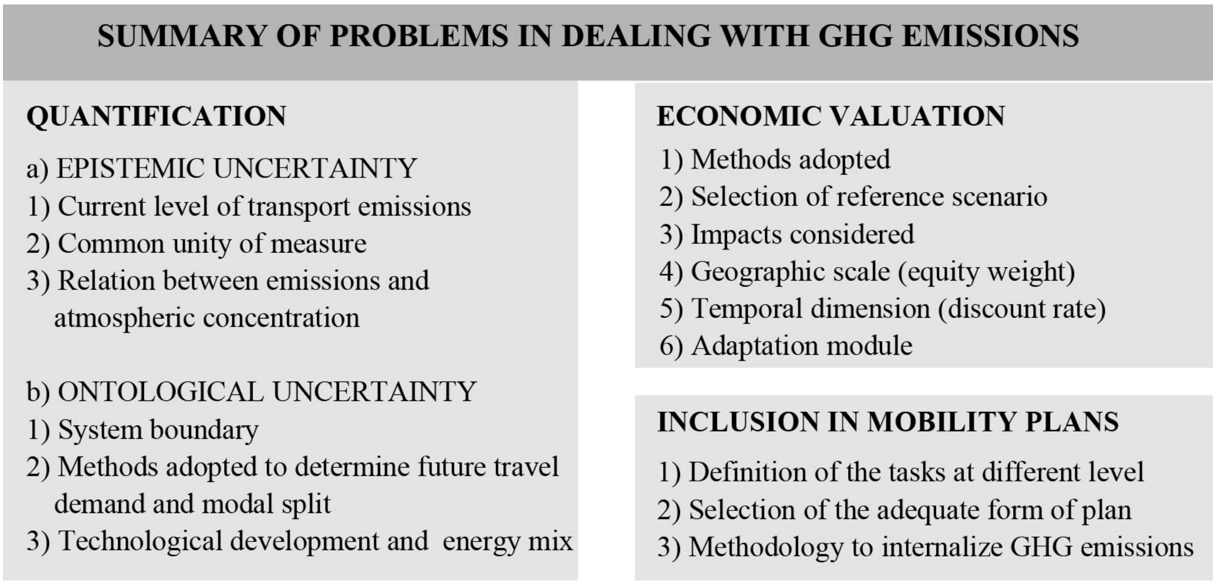
- Quantification of GHG emissions: Maino F., Cavallaro F., 2015; Cavallaro F., Maino F., Morelli V., 2013.
- Evaluation of GHG emissions: Nocera S., Cavallaro F., 2014a; Nocera S., Tonin S., Cavallaro F., 2015a; Nocera S., Murino M., Cavallaro F., 2014.

- Inclusion of GHG emissions into mobility plans: Nocera S., Cavallaro F., 2014b; Nocera S., Tonin S., Cavallaro F., 2015b.

The main findings and the practical implications in terms of transport policy and mobility planning are synthetized in section 4. Finally, section 5 is devoted to the definition of the open questions and the next steps to refine the results obtained so far.

2. PROBLEMS IN DEALING WITH GHG EMISSIONS

This section highlights the main problems in understanding the impacts of GHGs from transport and in proposing appropriate solutions. The issue has been discussed with accuracy since the beginning of the '90s. Clarkson and Deyes (2002) propose a general thematic distinction between scientific and economic uncertainties: the former make the quantification of the future emissions complex, the latter avoid the attribution of a fair unitary price to the unitary emissions. Natke and Ben-Haim (1996) suggest an alternative taxonomy, not specifically referred to GHGs, but applicable also to this context. It is based on the categories of "objective" and "subjective" uncertainties. The former are innate in humanity and are due to our limited knowledge; the latter are related to specific scientific and technological aspects, as well as to the ethical and political assumptions of the modeller and decision makers. Based on this classification, Salling et al. (2007) introduce the similar categories of epistemic and ontological uncertainties, trying to distinguish them according to the solutions that can be provided by modellers. This section takes into account the main aspects highlighted by these authors, but reformulate them according to the three phases of quantification, evaluation and inclusion in previously mentioned mobility plans. Figure 1 synthetizes the main aspects emerging from this classification.



SUMMARY OF PROBLEMS IN DEALING WITH GHG EMISSIONS

QUANTIFICATION

a) EPISTEMIC UNCERTAINTY
1) Current level of transport emissions
2) Common unity of measure
3) Relation between emissions and atmospheric concentration

b) ONTOLOGICAL UNCERTAINTY
1) System boundary
2) Methods adopted to determine future travel demand and modal split
3) Technological development and energy mix

ECONOMIC VALUATION

1) Methods adopted
2) Selection of reference scenario
3) Impacts considered
4) Geographic scale (equity weight)
5) Temporal dimension (discount rate)
6) Adaptation module

INCLUSION IN MOBILITY PLANS

1) Definition of the tasks at different level
2) Selection of the adequate form of plan
3) Methodology to internalize GHG emissions

Figure 1: Main problems in dealing with GHG emissions in transport planning

2.1. Quantification

Quantification aims at determining the amount of GHGs emitted -or expected to be emitted, in case of predictions- and the consequent variation of their atmospheric concentration. This type of analysis can be performed in several contexts and with different aims: at the local level, to understand the impact of specific measures on urban GHG emissions; at the regional level, to verify that transport policies produce positive results in an energy balance; along main (trans)national corridors, to assess the impact of passenger and freight transport policies. GHG quantification is particularly important for the realization of new infrastructures or transport systems (Nocera et al., 2012). In order to assess their carbon implications, the evaluator should make a comparison between the do-nothing option and the hypotheses that imply the new intervention in order to assess its carbon implications. Although the GHG potentiality of alternative transport systems has become a relevant transport issue, at the time this assessment of the literature was started, the information was not as vast as one could have expected. To serve as example, this section presents an overview of the assessments about rail infrastructures. Most of the study refers to CO_2 emissions, assuming this gas as representative for all GHGs. Von Rozycki et al. (2003) assessed the variation of CO_2 emissions after the introduction of a new high-speed railway line between Hanover and Würzburg. Booz Allen Hamilton Ltd. (2007) compared the CO_2 emissions deriving from the London-Edinburgh and the London-Manchester high speed lines with the corresponding air connection over a period of 60 years. Tuchschmid (2009) proposed a method to quantify the emissions of several pollutant gases (including CO_2) from the construction of new high-speed railway lines in Europe. The engineering company of the Italian State Railways (Italferr, 2010) calculated CO_2 emissions generated by a new railway line between Rho and Gallarate (in Lombardy). The scale and the degree of accuracy of such studies are different, but every author highlights the technical and scientific difficulties of obtaining reliable results. Some of them present methodological issues shared with other research fields, while others are specifically related to transport problems.

The list of methodological issues shared with other disciplines can be roughly synthetized in three main aspects. First, the accurate determination of the current levels of transport GHG emissions. This issue is common to all those fields based on dynamic or widespread sources (such as agriculture or building efficiency), while it has been already bypassed in stable sectors such as factories, power plants and installations, where quantifying emissions is possible thanks to measuring devices in the smoke stacks.

Second, the correspondence between GHG emissions and concentration in the atmosphere. Theoretically, there is a carbon balance between atmosphere and land biosphere, rocks and oceans (Dessler, 2012). Through photosynthesis and respiration processes, the atmosphere exchanges about 100 GtC of CO_2 yearly with the land biosphere. About 200 GtC are transferred between the oceans and the atmosphere (100 GtC with the superficial part and 100 GtC with the deep ocean), while rock exchange, through a process called *chemical weathering*, counts for about 0.1 GtC. In this framework, the quantity of carbon absorbed and returned by and to the atmosphere is in a condition of equilibrium. However, human activities have altered this balance, both with fossil fuel combustion (about 9.6 GtC were emitted in 2012 at global level; CDIAC, 2014a) and with deforestation. Furthermore, the acidification of oceans can reduce their absorbing potential. Hence, it is difficult to determine the future percentage of sequestration granted by natural sources. On the other hand, in last years, several artificial processes have been devised to avoid the emissions of human GHG into the atmosphere: carbon capture and storage (CCS; Akbilgic et al., 2015), or, more ambitiously, solar radiation management and carbon cycle engineering. Even in this case, the effect of the development and implementation of such tools is not easily quantifiable, since they are still in an experimental phase and are not part of a long-term strategy.

Third, the adoption of a unique unit of measure for all GHGs. The IPCC (1990) has proposed to adopt the Global Warming Potential (GWP), which is an attempt to convert all GHG emissions into CO_2 equivalent (CO_{2eq}). CO_{2eq} indicates the concentration of CO_2 that would cause the same level of radiative forcing as that caused by the GHGs over a period of 100 years. For example, the GWPs of methane and nitrous oxide are, respectively, 21 and 310: this means that one ton of methane and nitrous oxide are 21 and 310 times greater than one ton of CO_2. GWP has become the reference method to transform non-CO_2 emissions into a unique and comparable value. IPCC constantly monitors and updates the impact of GHGs and relative weights, through the regular publication of its technical reports. However, there is a huge debate about the conversion factors (O'Neill, 2000), mostly due to the different lifetime in the atmosphere of gasses (Jensen and Thelle, 2001): molecules of methane remain in the atmosphere for about 12 years, while CO_2 remain for over 100 years. This affects the marginal damages of emissions, as GHG atmospheric concentration is expected to rise over time. As a consequence, the scientific community is still vividly debating about the most suitable discount rates. Recalling the classification of Salling et al. (2007), these issues are part of the epistemic uncertainties, which are not easily solvable: the community is aware of their presence, but with the current scientific knowledge, it is not possible to give a final response on how to deal with these aspects effectively.

Most of the issues specifically related to the transport sector can be included in the ontological category. They are based on decisions taken by modellers and policy makers;

hence, they are more directly manageable. First, the selection of the most suitable method to calculate the specific emissions caused by the different types of vehicle. This means to fix the boundaries of the system under examination. In practice, this is function of the specific fuel and the phases included in the evaluation. The literature suggests different possibilities, which are function of the type of study to be realized (figure 2).

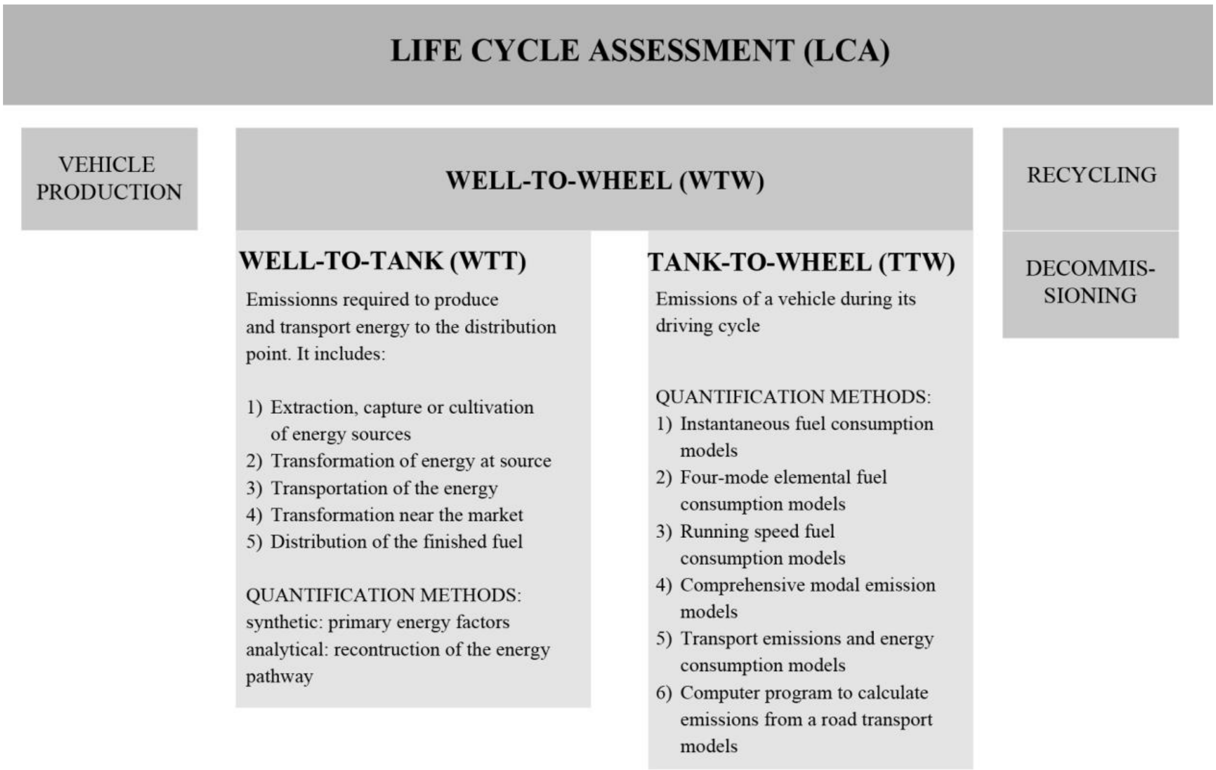


Figure 2: Different approaches to the quantification of GHG emissions

The most complete method is the *Life-Cycle-Assessment* (LCA; A3PS, 2015), which includes the entire life of an object, from the production to the final disposal and encompasses extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal. The *Well-To-Wheel* approach (WTW; Edwards et al., 2014) includes an assessment of the primary energy source, the energy required for its extraction, transformation, transportation, fuel production and characteristics of the vehicle using the fuel. This last phase can be calculated also independently, in the *Tank-To-Wheel* approach (TTW). TTW quantifies the unitary energy expended and the unitary pollutant substances emitted by a vehicle during its driving cycle. This is the method adopted by car manufacturers to certify the amount of pollutant substances nominally emitted by their vehicle fleet. Several factors concur in determining the final values: they can be included into the three categories of “vehicle conditions”, “vehicle route” and “operating conditions” (Vijayan et al., 2008). The first category consists of the technical characteristics of the vehicle (model, year, class, and size), the fuel type, the accrued kilometres, and the maintenance. The second group contains the type of infrastructure, the gradient, the pavement condition, the number of passenger and the traffic condition. The last group includes all the parameters referred to the operation, including the average speed, the load, the driver behaviour, the environmental conditions, etc. Normally, the quantification of TTW emissions requires the adoption of specific models; an overview of the most important ones is provided in Cavallaro et al. (2013).

To forecast future levels of GHG emissions, three main further scientific issues have to be considered: travel demand, modal choice and technological development/energy mix. Future travel demand is one of the main open issues in transport planning. It should allow an understanding of the number of users that are expected to travel along a new infrastructure or use a specific transport system. The methodological progress in this discipline is evident, mostly due to low-cost and high-speed computing (Ortúzar and Willumsen, 2011). Nevertheless, a rigorous ex-post analysis about the construction of new infrastructure (Flyvbjerg et al., 2005) has demonstrated not only that the accuracy in determining the future travel demand has not improved over the past 30 years, but also that road vehicle forecasts have become more inaccurate over time. Particularly, rail passenger forecasts are overestimated in 9 out of 10 cases, with an average overestimation of above 100%. Half of all road traffic forecasts are wrong by more than ±20%. Since the number of users and vehicles circulating is one of the most important variables, this relevant difference between expected and measured travel demand also has implications for the estimation of future GHG emissions.

There are different ways to deal with future predictions (Vanston and Vanston, 2004): each of them is a compromise between accuracy and costs. Modellers should adopt the most adequate according to the aim of the research and the funds at disposition. Figure 3 presents a list of the possible approaches in transport planning, according to their characteristics. Among them, scenarios play a significant role for its ductility. A scenario is not a forecast of the future condition, but a "*representation of visions/images of the future and courses of development organised in a systematic and consistent way*" (EC, 2008). A scenario is based on given hypotheses, which are crossed with the initial situation, thus leading to the future sequences of events that the hypotheses imply. Many parallel scenarios are developable, being everyone the fulfilment of different initial hypotheses. Scenarios should not become part of the political rhetoric aimed at showing voters that something is being done; indeed, it should be a control mechanism to assess the potential consequences deriving from the adoption of specific measures or actions (Flyvbjerg et al., 2005).

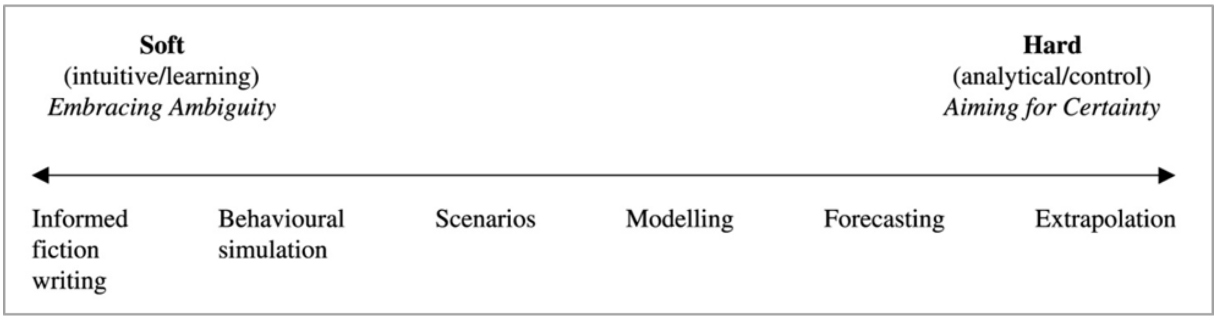


Figure 3: Methods used in the prediction of the future. Source: Chatterjee and Gordon, 2006

Other relevant technical issues are the future efficiency and technological improvement of vehicles, the use of alternative fuels and the composition of future energy mixes. King (2007) has stated that market ready technologies could reduce GHG emissions per new car by 30% within 5 to 10 years, with consequent economic fuel savings. Furthermore, alternative fuels, which today constitute only a market niche, could play a significant role in GHG reduction. Several alternatives are still available (Johnston et al., 2005): natural gas, methanol, ethanol, liquefied petroleum gas (LPG), biodiesel, electricity both plug-in and fuel cell, hydrogen, boron, Fischer-Tropsch fuel, p-series, electricity and solar fuel. Nowadays, the utilisation of such fuels is very different: some of them (e.g., methanol, natural gas, LPG) are already a valid alternative to fossil fuels, while others (e.g., boron, Fischer-Tropsch fuel, p-series, solar fuel) are more limited or still at an experimental phase, due to lack of infrastructures and high costs of production and distribution. The problem for the planner is two-fold: first, the planner has to determine the diffusion of such fuels in the future and, second, he has to understand their real incidence in terms of GHG emissions according to the method of quantification selected. Electricity is emblematic: if we consider only the TTW phase, GHG emissions of electric vehicles are zero; however, by considering the entire WTW process, the energy mix required to produce the electricity, which is the sum of different primary resources, also has to be analysed. For each of them, the evaluation has to include the provision (extraction and transport) of raw materials, the efficiency of energy production and its distribution.

All the aspects mentioned in this section concur in determining a vast degree of uncertainty about the quantification of current and, mostly, future GHG emissions. Furthermore, the uncertainties previously described can overlap, thus increasing the inaccuracy significantly.

For these reasons, a stochastic approach, which provides results probabilistically, should be preferred in dealing with such issues.

2.2. Economic valuation

Black (2010) indicates global pollutants (i.e., GHGs) as one of the main characteristics of transport unsustainability and considers their fair evaluation as an unavoidable step in order to understand the real cost of transport. Literature proposes some alternatives to evaluate the GHG impact from transport. Scarpellini et al. (2013) suggest including them in a more comprehensive *Multi Criteria Analysis* (MCA): MCA allows considering criteria in their own unit of measure, hence disregarding monetization problems; furthermore, it permits the selection of parameters that stakeholders should consider and it may add qualitative criteria to the evaluation. Thus, CO_{2eq} can be included in environmental analyses with other impacts, such as local and water pollution, noise, vibrations, land-use, accidents and congestions (Danielis, 2001). In this sense, MCA should grant a holistic view for the evaluation of external economic effects. However, it runs the risk of being affected by subjective biasing, such as in the choice of criteria (subjectivity, arbitrariness) and the assignment of weights (Browne and Ryan, 2011); therefore, particular attention should be paid to these two phases. An alternative to MCA could be the *Cost Effectiveness Analysis* (CEA). This method compares the costs of alternative approaches in producing the same (or similar) results, after the decision of the objective to be achieved. The result is a ranking of different solutions, which allows policy makers an evidence-based comparative analysis. However, CEA is by definition limited to the objective (in this case, GHG emissions) and cannot be extended to evaluate other aspects. Thus, to evaluate the GHG impacts deriving from transport, Sinha and Labi (2007) suggest the use of a *Cost Benefit Analysis* (CBA). CBA is largely adopted to analyse environmental policies of the transport sector, provided that a fair unitary price can be obtained (Turner, 2007). Monetizing GHG emissions means putting additional costs and benefits that are not directly expressed as expenditures and revenues onto the same monetary scale, in order to understand whether the costs overcome the benefits. The process converts the quantity determined in the quantification phase into monetary terms, by multiplying it by a unitary price. The cost of carbon dioxide is thus generally expressed in dollar ($), pound (£) or euro (€) per tCO_{2eq} or ton of carbon (tC), assuming a conversion factor of 3.664 (CDIAC, 2014b).

The main problem of monetization lies in the attribution of an adequate unitary price; to this aim, different methods can be adopted. The prices determined by the market (carbon trading), or by political decisions (carbon tax) should not be considered as representative because their value is largely affected by distortions. The carbon-trading price is founded on the "cap-and-trade" law (EU, 2012b). The maximum amount of CO_2 that factories, power plants and installations can emit without paying is limited to a given value or “cap”. Within this cap, companies receive emission allowances, which they can sell to or buy from one another if needed (“trade”). The cap for a given future temporal horizon is determined at some point during the current period and is usually valid for five years, thus facilitating the initial decision to implement the system, but making it inherently unsuitable for long-term forecasts (Ellerman et al., 2008). Furthermore, there are other practical problems: carbon-trading system, as introduced in EU, suffered from high volatility and price fluctuations, which increase the intrinsic difficulty of setting a fair reference price. On the other hand, the carbon tax is paid based on the carbon content of fuels or on the estimated carbon emitted in the fuel combustion process (Santos et al., 2010). However, the difference of unitary prices between countries is very vast: in Sweden, for example, the carbon tax is 105$/t$CO_2$, while in California a law proposal fixed it at 0.045$/t$CO_2$ (Sumner et al., 2009). For this reason, carbon tax does not grant a fair estimation of GHG.

Hence, alternative techniques are preferable. Two main ones are the *damage costs* and the *avoidance costs* methods (Clarkson and Deyes, 2002). *Damage costs* assesses the future physical impacts of climate change and link them with their effects on the economy and society. This method bases on a CBA that determines the optimal policies based on the expected environmental, social and economic consequences, and evaluates whether the benefits are likely to exceed the costs. *Avoidance costs* quantifies the money required to avoid an increase of GHG levels, to reduce such emissions and to remove GHG from the atmosphere. The method, based on a CEA, is strictly related to the development of policy targets that aim at lowering emissions for a fixed time horizon. *Damage costs* is expected to produce more reliable results, since it tries to link the economic consequences of increased emissions with the physical changes produced. This link is sought through the adoption of Integrated Assessment Models (IAMs). According to the macro-modules included in their computational phase, Ortiz and Markandya (2009) divide IAMs into three groups:

- Fully Integrated Assessment Models, which include economic growth/dynamics (energy sector comprised), damage and climate modules;
- Non-Computable General Equilibrium Models, which include only the climate and damage modules. Occasionally, they consist of an energy module as well but without

an economic optimization procedure and the adoption of scenarios provided by third parties;

- Computable General Equilibrium Models, which focus the economic optimization procedure on a greater number of sectors but do not include a climate module.

Nocera et al. (2015a) have analysed about 700 studies based on IAMs, finding an average unitary value of \$276.49/tC (standard deviation 668.78); the range, expressed in 2010 US dollars, goes from \$-10.00/tC to \$7,243.73/tC, which means to cover six orders of magnitude. The reasons of this vast interval are multiple. The first one is the determination of the future GHG level of emissions, concentrations and temperatures. Normally, the values are based on different scenarios defined by the IPCC (2007) and are then further developed or specified by the modellers. The reference scenarios are normally four, defined “A1”, “A2”, “B1” and “B2”. “A” scenarios represent a world with a high rate of economic growth, while “B” denotes a less pronounced growth; those characterized by “1” imply a reduction of poverty and disparities, while “2” implies an unaltered condition between the rich and the poor. These economic differences also have consequences on other aspects: among them, the GHG emissions and the consequent increase in temperatures.

Even by considering similar future concentrations, a large difference in final values can occur. This is due to which physical impacts modellers consider will be affected by the increase of GHG concentration. Potentially, such impacts are included into eight main groups (Watkiss et al., 2005; table 1): sea level rise, energy use, agricultural impacts, water supply, health impacts, ecosystems and biodiversity, extreme weather events and major events, each of these are then further characterized by specific phenomena. Each modeller can decide to consider only a portion of these impacts or all of them according to the aim and the scale of the assessment, with the risk of over- or underestimating certain aspects. For example, a relevant debate regards the inclusion of major events such as cyclones into the list of impacts and the understanding of the real consequences caused by global warming. Primarily, the question is to understand if a correlation between the two aspects exists, and later to assess the expected variation in frequency and intensity of the events (Knutson et al., 2010). This determines the inclusion or the exclusion of the damages deriving from this kind of event in the IAM. According to this, final economic values of GHG emissions could be largely different.

POTENTIAL IMPACTS OF CLIMATE CHANGE AT GLOBAL LEVEL

MACRO-GROUP	IMPACTS
Sea level rise	costs of additional protection measures loss of dry land, wetland loss increased likelihood of storm surges landward intrusion of salt water, risk for coastal ecosystems social and economic effects for inhabitants of small islands and/or low-lying coastal areas
Energy use	migration based on socially contingent effects summer increase due to air conditioning winter decrease in demand for heating
Agricultural impacts	changes in temperature and rainfall changes in cultivated areas and yields choice of crops development of new cultivars and other technical changes such as irrigation
Water supply	changes in rates of precipitation and evapotranspiration demand changes, affected by various climatic factors such as temperature and humidity exacerbation of water shortages in water scarce areas
Health impacts	increase in summer heat stress reduction in winter cold stress extension of the area amenable to parasitic and vector borne diseases socially contingent damage to health caused by 1, 2, 3, 4 threats in lower income populations, mostly in (sub)tropical countries
Ecosystems and biodiversity	alteration of ecological productivity and biodiversity risk of extinction of some vulnerable species. risk for some isolated systems, including unique and valuable systems (e.g. coral reefs) acidification of the oceans, impacts on marine ecosystems impact on fluxes of gases between ocean and atmosphere
Extreme weather events	heat waves, drought, floods and potentially storms, tropical cyclones and even super typhoons climate variability
Major events	loss of the West Antarctic ice sheet and the Greenland ice sheet; methane outbursts, instability or collapse of the Amazon Forest; changes in the thermohaline circulation, Indian monsoon transformation; change in stability of Saharan vegetation; Tibetan albedo change

Table 1: Potential impacts of climate change. Source: Nocera and Cavallaro, 2014a

In addition to the physical and scientific aspects highlighted so far, there are relevant economic issues that contribute to the increase of uncertainty in the final unitary price of GHG emissions. In IAMs, the calculation of the economic damage is a function of the temperature variation raised by a coefficient. The choice of this coefficient (usually quadratic) noticeably affects the value of the damage: in PAGE, for example, passing from a quadratic function to a cubic one determines a change of about 23% in final values (Dietz and Hope, 2007). The geographic scale is another important aspect: the emissions of GHGs do not have the same economic impact on every country, because of both its physical conformation and for its economy. The national GDP and national willingness to pay to avoid the environmental, economic and social consequences differ significantly. The adoption of the equity weight (Fankhauser et al., 1997) is an attempt to include this ethical issue within the final value of GHG emissions. The equity weight (formula 1) is based on the assumption that countries with consumption rate above the world average receive a low weight and vice versa.

$$D_w = \sum_{i=1}^{n} \left(\frac{c_w}{c_i} \right)^{\varepsilon} \cdot d_i \tag{1}$$

Where D_w is the global damage derived from GHG emissions; c_w is the world average per capita consumption; c_i is the average per capita consumption of a given nation i; ε is the elasticity of marginal utility; d_i is the damage derived from CO_2 emissions in country i. The value to be assigned is not univocally accepted and constitutes one of the main points of discussion in the scientific literature: estimates can differ even by two orders of magnitude due to the equity weight (Anthoff et al., 2006).

Modellers and decision makers have to consider not only the spatial dimension, but also the temporal issue: in environmental studies, this value coincides with the Social Rate of Time Preference (SRTP). It can be defined as “the rate at which individuals discount future consumption over present consumption, on the assumption of an unchanging level of consumption per capita over time” summed with “an additional element, if per capita consumption is expected to grow over time, reflecting the fact that these circumstances imply future consumption will be plentiful relative to the current position and thus have lower marginal utility” (HM Treasury, 2003). Higher discount rates mean a lower weight assigned to effects occurring in the future. This is a very critical aspect, which, since the beginning of the ‘90s, has led to a vivid debate within the scientific community about the choice of this value and its practical consequences. Very different positions can be found at the international level: Daly and Cobb (1994) consider discounting as a way to convert future large numbers into present small ones. The Stern Review (Stern, 2006), one of the most important and well-known assessment of the potential of climate change, adopts a low discount rate (1.4%). On the contrary, Nordhaus, in using his own DICE model, suggests the adoption of a discount rate of about 4.3% (Goulder and Williams, 2012). As pointed out by Clarkson and Deyes (2002), an agreement on the correct formulation for the SRTP and the discount rate would be an improvement of the evaluation. Unfortunately, such agreement is not easy to find. A valid approach is to perform a sensitivity analysis with values in the range 1% to 10%, which was the solution proposed by Cline (1992).

The last technical aspect that affects the final price of GHG emissions is the nature of the effects included in the analysis. The conceptual distinction between adaptation and mitigation has been already discussed in the introduction. In IAMs, adaptation is a variable of the estimate function, which describes the efforts required to handle the consequences of climate change. It concerns complex behavioural, technological, and institutional adjustments at all levels of society. Some IAMs (e.g., DICE) do not contain structural components that represent adaptation explicitly, whereas other models (e.g., FUND) adopt it as a variable of the model (Tol, 2005).

2.3. Inclusion in mobility plans

After the quantification of CO_2 emissions and the evaluation of their impacts, the last step of the methodology is the inclusion of results into an adequate form of transport plan. This aspect is particularly delicate and requires a preliminary discussion about the appropriate scale of intervention. Global warming is by definition a problem that affects the entire planet and should be addressed at a large scale. The international resolutions, protocols and EU strategies recalled in the introduction are conceived according to this criterion. However, such documents cannot face the issue through the implementation of effective measures, because they cannot consider all the local specificities and characteristics that make a general approach operative and in most cases are not mandatory. To address the issue appropriately, the UN meeting held in Durban (2011) clearly highlighted the contributions required from the local (urban) scale: cities manage very large funds, investments and public infrastructures (including transports), and are thus able to address the theme of global warming effectively. The development of appropriate local plans creates the opportunity to define policies and concrete measures that can be directly implemented. Incidentally, this is legitimated by data about CO_2 emissions: according to Dodman (2009), urban emissions constitute roughly 80% of total emissions and because of the expansion of urban areas and the loss of natural spaces, this percentage is constantly growing. Transport is actively responsible for this critical condition and covers about 40% of the overall emissions (Glaeser and Kahn, 2010). Hence, the local level can operatively address the reduction of CO_2 emissions from transport, under a common (inter)national framework.

In practice, such theoretical framework is rather different. At the local level, GHGs are often perceived as a global problem and politicians may prefer to mostly address issues related to the local scale in order to increase their consensus throughout their potential voters. This section presents an overview of the Italian situation, confirming the difficulties of dealing with this theme[1]. The Italian Ministry of Infrastructure and Transport (MIT) provides the general guidelines for the development of the national transport plan[2]. Because of the vast territorial scale and the differences of specific cities, the Ministry is responsible only for the main infrastructural networks and for other relevant aspects considered of general interest and which cannot be assigned to the lower levels. For example, this is the case of the recent approval of the national infrastructural plan on recharging points for electric vehicles (*piano nazionale infrastrutturale per la ricarica dei veicoli alimentati ad energia elettrica,* GU n.280, 2-12-2014); this project could contribute to a strategic redefinition of the role assigned to electricity among the national alternative fuels.

Indeed, the implementation of concrete solutions is assigned to the local level, with the adoption of regional, provincial and local mobility plans. The competencies of each form of plans are different, but the main operative issues belong to the urban level. Here, the Italian legislation includes two main types of plan: the *Piano Urbano del Traffico* (Urban Traffic Plan, UTP) and the *Piano Urbano della Mobilità* (Urban Mobility Plan, UMP). UTP is constituted by a set of interventions aiming at improving urban road circulation of pedestrians, public and private vehicles. The plan is compulsory for all municipalities exceeding 30,000 inhabitants and for those municipalities characterized by a relevant seasonal flow of tourists. UTP is a programming instrument, valid for a short period (usually 2 years), which hypothesizes an unvaried infrastructural urban network. The aim of the plan is the satisfaction of four main objectives (MIT, 1992): improvement of circulation (here including both movement and parking); improvement of road safety and security; reduction of criteria pollutants and acoustic pollutants; energy saving (Cascetta and Montella, 1998). The improvement of these technical performances is expected to have positive results on other social and environmental aspects, including the reduction of GHG emissions. However, this is an indirect consequence. In some cases, GHG emissions are not even mentioned (e.g., the old UTP of Rome; MoR, 1999). This is not surprising: the temporal validity and the solutions

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[1] Readers interested to the European level may refer to Nocera and Cavallaro (2014b).

[2] In Italy the last comprehensive plan ("*Piano Generale dei Trasporti e della Logistica*") was provided in 2001, while an updated version, but limited only to the freight transport and logistics has been provided in 2011 ("*Piano Nazionale della Logistica 2011-2020*").

proposed by the UTP do not place it as the most suitable type of plan to deal with long-term issues such as climate change.

UMP is a more comprehensive form of plan, which aims at improving the mobility system of a city, not limiting its analysis only at the vehicular circulation. Covering a temporal horizon of at least 10 years, this plan is appropriate to deal with long-term transport aspects and includes GHG transport emissions. Municipalities can adopt a UMP only on a voluntary basis. This plan aims at integrating the urban interventions with European and national policies regarding the development of infrastructures, thus constituting a link between the upper mobility plans and the urban traffic plans previously described. The overall objectives of a UMP are clearly expressed by the National Law 340/2000: ensuring the accessibility of jobs and services to all; improving safety and security; reducing pollution, GHG emissions and energy consumption; increasing the efficiency and cost-effectiveness of the transportation of persons and goods; enhancing the attractiveness and quality of the urban environment. The framework is comprehensive and detailed; however, the practical implementation was not successful. The national fund necessary to implement the measures has never been operative and the contribution of MIT has been limited to the drafting of the plan. This has created a discrepancy between the planning and the operative phases, which in most cases remain at the stage of intentions and do not become part of a long-term strategy. Another relevant criticism concerns the integration between levels: the national guidelines focus on the realization of infrastructures in metropolitan areas, but ignore the connection to the national and regional level (ISFoRT, 2011). Finally, there are no procedures to integrate UMP with spatial plans and UTP. The result is an incomplete tool, which has to prioritize the interventions, thus losing its strategic approach. In this context, aspects related to environment and health (including CO_2 emissions) have been considered ancillary and obtained indirectly by solving the problems of congestion and modal shift. The example of Rome (MoR, 2009) is emblematic: environmental considerations are primarily related to criteria pollutants, while GHGs are mentioned only briefly, in a scenario not even described in its basic assumptions.

The issues regarding mobility and energy are faced not only by transport planning, but also by other disciplines. Regions have to compile a *Bilancio Energetico Regionale* (Energy Balance Sheet, EBS), which analyses the energy supply and demand, distinguishing the different sources and the quantity consumed in each civil sector: the macro-groups considered in this analysis are buildings, industry, agriculture and transport. This is the basis for the development of provincial and municipal energy plans, which have the task to set the interventions and decisions that regulate the energy production and consumption for the next years. This can have relevant implications regarding the use of electric or alternative vehicles, because it can determine also the number and the location of the recharging points.

Another alternative form of local plan (not legally mandatory) that deals with transport and CO_2 emissions is the Sustainable Energy Action Plan (SEAP; Covenant of Mayors, 2010). SEAP is largely supported by the EU as an instrument present at the local level to achieve EU "20 20 20" targets. Italian cities have largely adopted this type of plan, facilitated by the (inter)national funds granted for its writing. SEAP includes different sectors of civil society, such as buildings, equipment/facilities, local electricity production, transport and local heating/cooling generation. The guidelines of SEAPs suggest calculating the adoption of the fuel sold at municipal or provincial level by petrol stations, as well as the electricity adopted for the circulation of trains and electric-powered means of transport. Through appropriate coefficients of transformation, it is possible to derive the CO_2 emissions from the electricity and petrol used in a given locality, thus obtaining the baseline emission inventory (BEI). Subsequently, a set of transport measures has to be chosen, according to the reduction target fixed by the mobility plans. To this aim, each measure has to be accompanied by a description of the activities required for their complete adoption, the cost estimation, timing, energy savings and CO_2 reductions, in order to make the choice as transparent as possible. However, these plans do not seem to be the appropriate solution to address the issue of transport emissions, because they focus only on the energetic aspects, leaving aside the other transport implications. Indeed, a mobility plan is very complex thematically and normally requires a holistic approach that includes the relevant values related to traffic circulation, transport modes, etc. CO_2 emissions are one of these points, but cannot be the exclusive one. Furthermore, the relationship with traditional forms of transport planning is not clear and can create overlapping and even contradictions.

To summarize, the Italian framework of transport planning offers several opportunities to deal with the theme of GHGs. Urban mobility plans seem to be the most suitable, due to their comprehensive nature. However, there is a significant discrepancy between the overall goals of a typical urban mobility plan (GHG reduction is considered among the main aims) and the effective policies adopted (there are no measures directly related to the reduction of carbon emissions). This does not necessarily mean that GHGs are ignored. It means that measures conceived for other purposes (e.g., reduction of traffic, increase in the use of public transport, fostering alternative means of transport, reduction of criteria pollutants) are expected to give a possible carbon gain as a secondary effect.

3. SOLUTIONS

3.1. Quantification: CO_2 balance

The method proposed to solve the quantification problem is a balance: an analysis to assess the impact of a given project or activity over time, for the purpose of climate protection and the prevention of detrimental effects on human health. In this and the following sections (except for the parts where it is expressly indicated), CO_2 is considered as representative of GHGs, thus reducing the uncertainties about conversions into CO_{2eq} (as described in 2.1). The balance of the system *X* (formula 2) founds on a comparison between the do-nothing scenario (*N*) and one -or more- system(s) with the new project or measure (*P*).

$$BAL_{CO2}(X) = N - P \tag{2}$$

The balance is positive, with a consequent potential gain for the community, if CO_2 emissions produced by *P* are lower than the ones generated by *N*. On the contrary, if the balance is negative (with $P>N$), the new system leads to a rise in emissions.

The balance is adoptable for each kind of transport intervention (e.g., realization of a new infrastructure, introduction of a new transport system, adoption of specific transport policies or measures). Referring to the evaluation of a new infrastructure, four macro-phases characterize *P*: design, construction, operation and decommissioning (Nocera et al., 2012). Considering that design, construction and decommissioning are not to be considered in do-nothing, the terms contained in formula (2) can also be expressed by 3) and 4):

$$P = D_P + C_P + O_P + De_P \tag{3}$$

$$N = O_N \tag{4}$$

Where:

P are the total CO_2 emissions related to the project analysed; D_P, C_P, O_P, De_P are CO_2 emissions resulting, respectively, from the phases of design, construction, operation and decommissioning; O_N are the total CO_2 emissions resulting from the operative phase of the do-nothing scenario.

For the sake of effectiveness, the emissions resulting from both the design and the decommissioning phases are negligible. The former is of scarce relevance because of their value well below the overall uncertainty (less than 0.03% in comparison with overall construction phase; Italferr, 2010). The latter concerns interventions that are supposed to have a long life and therefore have a timeframe difficult to be included in the current evaluations; for main infrastructures, the expected operational phase is at least 50 years, with peaks of over 100 years; (IPCC, 2014a).

Assuming 1 as the first year of operation of the new infrastructure and *n* as the last year to be included in the balance, letting *m* be the year in which construction of the infrastructure is accomplished (with $m \leq n$), formulas (3) and (4) can be written as (5) and (6). The choice of the time horizon 1-*n* must be well weighed, being based on several factors such as the expected lifetime of the infrastructure, the reliability of future forecasts, the objective of the assessment, the validity of the measures, etc.

$$P = \sum_{i=1}^{n} P_i = \sum_{j=1}^{m} C_{Pj} + \sum_{i=1}^{n} O_{Pi} \tag{5}$$

$$N = \sum_{i=1}^{n} N_i = \sum_{i=1}^{n} O_{Zi} \tag{6}$$

The two articles proposed in this section explain in detail how to realize a CO_2 balance deriving from the introduction of a new main infrastructure, thus limiting the analysis to a particular infrastructural measure. However, adequate adaptations allows an enlargement of the method to other types of intervention. The method is tested on a relevant case study at the European level: the high speed/high capacity (HS/HC) Brenner railway line. "*Quantification of CO_2 emissions deriving from the construction of a railway tunnel: the Brenner base tunnel*" (Maino and Cavallaro, 2015) focusses on the phase of construction of a new infrastructure, by providing a methodology to calculate CO_2 emissions during the different phases of excavation, production and application of building materials, operability of tunnels and construction sites.

"*A new method for forecasting CO_2 operation emissions along an infrastructure corridor*" (Cavallaro et al., 2013) focusses on the operational phase, illustrating how to perform a simulation of the current and future energy requirements (and the consequent CO_2 emissions), to let the railway infrastructure and trains working properly. The method is based on road and rail simulations and compares the impact of one ton of freight transported for each of the two transport modes. This allows also knowing the quantity of freight necessary to compensate the CO_2 emissions deriving from the construction of the new infrastructure, as calculated in Cavallaro et al. (2013).

3.1.1. Quantification of CO_2 Emissions deriving from the Construction of a Railway Tunnel: the Brenner Base Tunnel

OSSERVATORIO

La quantificazione delle emissioni di CO_2 derivanti dalla costruzione di una galleria ferroviaria: il tunnel di base del Brennero

Quantification of CO_2 emissions deriving from the construction of a railway tunnel: the Brenner base tunnel

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1. Premessa

Il presente contributo propone un metodo per il calcolo e la valutazione delle emissioni di CO_2 derivanti dalla realizzazione di una grande opera infrastrutturale. Il metodo si basa su un *Hybrid Life-Cycle Assessment*, che considera le specificità territoriali e geografiche nel calcolo dei consumi energetici e delle relative emissioni. Vengono identificate quattro macro fasi del processo di realizzazione (scavo, produzione e applicazione dei materiali da costruzione, operatività delle gallerie e dei cantieri), ciascuna delle quali è scomposta in specifiche sotto-attività. Il metodo viene testato sul tunnel di base del Brennero, per il quale si stimano emissioni pari a 2,28 Mt CO_2. La maggior parte di esse (85%) deriva dalla produzione di calcestruzzo e acciaio, mentre le altre fasi contribuiscono in misura più limitata. I risultati sono utili in fase di ottimizzazione dei processi realizzativi, fornendo indicazioni sui fattori da considerare per ridurre le emissioni di CO_2. Inoltre, il metodo può servire ai decisori per una valutazione delle politiche trasportistiche più attenta alle problematiche ambientali.

Parole chiave: tunnel ferroviario, fase di costruzione, emissioni CO_2, Hybrid LCA, linea AV/AC Brennero.

2. Introduzione

I trasporti rivestono un ruolo chiave per limitare le conseguenze derivanti dal riscaldamento globale: essi sono infatti responsabili per circa il 26% delle emissioni di gas serra (GHG) e le loro emissioni sono in continua crescita (+30% rispetto al 1990 [1]). L'anidride carbonica

1. Foreword

This paper proposes a method for the calculation and evaluation of CO_2 emissions resulting from the implementation of a large-scale infrastructure. The method is based on a Hybrid Life-Cycle Assessment, *which considers the territorial and geographical characteristics in the calculation of energy consumption and associated emissions. It identifies four macro phases of the construction process (excavation, production and application of building materials, operability of tunnels and construction sites), each of which is broken down into specific sub-activities. The method is tested on the Brenner base tunnel, for which emissions equal to 2.28 m of CO_2 are estimated. The majority of them (85%) derives from the production of concrete and steel, while the other phases contribute to a more limited extent. The results are useful in the process of optimisation of the implementation processes, providing guidance on factors to consider in order to reduce CO_2 emissions. In addition, the method can serve to decision makers for an assessment of transport policies that is more attentive to environmental issues.*

Keywords: *railway tunnel, construction phase, CO_2 emissions, Hybrid LCA, Brenner HS/HC line.*

2. Introduction

Transport plays a key role in limiting the consequences of global warming: it is indeed responsible for about 26% of greenhouse gas (GHG) emissions and their emissions are increasing (+30% compared to 1990 [1]). Carbon diox-

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(CO_2) riveste un ruolo preponderante, costituendo circa il 75% di tutti i GHG [2].

Per contrastare tale tendenza, l'Unione Europea [3] ha proposto un modello di crescita volto a favorire i mezzi di trasporto più sostenibili e meno impattanti da un punto di vista delle emissioni di sostanze inquinanti. Nel caso del trasporto terrestre, ciò coincide con la ferrovia [4].

Con tale scopo, sono stati ideati i corridoi TEN-T (Trans-European Networks-Transport), reti transnazionali di collegamento tra le principali città europee [5]. Nelle sue tratte principali, la rete TEN-T è prevista operativa entro il 2030 ed entro il 2050 le ferrovie Alta Velocità/Alta Capacità (AV/AC), assi portanti di tali reti, devono diventare il mezzo di trasporto maggiormente utilizzato per gli spostamenti di medio raggio. A seguito di tali decisioni, negli ultimi anni gli investimenti a favore del potenziamento ferroviario sono stati significativi e dovrebbero portare all'ammodernamento o alla costruzione di nuove linee transnazionali.

Nei tratti in cui attraversano le Alpi, queste linee necessitano di gallerie di base, ovvero tunnel che corrono in piano o con pendenze limitate, tali da consentire ai treni una prestazione costante a fronte di un'orografia più complessa. Queste opere ingegneristiche sono tanto complesse da un punto di vista tecnico, quanto di difficile valutazione rispetto agli impatti che producono. Si conoscono infatti le principali caratteristiche tecniche: costi (presunti), tempi di realizzazione, durata dei lavori, risparmio in termini di tempo, ma gli impatti a livello territoriale e ambientale sono di più difficile valutazione e non sempre vengono analizzati in maniera esaustiva.

A livello normativo, la valutazione di impatto ambientale (VIA) e la valutazione ambientale strategica (VAS) sono gli strumenti predisposti all'analisi di questi aspetti. Tuttavia, nella pratica, essi si soffermano perlopiù su problematiche relative all'impatto paesaggistico e alle risorse naturali, spesso trascurando la parte relativa agli impatti energetici e agli inquinanti atmosferici che ne derivano. Ciò è dovuto anche alla mancanza di una metodologia condivisa.

In alcune memorie ([6], [7]) è stata definita una metodologia per la quantificazione delle emissioni di CO_2 derivanti da una nuova linea ferroviaria come strumento integrativo rispetto alla VIA. In [8] è stato valutato l'impatto in termini di CO_2 relativo all'introduzione di una nuova infrastruttura di trasporto in un territorio. In particolare, considerando diversi scenari di traffico sul lungo periodo, è stata considerata l'opportunità o meno di realizzare l'opera e si è stimato il potenziale risparmio di CO_2.

Il presente contributo si propone di approfondire la fase di costruzione dell'opera, con la definizione delle sue operazioni principali e le relative modalità di calcolo delle emissioni di CO_2. L'obiettivo è quello di fornire una metodologia esaustiva e replicabile per valutare e monitorare le emissioni anche durante la realizzazione dell'opera. Differenziandosi dai tradizionali approcci di *Life-Cycle Assessment* (LCA), la valutazione si basa su un *Hy-*

ide (CO_2) plays a major role, forming about 75% of all GHG [2].

To contrast this trend, the European Union [3] proposed a growth model aimed at promoting more sustainable and less impacting transport means from the point of view of emissions of pollutants. In the case of land transport, this coincides with conventional rail [4].

With this purpose, TEN-T (Trans-European Networks-Transport) corridors, transnational networks were designed linking major cities in Europe [5]. In its main routes, the TEN-T network is planned to be operational by 2030 and the High Speed/High Capacity railways (HS/HC) by 2050, cornerstones of such networks, must become the most widely used means of transport for medium range travel. Following these decisions, in recent years, investments in favour of railway development were significant and should lead to the modernisation or construction of new trans-national lines.

In sections where they cross the Alps, these lines need base tunnels, or tunnels that run flat or with limited gradients, such as to enable trains to travel at constant performance in the face of a more complex orography. These engineering works are equally complex from a technical standpoint, as difficult to assess compared to the effects they produce. In fact the main technical characteristics are known: (alleged) costs, lead times, duration of the works, time-saving, but the impacts on the territory and the environment are more difficult to evaluate and not always analysed exhaustively.

At a regulatory level, the environmental impact assessment (EIA) and Strategic Environmental Assessment (SEA) are the instruments available for the analysis of these aspects. However, in practice, they dwell mostly on issues concerning the landscape and natural resources impact, often neglecting that part relating to the resulting energy and air pollutants impacts. This is also due to the lack of a common methodology.

In some essays ([6], [7]) a methodology for quantifying CO_2 emissions resulting from a new railway line was defined as a complementary tool compared to the EIA. In [8] the impact in terms of CO_2 relating to the introduction of a new transport infrastructure in the territory was assessed. In particular, considering different scenarios of traffic in the long term, the opportunity or not to build the work was considered and the potential CO_2 savings were estimated.

This paper aims at examining the construction phase of the work, with the definition of its main operations and the related CO_2 emissions calculation methods. The aim is to provide a comprehensive and replicable methodology to assess and monitor emissions even during the project execution. Differentiating itself from the traditional approaches of Life-Cycle Assessment *(LCA), the assessment is based on a* Hybrid *LCA [9], a method that takes into account the* *brid* LCA [9], metodo che tiene in considerazione le particolarità del processo di costruzione, il contesto territoriale e le specificità geografiche. Tale approccio è stato già adottato per alcuni sistemi infrastrutturali quali i ponti [10] o la pavimentazione autostradale [9], ma non ci sono in letteratura studi analoghi riguardante la realizzazione di gallerie.

L'articolo è strutturato nel seguente modo: nel paragrafo 3 vengono descritte le fasi per il calcolo delle emissioni, mentre nel paragrafo 4 la metodologia viene testata sul caso studio della galleria di base del Brennero. Il paragrafo 5 è dedicato ad un riepilogo delle emissioni complessive e a un confronto rispetto alla fase di esercizio. Alcune note finali, comprensive di indicazioni in termini di replicabilità e adattabilità in altri contesti, concludono il contributo.

3. Metodologia di calcolo

Il metodo per calcolare le emissioni di CO_2 derivanti dalla realizzazione di un tunnel ferroviario differisce dalle tradizionali valutazioni LCA di un prodotto perché il risultato non presuppone assunzioni universalmente valide da un punto di vista energetico, né il ricorso a valori adottabili in ogni contesto. La costruzione di un tunnel ferroviario è il frutto di un processo che si compone di una serie articolata di operazioni, macchinari e materiali, la cui scelta solitamente dipende dai progettisti e dalle ditte esecutrici, oltre che dalle indicazioni normative. Inoltre nella determinazione dei consumi energetici e delle relative emissioni, bisogna considerare il contesto territoriale in cui l'opera viene realizzata. L'approccio *Hybrid* LCA prevede inizialmente l'identificazione delle macro fasi che compongono il processo. Per quanto riguarda la realizzazione di una galleria ferroviaria, le emissioni di CO_2 includono la fase di progettazione, la costruzione e la fase di dismissione. In questo contributo ci si sofferma sulla fase di costruzione vera e propria, in quanto responsabile della quota principale di emissioni [8]: la fase di progettazione incide infatti in maniera poco significativa (circa lo 0,03% dell'intera fase di costruzione [11], mentre la fase di dismissione può essere trascurata, considerata la lunga vita operativa di tali opere (generalmente valutata in almeno 100 anni).

Nella fase di costruzione, le operazioni di scavo delle gallerie, la produzione e il trasporto del materiale da costruzione per la stabilizzazione dello scavo, l'operatività delle gallerie e il funzionamento dei cantieri sono le attività che incidono maggiormente dal punto di vista delle emissioni di CO_2. Al fine di impostare la fase di calcolo, queste quattro macro-fasi possono essere ulteriormente dettagliate in singole operazioni (fig. 1).

Nelle operazioni di scavo si distinguono lo scavo convenzionale e lo scavo meccanizzato. In riferimento ai materiali utilizzati, il contributo più consistente in termini di emissioni di CO_2 deriva dalla produzione di cemento e acciaio, mentre sono considerabili marginali il materiale plastico utilizzato per le tubazioni e altri materiali di fini-

particularities of the construction process, the local context and geographical circumstances. This approach has already been adopted for some infrastructure systems such as bridges [10] or the motorway paving [9], but there are no similar studies in literature concerning the construction of tunnels.

The article is structured as follows: paragraph 3 describes the steps for calculating emissions, while in paragraph 4 the methodology is tested on the case study of the Brenner base tunnel. Paragraph 5 is dedicated to a summary of the overall emissions and a comparison with respect to the operation phase. Some final notes, including indications in terms of replicability and adaptability to other contexts, conclude the contribution.

3. Calculation methodology

The method for calculating CO_2 emissions from the construction of a railway tunnel differs from traditional LCA assessments of a product because the result does not presuppose universally valid assumptions from an energy point of view, nor the use of values that can be adopted in all settings. The construction of a railway tunnel is the result of a process that consists of an articulated series of operations, machinery and materials, the choice of which usually depends on the designers and the executor firms, in addition to the regulatory guidelines. Also in the determination of energy consumption and emissions, we must consider the local context in which the work is performed. The Hybrid *LCA approach initially includes identifying macro phases of the process. Regarding the construction of a railway tunnel, CO_2 emissions include the design, construction and decommissioning phase. In this paper we focus on the construction phase itself, as responsible for the largest share of emissions [8]: the planning phase in fact does not have a significant impact (approximately 0.03% of the entire construction phase [11], while the decommissioning process can be neglected, given the long operational life of these works (generally evaluated in at least 100 years).*

During the construction phase, the excavation of the galleries, production and transportation of building material for the stabilisation of the excavation, the operability of the galleries and the operation of sites are activities that have the greatest effect in terms of CO_2 emissions. In order to set up the calculation phase, these four macro-phases can be further detailed in individual operations (fig. 1).

Excavation operations are distinguished in conventional excavation and mechanised excavation. In reference to the materials used, the most substantial contribution in terms of CO_2 emissions comes from the production of cement and steel, while the plastic material used for piping and other finishing materials are considered marginal. Transporting building materials and excavation material up to deposits, distinguishing between conveyor belt and

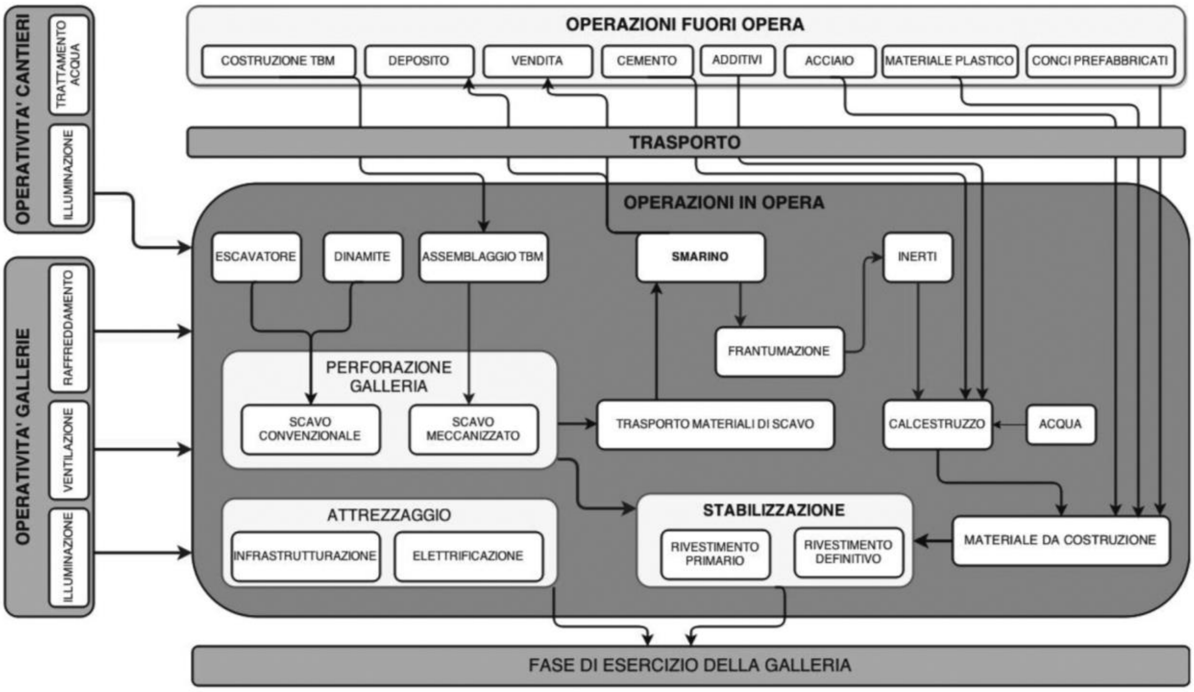

Fig. 1 - Schema delle fasi di costruzione di un'infrastruttura ferroviaria.
Fig. 1 - Diagram of the railway infrastructure construction phases.

tura. Deve inoltre essere considerato il trasporto dei materiali da costruzione e del materiale di scavo fino ai depositi, distinguendo tra nastro trasportatore e camion. Le emissioni derivanti dalle operazioni di cantiere sono causate principalmente dall'illuminazione delle aree esterne, dal funzionamento delle officine meccaniche e degli uffici, e dagli impianti per il trattamento delle acque. Infine, il contributo dovuto all'operatività delle gallerie include le emissioni prodotte per l'illuminazione, la ventilazione e il raffreddamento.

Definite le fasi principali che compongono il processo, l'approccio *Hybrid LCA* presuppone una raccolta accurata dei dati. Gli strumenti più utili risultano l'analisi della documentazione progettuale disponibile, il confronto con i progettisti e le ditte costruttrici, nonché le rilevazioni dirette effettuate in cantiere. Se invece l'analisi è condotta quando il progetto è ancora allo stato di previsione, la conoscenza delle fasi e delle tecniche utilizzate per la costruzione è limitata. Per ovviare a tale problema si rende necessario ricorrere ai dati presenti in letteratura, a stime basate sull'analogia e alla raccolta di informazioni presso ditte specializzate, adattandoli ove possibile al caso in esame.

Il calcolo vero e proprio si basa su un processo sintetizzabile in tre fasi: combustione, produzione energetica ed emissioni di CO_2. La CO_2 di origine antropica è infatti rilasciata durante tutte le attività connesse alla produzione e trasformazione di energia associate ad una combu-

truck must also be considered. Emissions from construction site operations are mainly caused by the lighting of outdoor areas, operation of mechanical workshops and offices, and by water treatment plants. Finally, the contribution due to the operability of the galleries includes emissions for lighting, ventilation and cooling.

Once the main phases that make up the process have been defined, the Hybrid *LCA approach presupposes thorough data collection. The most useful tools are the analysis of the project documentation available, the comparison with designers and construction companies, as well as direct surveys carried out on site. However, if the analysis is carried out when the project is still in the forecasting phase, the knowledge of the building steps and techniques is limited. To work around this problem data in literature, estimates based on analogy and the collection of information at specialised companies must be used, adapting them where possible to the present case.*

The actual calculation is based on a process that can be summed up in three stages: combustion, energy production and CO_2 emissions. Anthropogenic CO_2 is in fact released during all activities related to the production and processing of energy associated with combustion. Since it is not always possible to trace CO_2 emissions directly, the lack of data can be overcome by estimating the final energy consumption and translating the latter, through appropriate factors, into CO_2 emissions according to the report (formula 1):

stione. Poiché non sempre è possibile risalire in maniera diretta alle emissioni di CO_2, si può sopperire alla mancanza di dati stimando i consumi finali di energia e tradurre quest'ultimi, attraverso opportuni fattori, in emissioni di CO_2 secondo la relazione (formula 1):

$$E_c = \Sigma_m q_m \cdot h_m + \Sigma_v f_v \cdot h_v \qquad (1)$$

dove:

- E_c indica le emissioni di CO_2 della fase di costruzione;
- m è il tipo di materiale;
- q_m è la quantità di materiale;
- h_m è il fattore di emissione di CO_2 relativa al materiale m;
- v è il vettore energetico(1);
- f_v è il fabbisogno di energia ottenuto da ciascun vettore energetico v;
- h_v è il fattore di emissione di CO_2 relativa al vettore energetico v.

In letteratura sono state prodotte diverse banche dati che analizzano i vettori energetici e i materiali [12], [13], [14], [15]; in entrambi i casi, i fattori di emissione di CO_2 sono funzione del metodo utilizzato e della dimensione geografica considerata. In mancanza di dati diretti sulle emissioni di CO_2, sono da preferire i fattori aderenti alla realtà locale. Inoltre, è importante considerare in maniera omogenea le quote di CO_2 relative all'intero ciclo di produzione delle fonti energetiche e le quote relative a tutto il ciclo di vita dei materiali. Si tratta di considerare trascurabili o meno le emissioni di CO_2 prodotte a seguito dell'estrazione delle materie prime, trasporto, lavorazione e smaltimento dei materiali, e quelle relative alla produzione, trasporto della fonte energetica considerata, oltre agli eventuali produzione, utilizzo e manutenzione degli impianti utilizzati per il suo sfruttamento.

Bisogna considerare, tuttavia, che essi hanno un peso non secondario nell'intero processo e la scelta deve essere compiuta in maniera consapevole e giustificata. Le fasi qui esaminate vengono valutate nel prossimo paragrafo su un caso studio reale (il tunnel di base del Brennero), in modo da comprendere quali sono le componenti che impattano maggiormente sulle emissioni di CO_2 ed ottimizzare il processo realizzativo dell'opera stessa.

4. Emissioni di CO_2 per la costruzione del BBT

4.1. Il corridoio Verona-Monaco, descrizione dell'infrastruttura e del BBT

Il corridoio Verona-Monaco, parte centrale della linea TEN-T n°1, rientra tra le maggiori linee ferroviarie AV/AC

$$E_c = \Sigma_m q_m \cdot h_m + \Sigma_v f_v \cdot h_v \qquad (1)$$

where:

- *E_c indicates CO_2 emissions during construction;*
- *m is the type of material;*
- *q_m is the amount of material;*
- *h_m is the CO_2 emission factor for the m material;*
- *v is the energy carrier(1);*
- *f_v is the energy requirement obtained from each energy carrier v;*
- *h_v is the CO_2 emission factor related to the energy carrier v.*

In literature various databases were produced to analyse the energy carriers and materials [12], [13], [14], [15]; in both cases, the CO_2 emission factors are a function of the method used and the geographic dimension considered. In the absence of direct data on CO_2 emissions, factors pertinent to the local reality are preferable. In addition, it is important to consider the CO_2 percentage concerning the entire production cycle of energy sources in a homogeneous manner and the amount related to the whole life cycle of the materials. It is a matter of considering negligible or less CO_2 emissions produced as a result of raw material extraction, transport, processing and disposal of materials, and those related to production, transport of the energy source considered, in addition to any production, use and maintenance of systems used for the exploitation thereof.

We must consider, however, that they do not have secondary importance in the whole process and the choice must be made in a conscious and justified manner. The steps here examined are evaluated in the next paragraph on a real case study (the Brenner base tunnel), so as to understand what are the components that have a major impact on CO_2 emissions and optimise the implementation process of the work itself.

4. CO_2 emissions for the construction of the BBT

4.1. Verona-Munich corridor, description of the infrastructure and of the BBT

The Verona-Munich corridor, the central part of the TEN-T n° 1 line, is one of the major HS/HC railway lines in Europe: it is the main link between Germany (Bavaria), Austria (Tyrol) and Italy (South Tyrol, Trentino and Veneto), for both freight and passenger transport. Considering the North-South direction, the corridor begins in Monaco and ends in Verona, passing through the valleys of the low-

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(1) Per vettori energetici si intendono i mezzi, le apparecchiature o i fluidi che consentono il trasporto dell'energia. In senso figurato, tra i vettori si annovera anche l'energia elettrica, la quale viene contemporaneamente considerata sia un vettore, sia una fonte energetica.

(1) The meaning of energy carriers is the means, equipment or fluids that allow carrying energy. Figuratively, electricity is among carriers that is considered a carrier and an energy source at the same time.

europee: essa rappresenta il principale collegamento tra la Germania (Baviera), l'Austria (Tirolo) e l'Italia (Alto Adige, Trentino e Veneto), sia per il trasporto merci, sia per il trasporto passeggeri. Considerando la direzione Nord-Sud, il corridoio inizia a Monaco e finisce a Verona, passando attraverso le valli del basso Inn (Kufstein-Innsbruck), del Sill (Innsbruck-Brennero), dell'Isarco (Brennero-Bolzano) e dell'Adige (Bolzano-Verona). La nuova ferrovia AV/AC è divisa in tre sezioni: la tratta di accesso nord (Monaco-Kufstein, Kufstein-Kundl, Kundl-Baumkirchen); il Tunnel di Base del Brennero (BBT); la tratta di accesso sud (Fortezza-Ponte Gardena, e la circonvallazione di Bolzano, Trento e Verona).

Il BBT (fig. 2), galleria ferroviaria di base lunga circa 55 km che collega Innsbruck (A) a Fortezza (I)(2), è l'opera più complessa della linea. Esso accorcerà l'attuale linea ferroviaria di circa 20 km nella tratta tra Innsbruck e Fortezza e di 35 km tra Monaco e Verona, con un andamento rettilineo che elimina le problematiche relative ai raggi di curvatura. Rispetto alla linea storica (dove, per la tratta Innsbruck-Brennero, si registrano punte del 26‰), il BBT prevede una pendenza determinante in direzione nord – sud del 6,7‰, e in direzione sud – nord del 4‰. Il culmine del BBT, presso il confine di stato, risulterà ad un'altezza di 794 m s.l.m., a fronte degli attuali 1.370 m.s.l.m. [16]. I tempi di percorrenza tra Verona e Monaco diminuiranno di circa 2 ore e 30 minuti, passando dalle attuali 5 ore e 23 minuti a 3 ore, diventando al contempo di circa un'ora e trenta minuti più veloci rispetto all'autovettura.

I lavori preliminari, iniziati nel 1999, si trovano attualmente in una fase avanzata di realizzazione. Gli scavi per la galleria principale sono iniziati nel 2011 e la messa in esercizio dell'intero sistema è attesa per l'anno 2025. I costi di costruzione sono stimati in circa 7,9 Mld €.

Da un punto di vista tecnico, il BBT è un sistema a due canne, che distano 70 m l'una dall'altra e sono collegate ogni 333 metri da cunicoli percorribili a piedi per permettere l'evacuazione in caso di incidente. Alcuni di essi, posti a una distanza di 2 km l'uno dall'altro, ospitano anche gli impianti tecnologici. Ogni 6 km, inoltre, i cunicoli sono atti a contenere vasche di accumulo per l'acqua, necessaria per lo spegnimento di eventuali incendi.

In asse alle due gallerie ferroviarie, ad una quota inferiore di circa 10 m, si trova il cunicolo esplorativo (o di servizio). Esso si è reso necessario soprattutto per effettuare, preliminarmente alla costruzione delle gallerie principali, le prospezioni geologiche, quali sondaggi preliminari, sondaggi verticali rispetto all'asse della galleria, misurazioni delle deformazioni, ecc. Il cunicolo ha inoltre un ruolo importante nella logistica della costruzione limitando al minimo gli impatti sull'esterno, poiché viene utilizzato per il trasporto di materiale di scavo e del materiale di costruzione della galleria principale.

er Inn (Kufstein-Innsbruck), Sill (Innsbruck-Brenner), Isarco (Brenner-Bolzano) and Adige (Bolzano-Verona) valleys. The new HS/HC railway line is divided into three sections: the North access route (Munich-Kufstein, Kufstein-Kundl Kundl-Baumkirchen); the Brenner Base Tunnel (BBT); the southern access route (Fortezza-Ponte Gardena, and the Bolzano, Trento and Verona ring section).

The BBT (fig. 2), base railway tunnel with a length of about 55 km, connecting Innsbruck (A) to Fortezza (I) (2), is the most complex work of the line. It will shorten the current railway line of about 20 km in the section between Innsbruck and Fortezza and of 35 km between Munich and Verona, with a straight line course that eliminates problems related to the radius of curvature. Compared to the old line (where for the Innsbruck-Brennero route, there are peaks of 26 ‰), the BBT provides a crucial North – South slope of 6.7 ‰, and of 4‰ in the South – North direction of travel. The BBT peak, at the state border, will be at an elevation of 794 m above sea level, compared to the current 1.370 m above sea level [16]. Travel times between Verona and Munich will decrease by about 2 hours and thirty minutes, passing from the current 5 hours and 23 minutes to 3 hours, becoming at the same time approximately one hour and thirty minutes faster than cars.

Preliminary works that began in 1999 are currently at an advanced implementation phase. Excavations for the main gallery began in 2011 and commissioning of the entire system is expected by the year 2025. Construction costs are estimated at about 7.9 billion €.

From a technical point of view, the BBT is a two-hole system, spaced 70 m from each other and connected every 333 metres by tunnels practicable on foot to allow evacuation in case of an accident. Some of them, placed at a distance of 2 km from each other, are also home to the technological systems. Furthermore every 6 km, the tunnels are also suitable to contain water storage tanks, needed to extinguish any possible fires.

In the centre line of the two railway tunnels, at an altitude less than about 10 m, lies the exploratory (or service) tunnel. It was necessary above all to implement geological explorations, before the construction of the main tunnels, such as preliminary surveys, vertical surveys compared to the axis of the gallery, deformation measurements, etc. The exploratory tunnel has also an important role in the construction logistics minimising impacts on the outside, because it is used for the transport of excavated material and construction material of the main gallery.

The gallery will host three multifunction places (Innsbruck, St Jodok and Trens), accessible from the outside through the vehicular driveways of Ahrntal, Wolf and

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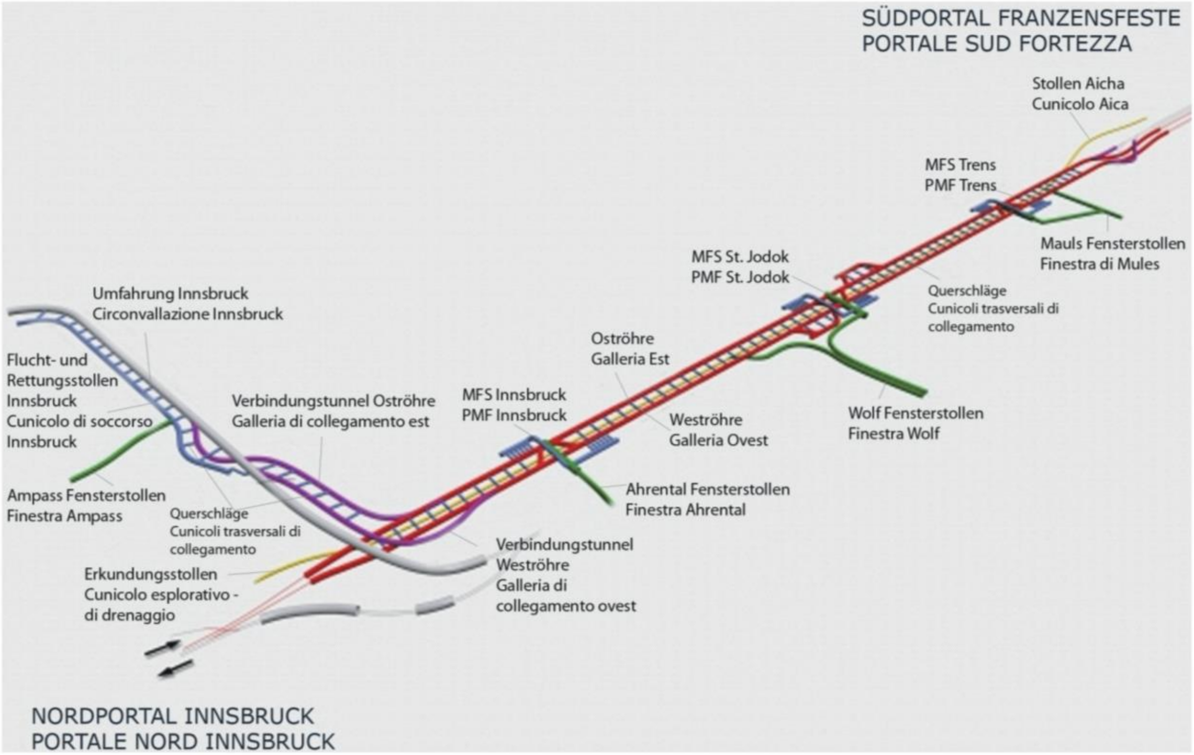
(2) Se si considera anche la circonvallazione di Innsbruck, la lunghezza è pari a 64 km.

(2) If the Innsbruck ring section is considered, the length is 64 km.



(Fonte - Source*: [17])*

Fig. 2 - Il sistema BBT.
Fig. 2 - The BBT system.

La galleria ospiterà tre posti multifunzione (Innsbruck, St. Jodok e Trens), accessibili dall'esterno attraverso le gallerie carrabili di Ahrntal, Wolf e Mules. I posti multifunzione sono collocati a una distanza di 15-25 km tra loro e sono dotati di fermate d'emergenza per il soccorso di passeggeri in treni incidentati, di impianti per la gestione dell'esercizio e dei lavori di manutenzione.

Il BBT si collega all'infrastruttura esistente nelle stazioni di Innsbruck e di Fortezza. Nella città austriaca, dalla stazione centrale, un collegamento a cielo aperto corre parallelo ai binari esistenti. L'adiacente circonvallazione, ora adibita al trasporto merci, verrà potenziata realizzando un cunicolo di soccorso e la finestra di accesso di Ampass, per renderla adatta al trasporto passeggeri. Le gallerie di collegamento tra la circonvallazione e il BBT sono a binario unico e permettono, senza far ricorso ad intersezioni a raso, di variare il binario legale dal destro, usato in Austria, al sinistro, tipico dell'Italia. Nel suo percorso, il BBT attraversa due volte il fiume Sill (tramite ponti), e l'Isarco (in sotterraneo), raggiungendo la stazione di Fortezza, dove i binari della nuova linea ferroviaria vengono collocati a sud-ovest. Attraverso un collegamento a raso rispetto alla tratta storica, i treni possono venire deviati dall'una all'altra linea.

Mules. The multifunction places are set at a distance of 15-25 km between them and are equipped with emergency stops to rescue passengers in train accidents, systems for operation management and maintenance works.

The BBT connects to the existing infrastructure in the stations of Innsbruck and Fortezza. In the Austrian town, an open-air connection runs parallel to existing tracks from the central station. Creating a rescue tunnel and the Ampass access window, will enhance the adjacent ring section, now used for freight transport, and will make it suitable for passenger transport. The connection tunnels between the ring section and the BBT are single track and, without recourse to on grade intersections, allow changing the right line from right-side, used in Austria, to left-side, typical of Italy. Along its path, the BBT crosses the Sill River twice (with bridges), and the Isarco (underground), reaching the Fortezza station, where the tracks of the new railway are placed south-west. Through an on grade connection compared to the historical one, trains can be diverted from one line to the other.

4.2. Data collection and calculation assumptions

As stated in the definition of methodology, the data and information listed below are primarily derived from the

4.2. Raccolta dati e ipotesi di calcolo

Come precisato in sede di definizione metodologica, i dati e le informazioni di seguito riportati derivano principalmente dalla documentazione tecnica fornita dalla società BBT SE e dalle rilevazioni dirette effettuate presso i cantieri di Aica e Mules, nonché da un confronto diretto con i progettisti dell'opera. Inoltre, per coprire tutti i settori, si sono raccolte informazioni da esperienze di costruzione di opere analoghe; al contempo sono state approfondite le diverse tecniche costruttive richiedendo informazioni a ditte specializzate ed effettuando specifiche ricerche in letteratura. Infine, nel presente paragrafo si fa riferimento a una serie di tabelle e di dati che in taluni casi non è stato possibile riportare nella loro interezza, considerata la complessità dei calcoli. Si è pertanto deciso di riportare solo quelli fondamentali alla comprensione dell'intero processo; il lettore interessato trova ulteriori approfondimenti in [18].

Per quanto riguarda i vettori energetici e i materiali, al fine di poter eseguire un confronto tra le varie voci di calcolo considerate, sono stati utilizzati quei fattori che tengono in considerazione le emissioni di CO_2 relative all'intero ciclo di produzione delle fonti energetiche, e a tutto il ciclo di vita dei materiali. Inoltre sono stati preferiti quelli coerenti con il contesto territoriale (tabella 1). Per il cemento pozzolanico e Portland, i tipi di cemento maggiormente utilizzati nei cantieri, i dati sono stati forniti direttamente da BBT SE.

I valori utilizzati risultano in linea con i dati presenti in letteratura relativi ad altri tipi di cemento o ad altre realtà geografiche [15], [19]. In riferimento all'acciaio, non essendo disponibili valori nazionali per Italia ed Austria, si è fatto riferimento ai valori forniti dal centro di ricerca per l'economia energetica di Monaco [15]. Per il calcolo delle emissioni derivanti dalla combustione dei derivati petroliferi, il riferimento sono le indicazioni dell'IPCC [12]. Infine, i fattori di emissione dell energia elettrica derivano dai mix italiani ed austriaci forniti dal gruppo Terna, azienda che gestisce la trasmissione della rete nazionale italiana. Essendo l'infrastruttura per il

technical documentation supplied by the company BBT SE and from surveys conducted directly at the Aica and Mules sites, as well as from a direct confrontation with the designers of the work. Also, to cover all sectors, information was gathered from experiences of similar construction works; at the same time different construction techniques were studied requesting information to specialised companies and carrying out specific research in the literature. Finally, this paragraph refers to a series of tables and data that in some cases was impossible to report in their entirety, considering the complexity of the calculations. It was therefore decided to report only those essential to the understanding of the entire process; the interested reader will find further information in [18].

As far as energy carriers and materials are concerned, in order to make a comparison between the various items considered in the calculation, those factors were used taking into account CO_2 emissions related to the whole production cycle of energy sources and to the whole life cycle of the materials. Furthermore those consistent with the territorial context were preferred (table 1). For pozzolanic and Portland cement, the cement types most commonly used in construction sites, the data has been provided directly by BBT SE.

The values used are in line with the data in literature about other types of cement or other geographical areas [15], [19]. With reference to steel, national values not being available for Italy and Austria, reference was made to the values provided by the Research Centre for energy economy of Munich [15]. For the calculation of emissions from the combustion of petroleum derivatives, reference is to be made to the IPCC indications [12]. Finally, electricity emission factors derive from Italian and Austrian mixes provided by the Terna group, a company that manages the Italian national network transmission. As the infrastructure is 60% in Austria and 40% in the Italian territory, 0.304 kg CO_2/kWh was taken as conversion factor, the weighted average of the values of the two nations. If the electricity produced not at national level had been taken into considera-

TABELLA 1 – *TABLE 1*

Fattori di emissione di CO_2 dei materiali e dei vettori energetici maggiormente impiegati nella costruzione del BBT
CO_2 emission factors for materials and energy carriers mainly used in the construction of the BBT

Materiale ***Material***	**Fattore emissione** ***Emission factor*** **[Kg CO_2/t]**	**Fonte** ***Source***	**Vettore energetico** ***Energy carrier***	**Fattore emissione** ***Emission factor*** **[Kg CO_2/kWh]**	**Fonte** ***Source***
Acciaio strutturale *Structural steel*	1.980	[15]	Gas naturale *Natural gas*	0,202	[12]
Acciaio macchine *Machine steel*	1.449	[15]	Gasolio *Diesel oil*	0,267	[12]
Cemento Portland *Portland cement*	622	[21]	Energia elettrica (A) *Electric power (A)*	0,216	[22]
Cemento pozzolanico *Pozzolanic cement*	576	[21]	Energia elettrica (IT) *Electric power (IT)*	0,435	[22]

60% in territorio austriaco e per il 40% in territorio italiano, si è preso come fattore di conversione 0,304 kg CO$_2$/kWh, media pesata dei valori delle due nazioni. Se fosse stata considerata l'energia elettrica prodotta non a livello nazionale, ma regionale (Alto Adige per l'Italia e Tirolo per l'Austria), le emissioni sarebbero risultate significativamente inferiori: nel 2009, la componente idroelettrica (la cui produzione è tra le meno impattanti in termini di CO$_2$) in Alto Adige ha rappresentato il 96,1% della produzione totale di energia elettrica, a fronte di un 10,9% a livello nazionale [20] e valori elevati sono stati raggiunti anche in Tirolo.

La scelta di far riferimento ai valori nazionali dipende da questioni di opportunità: essendo la rete elettrica dell'Alto Adige collegata con quella delle regioni limitrofe, non è possibile determinare con precisione da quale fonte sia stata prodotta l'energia consumata a livello locale. La scala nazionale, in forma cautelativa, rappresenta quindi la dimensione preferibile. Infine si segnala che, nell'incertezza di determinare quale sarà l'evoluzione futura dei mix elettrici nazionali, si è fatto riferimento ai fattori di conversione relativi al 2008, anno che è stato scelto come riferimento nell analisi perché consente di disporre di una serie di dati completa. Questi valori sono la base per il calcolo delle attività nelle diverse fasi descritte in figura 1.

4.3. Scavo delle gallerie

L'operazione di scavo prevede la ciclica ripetizione delle fasi di perforazione e di trasporto del materiale di scavo ai depositi.

4.3.1. Perforazione

Per la perforazione si utilizzano due metodi: quello convenzionale, con escavatori ed esplosivo e quello meccanizzato, con la Tunnel Boring Machine (TBM). Sono scavati con metodo convenzionale le finestre di accesso, il 38% delle due canne principali (galleria est e ovest), i cunicoli trasversali di collegamento, le componenti delle stazioni multifunzione e della circonvallazione di Innsbruck [23], [24] e il 35% del cunicolo esplorativo [25], per un totale di 119 km. Lo scavo convenzionale prevede che vengano mediamente effettuate due volate al giorno, ciascuna delle quali permette, a seconda della conformazione della roccia, un avanzamento dai 3 ai 4 m [26].

Nei cantieri si utilizza una macchina tipo Jumbo, la cui potenza è pari a 255 kW [27]. La macchina, alimentata elettricamente, è in funzione mediamente 7 giorni su 7, 6 ore al giorno. Ipotizzando un avanzamento medio giornaliero di 5 m, le emissioni derivanti dalla macchina Jumbo sono pari a 94,72 kg/m. In seguito alla fase di brillamento, vengono impiegati altri escavatori, attrezzati con speciali martelli o scalpelli idraulici: essi servono alla

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(3) Materiale roccioso frantumato che risulta dalla perforazione delle gallerie in roccia.

tion, but the regional one (South Tyrol for Italy and Tyrol for Austria), emissions would have been significantly lower: in 2009, the hydroelectric component (whose production is among the less impacting in terms of CO$_2$) in South Tyrol accounted for 96.1% of the total electricity production, compared with 10.9% nationally [20] and high values were reached in Tyrol also.

The decision to refer to national values depends on matters of opportunity: being the electricity network in South Tyrol connected with that of the neighbouring regions, it is not possible to accurately determine from what source the energy consumed locally has been produced. The national scale, in a precautionary form, is the preferable dimension. Finally it should be noted that, in the uncertainty of determining what the future evolution of national electric mixes will be, reference was made to the conversion factors for the year 2008, a year that was chosen as reference in the analysis because it allows having a complete data set. These values are the basis for the calculation of activities in the different stages described in fig. 1.

4.3. Excavation of the galleries

The excavation provides for the cyclic repetition of the drilling and transportation phases of excavated material to deposits.

4.3.1. Drilling

Two methods are used for drilling: the conventional one, with excavators and explosives and the mechanised one, with the Tunnel Boring Machine (TBM). Access windows are excavated using the conventional method, 38% of the two main tubes (east and west tunnel), the cross connection burrows, the components of the multi-function stations and of the Innsbruck ring section [23], [24] and 35 % of the exploratory tunnel [25], for a total of 119 km. The conventional excavation provides for the execution of two drilling and blasting operations a day on average, each of which allows, a progress of 3 to 4 m, depending on the conformation of the rock [26].

A jumbo type machine is used on construction sites, whose power is equal to 255 kW [27]. The electrically powered machine is in operation on average 7/ 7 days, 6 hours a day. Assuming an average daily progress of 5 m, the emissions from the Jumbo machine amounted to 94.72 kg/m. Following the blasting phase, other excavators are used, equipped with special hydraulic hammers or chisels: they serve to the accommodation and cleaning of the excavation surface. Their contribution, equal to 54 kg/m, determines the overall emission of the conventional excavation equal to 149 kg/m. The explosive is also among the factors that

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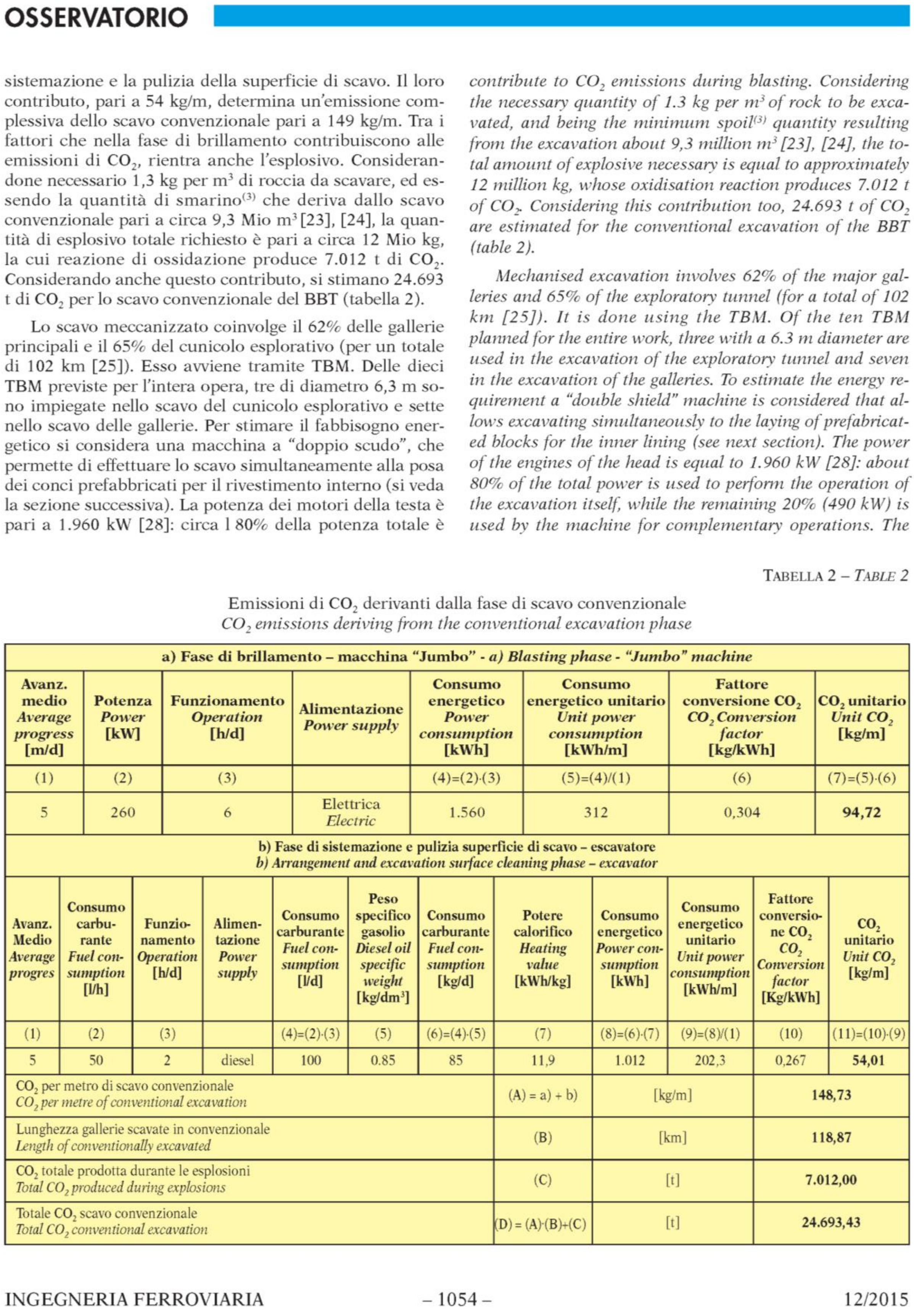
(3) Crushed rocky material from the drilling of rock galleries.



sistemazione e la pulizia della superficie di scavo. Il loro contributo, pari a 54 kg/m, determina un'emissione complessiva dello scavo convenzionale pari a 149 kg/m. Tra i fattori che nella fase di brillamento contribuiscono alle emissioni di CO_2, rientra anche l'esplosivo. Considerandone necessario 1,3 kg per m^3 di roccia da scavare, ed essendo la quantità di smarino[(3)] che deriva dallo scavo convenzionale pari a circa 9,3 Mio m^3 [23], [24], la quantità di esplosivo totale richiesto è pari a circa 12 Mio kg, la cui reazione di ossidazione produce 7.012 t di CO_2. Considerando anche questo contributo, si stimano 24.693 t di CO_2 per lo scavo convenzionale del BBT (tabella 2).

Lo scavo meccanizzato coinvolge il 62% delle gallerie principali e il 65% del cunicolo esplorativo (per un totale di 102 km [25]). Esso avviene tramite TBM. Delle dieci TBM previste per l'intera opera, tre di diametro 6,3 m sono impiegate nello scavo del cunicolo esplorativo e sette nello scavo delle gallerie. Per stimare il fabbisogno energetico si considera una macchina a "doppio scudo", che permette di effettuare lo scavo simultaneamente alla posa dei conci prefabbricati per il rivestimento interno (si veda la sezione successiva). La potenza dei motori della testa è pari a 1.960 kW [28]: circa l 80% della potenza totale è

contribute to CO_2 emissions during blasting. Considering the necessary quantity of 1.3 kg per m^3 of rock to be excavated, and being the minimum spoil[(3)] quantity resulting from the excavation about 9,3 million m^3 [23], [24], the total amount of explosive necessary is equal to approximately 12 million kg, whose oxidisation reaction produces 7.012 t of CO_2. Considering this contribution too, 24.693 t of CO_2 are estimated for the conventional excavation of the BBT (table 2).

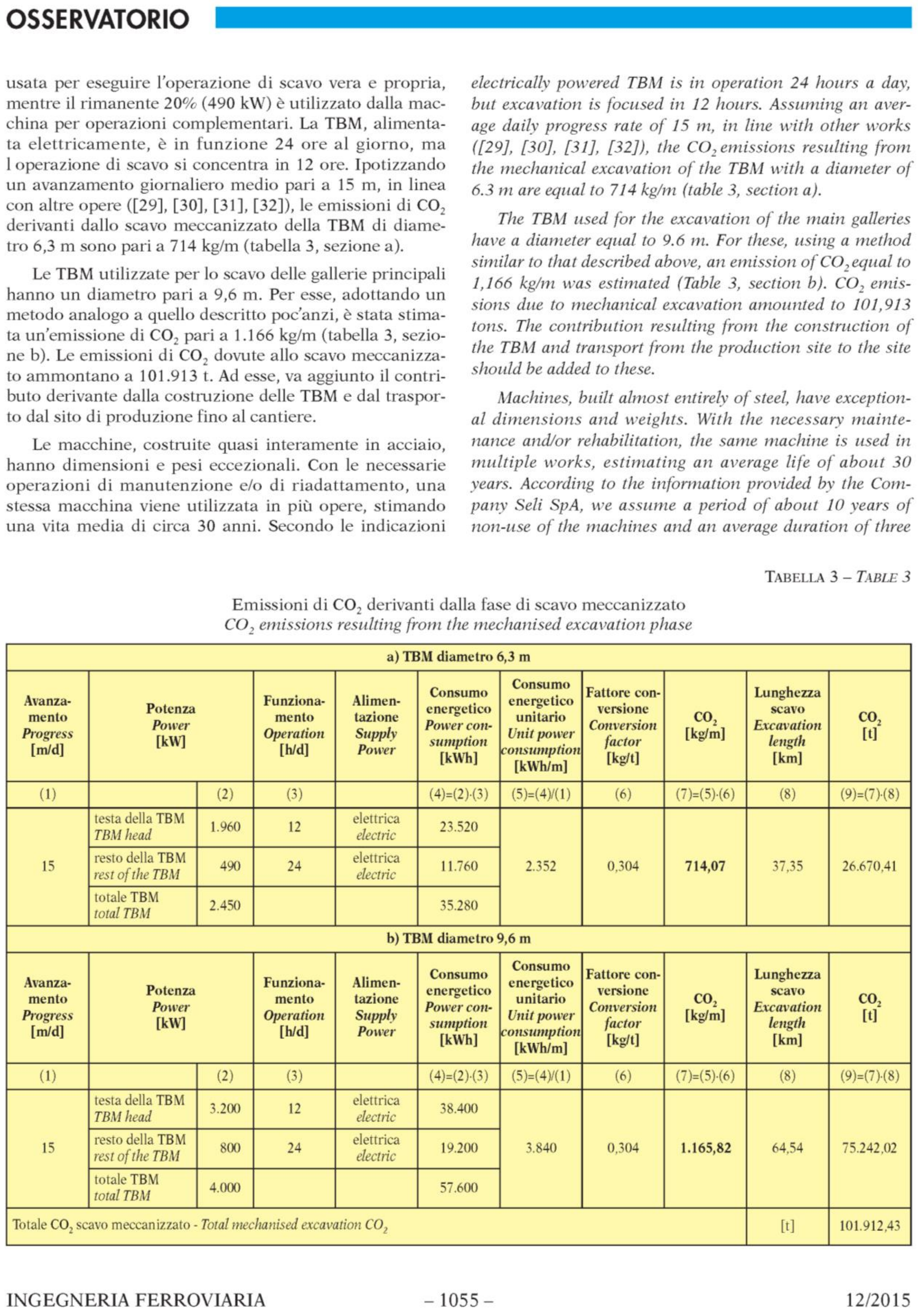
Mechanised excavation involves 62% of the major galleries and 65% of the exploratory tunnel (for a total of 102 km [25]). It is done using the TBM. Of the ten TBM planned for the entire work, three with a 6.3 m diameter are used in the excavation of the exploratory tunnel and seven in the excavation of the galleries. To estimate the energy requirement a "double shield" machine is considered that allows excavating simultaneously to the laying of prefabricated blocks for the inner lining (see next section). The power of the engines of the head is equal to 1.960 kW [28]: about 80% of the total power is used to perform the operation of the excavation itself, while the remaining 20% (490 kW) is used by the machine for complementary operations. The

TABELLA 2 – *TABLE 2*

Emissioni di CO_2 derivanti dalla fase di scavo convenzionale
CO_2 emissions deriving from the conventional excavation phase

a) Fase di brillamento – macchina "Jumbo" - *a) Blasting phase - "Jumbo" machine*							
Avanz. medio *Average progress* [m/d]	**Potenza *Power* [kW]**	**Funzionamento *Operation* [h/d]**	**Alimentazione *Power supply***	**Consumo energetico *Power consumption* [kWh]**	**Consumo energetico unitario *Unit power consumption* [kWh/m]**	**Fattore conversione CO_2 *CO_2 Conversion factor* [kg/kWh]**	**CO_2 unitario *Unit CO_2* [kg/m]**
(1)	(2)	(3)		(4)=(2)·(3)	(5)=(4)/(1)	(6)	(7)=(5)·(6)
5	260	6	Elettrica *Electric*	1.560	312	0,304	**94,72**

b) Fase di sistemazione e pulizia superficie di scavo – escavatore *b) Arrangement and excavation surface cleaning phase – excavator*										
Avanz. Medio *Average progres*	**Consumo carburante *Fuel consumption* [l/h]**	**Funzionamento *Operation* [h/d]**	**Alimentazione *Power supply***	**Consumo carburante *Fuel consumption* [l/d]**	**Peso specifico gasolio *Diesel oil specific weight* [kg/dm^3]**	**Consumo carburante *Fuel consumption* [kg/d]**	**Potere calorifico *Heating value* [kWh/kg]**	**Consumo energetico *Power consumption* [kWh]**	**Consumo energetico unitario *Unit power consumption* [kWh/m]**	**Fattore conversione CO_2 *CO_2 Conversion factor* [Kg/kWh]**	**CO_2 unitario *Unit CO_2* [kg/m]**
(1)	(2)	(3)		(4)=(2)·(3)	(5)	(6)=(4)·(5)	(7)	(8)=(6)·(7)	(9)=(8)/(1)	(10)	(11)=(10)·(9)
5	50	2	diesel	100	0.85	85	11,9	1.012	202,3	0,267	**54,01**
CO_2 per metro di scavo convenzionale *CO_2 per metre of conventional excavation*							(A) = a) + b)	[kg/m]		**148,73**	
Lunghezza gallerie scavate in convenzionale *Length of conventionally excavated*							(B)	[km]		**118,87**	
CO_2 totale prodotta durante le esplosioni *Total CO_2 produced during explosions*							(C)	[t]		**7.012,00**	
Totale CO_2 scavo convenzionale *Total CO_2 conventional excavation*							(D) = (A)·(B)+(C)	[t]		**24.693,43**	



usata per eseguire l'operazione di scavo vera e propria, mentre il rimanente 20% (490 kW) è utilizzato dalla macchina per operazioni complementari. La TBM, alimentata elettricamente, è in funzione 24 ore al giorno, ma l operazione di scavo si concentra in 12 ore. Ipotizzando un avanzamento giornaliero medio pari a 15 m, in linea con altre opere ([29], [30], [31], [32]), le emissioni di CO_2 derivanti dallo scavo meccanizzato della TBM di diametro 6,3 m sono pari a 714 kg/m (tabella 3, sezione a).

Le TBM utilizzate per lo scavo delle gallerie principali hanno un diametro pari a 9,6 m. Per esse, adottando un metodo analogo a quello descritto poc'anzi, è stata stimata un'emissione di CO_2 pari a 1.166 kg/m (tabella 3, sezione b). Le emissioni di CO_2 dovute allo scavo meccanizzato ammontano a 101.913 t. Ad esse, va aggiunto il contributo derivante dalla costruzione delle TBM e dal trasporto dal sito di produzione fino al cantiere.

Le macchine, costruite quasi interamente in acciaio, hanno dimensioni e pesi eccezionali. Con le necessarie operazioni di manutenzione e/o di riadattamento, una stessa macchina viene utilizzata in più opere, stimando una vita media di circa 30 anni. Secondo le indicazioni

electrically powered TBM is in operation 24 hours a day, but excavation is focused in 12 hours. Assuming an average daily progress rate of 15 m, in line with other works ([29], [30], [31], [32]), the CO_2 emissions resulting from the mechanical excavation of the TBM with a diameter of 6.3 m are equal to 714 kg/m (table 3, section a).

The TBM used for the excavation of the main galleries have a diameter equal to 9.6 m. For these, using a method similar to that described above, an emission of CO_2 equal to 1,166 kg/m was estimated (Table 3, section b). CO_2 emissions due to mechanical excavation amounted to 101,913 tons. The contribution resulting from the construction of the TBM and transport from the production site to the site should be added to these.

Machines, built almost entirely of steel, have exceptional dimensions and weights. With the necessary maintenance and/or rehabilitation, the same machine is used in multiple works, estimating an average life of about 30 years. According to the information provided by the Company Seli SpA, we assume a period of about 10 years of non-use of the machines and an average duration of three

TABELLA 3 – *TABLE 3*

Emissioni di CO_2 derivanti dalla fase di scavo meccanizzato
CO_2 emissions resulting from the mechanised excavation phase

a) TBM diametro 6,3 m										
Avanzamento *Progress* **[m/d]**	**Potenza** *Power* **[kW]**		**Funzionamento** *Operation* **[h/d]**	**Alimentazione** *Supply Power*	**Consumo energetico** *Power consumption* **[kWh]**	**Consumo energetico unitario** *Unit power consumption* **[kWh/m]**	**Fattore conversione** *Conversion factor* **[kg/t]**	**CO_2 [kg/m]**	**Lunghezza scavo** *Excavation length* **[km]**	**CO_2 [t]**
(1)		(2)	(3)		(4)=(2)·(3)	(5)=(4)/(1)	(6)	(7)=(5)·(6)	(8)	(9)=(7)·(8)
15	testa della TBM *TBM head*	1.960	12	elettrica *electric*	23.520	2.352	0,304	**714,07**	37,35	26.670,41
	resto della TBM *rest of the TBM*	490	24	elettrica *electric*	11.760					
	totale TBM *total TBM*	2.450			35.280					
b) TBM diametro 9,6 m										
Avanzamento *Progress* **[m/d]**	**Potenza** *Power* **[kW]**		**Funzionamento** *Operation* **[h/d]**	**Alimentazione** *Supply Power*	**Consumo energetico** *Power consumption* **[kWh]**	**Consumo energetico unitario** *Unit power consumption* **[kWh/m]**	**Fattore conversione** *Conversion factor* **[kg/t]**	**CO_2 [kg/m]**	**Lunghezza scavo** *Excavation length* **[km]**	**CO_2 [t]**
(1)		(2)	(3)		(4)=(2)·(3)	(5)=(4)/(1)	(6)	(7)=(5)·(6)	(8)	(9)=(7)·(8)
15	testa della TBM *TBM head*	3.200	12	elettrica *electric*	38.400	3.840	0,304	**1.165,82**	64,54	75.242,02
	resto della TBM *rest of the TBM*	800	24	elettrica *electric*	19.200					
	totale TBM *total TBM*	4.000			57.600					
Totale CO_2 scavo meccanizzato - *Total mechanised excavation CO_2*									[t]	101.912,43

fornite dalla ditta Seli SpA, si ipotizza un periodo di circa 10 anni di non utilizzo delle macchine e una durata temporale media di tre anni per cantiere. Approssimando quindi a 6 il numero totale di opere per le quali è utilizzata una stessa TBM durante il suo ciclo di vita, è stato applicato un coefficiente riduttivo di 1/6 alle emissioni di CO_2 dovute alla produzione delle macchine, ottenendo un contributo pari a 3.103 t. Il trasporto delle macchine, infine, avviene via camion per parti, successivamente assemblate in cantiere. Per il cuscinetto della TBM, la componente più fragile e non scomponibile della macchina, si ricorre ad un trasporto di tipo eccezionale. Per il trasporto di tutte le TBM dal luogo di costruzione (Aprilia, LT) al cantiere di Aica (circa 700 km) è stata stimata un'emissione di CO_2 pari a 364 t.

4.3.2. Trasporto del materiale di scavo

La fase successiva riguarda il trasporto dello smarino, il cui volume complessivo ammonta a circa 21,5 Mio m^3. Esso è funzione della gestione del materiale, per la quale si possono individuare tre possibilità [33]: il materiale è pregiato ed adatto alla produzione di inerti per il calcestruzzo (classe A); il materiale è utilizzabile per rilevati e rinterri (classe B); il materiale non è utilizzabile ed è destinato al deposito in maniera definitiva (classe C).

A partire da questa classificazione, viene stabilita la quantità di smarino allocata nei depositi temporanei (prima di essere riutilizzata) e quella invece destinata ai depositi definitivi, considerando che il materiale di buona qualità non riutilizzato nei cantieri può essere anche venduto. Si distinguono quindi due fasi: il trasporto dal luogo di scavo fino ai portali e dai portali fino ai depositi. Il trasporto dello smarino dai fronti di scavo fino ai portali avviene prevalentemente all'interno delle gallerie; si adotta il trasporto esterno solo in casi inevitabili.

Durante le fasi di scavo meccanizzato, lo smarino viene evacuato tramite nastro trasportatore, modalità che si combina in modo ideale con le macchine TBM. Anche nelle fasi di scavo convenzionale viene preferito il nastro trasportatore; tuttavia, possono anche essere adottati camion o dumper.

Per il calcolo delle emissioni di CO_2 di seguito riportate, viene fatto riferimento al nastro trasportatore utilizzato nel cantiere di Aica, con capacità pari a 300 m^3/h, alimentazione di tipo elettrico e potenza pari a 90 kW/km. I camion utilizzati in cantiere sono di classe Euro IV, con una capacità di 12 t e un consumo di 30 l ogni 100 km [34]. La CO_2 emessa per il trasporto dello smarino dal fronte di scavo fino ai portali è stata stimata conoscendo le quantità di materiale di scavo, le modalità di trasporto e i depositi a cui sono destinate.

Le emissioni sono pari a 18.361 t: 5.745 via camion e 12.616 via nastro. La seconda fase del trasporto del materiale di scavo, dai portali fino ai depositi, avviene via nastro trasportatore: replicando il metodo descritto in precedenza, nota la distanza dal deposito, si calcolano le emissioni di CO_2 dovute al trasporto dello smarino dai portali fino ai depositi, che ammontano a 2.086 t. Infine, è stato valutato

years per construction site. Being approximately 6 the total number of works for which the same TBM is used during its lifetime, a reductive factor of 1/6 of CO_2 emissions due to the production of machines was applied, resulting in a contribution of 3,103 t. Transport of machines in parts finally takes place via truck that are then assembled on site. For the TBM bearing, the most fragile component of the machine that cannot be dismantled, we resort to an exceptionally large goods vehicle. To transport all TBMs from the manufacturing site (Aprilia, LT) to the Aica construction site (about 700 km) CO_2 emissions of 364 were estimated.

4.3.2. Transport of excavation material

The next phase is the transport of the spoils, whose total volume amounts to approximately 21.5 million m^3. It is a function of material management, for which there are three possibilities [33]: the material is valuable and suitable for the production of aggregates for concrete (class A); the material is usable for embankments and backfills (class B); the material is unusable and is intended to be permanently stored (class C).

Starting from this classification, the amount of spoils allocated in the temporary deposits is established (before being reused) and that intended for final deposits, considering that good quality material not reused in construction can also be sold. Two phases can be distinguished: transport from the excavation site to the portals and from the portals to the deposits. Transporting the spoils from the front lines of excavation to the portals is done mainly within the galleries; external transport occurs only in unavoidable cases.

During the mechanised excavation phases, the spoils are evacuated using a conveyor belt, which combines perfectly with the TBM machines. The conveyor is preferred even during conventional excavation; however, trucks or dumpers can also be used.

For the calculation of CO_2 emissions shown below, reference is made to the conveyor belt used in the Aica construction site, with a capacity of 300 m^3/h, electrically powered and a capacity of 90 kW/km. Trucks used on the site are Euro IV class, with a capacity of 12 t and a consumption of 30 l per 100 km [34]. CO_2 emissions to transport spoils from the excavation front lines to the portals were estimated by knowing the amount of excavated material, transport arrangements and deposits for which they are intended.

Emissions are equal to 18361 t: 5745 via truck and 12616 using the conveyor. The second phase of the transport of excavation material, from the portals to the deposits, takes place using a conveyor belt: replicating the method described above, knowing the distance from the storage, the CO_2 emissions caused by transporting the spoils from the portals to deposits are calculated, which totalled 2.086 t. Finally, the contribution was evaluated in terms of CO_2 production due to transport of excavated material destined for sale.

il contributo in termini di produzione di CO_2 dovuto al trasporto del materiale di scavo destinato alla vendita.

Secondo la delibera della Giunta Provinciale di Bolzano n. 3937 del 27.10.2008, il materiale di scavo può essere trasportato tramite camion per distanze inferiori ai 20 km. Oltre tale distanza, si deve ricorrere a sistemi di trasporto alternativi. Avendo identificato le ditte produttrici di calcestruzzo nel raggio di 20 km, si nota come la loro distanza dai cantieri BBT sia inferiore alla distanza media dalle cave di utilizzo dove essi si approvvigionano. Da ciò, ne deriva che il contributo della vendita del materiale di scavo (stimato in misura non superiore al 3% dello smarino) sia da considerarsi di riduzione al totale delle emissioni di CO_2: conseguentemente, tale quantità è stata trascurata nel calcolo.

4.4. Produzione materiali da costruzione e stabilizzazione dell'ammasso roccioso

La stabilizzazione dell'ammasso roccioso include la produzione dei materiali da costruzione, il loro trasporto in cantiere e la loro applicazione in opera. Quando la galleria è scavata con metodo convenzionale, dapprima viene dimensionato un rivestimento primario, al fine di garantire il sostegno per la durata della fase di costruzione, quindi viene aggiunto un rivestimento definitivo.

Il rivestimento primario è ottenuto tramite l applicazione di uno strato di calcestruzzo proiettato (spritzbeton) di spessore variabile, rinforzato con acciaio sotto forma di reti metalliche o di fibre. Il rivestimento definitivo, invece, consiste in calcestruzzo gettato in opera, dello spessore variabile da 30 a 60 cm a seconda del tipo di roccia; il calcestruzzo è armato solo nelle tratte più critiche, prevalentemente in corrispondenza delle stazioni multifunzione, dei cameroni e dei cunicoli trasversali.

Con lo scavo meccanizzato, il rivestimento primario della galleria può avvenire in modo analogo a quello appena descritto, ma più frequentemente si ricorre a conci prefabbricati posati in opera dalla TBM. Il calcestruzzo armato rappresenta il materiale che incide in misura maggiore sulle emissioni di CO_2. Note le quantità di materiali necessarie per la sua fabbricazione, per calcolare le emissioni di CO_2 dovute alla sua produzione, si scompone il processo nelle sue diverse fasi (frantumazione dell'inerte, produzione del cemento, impianto di betonaggio, produzione del calcestruzzo prefabbricato, applicazione del calcestruzzo proiettato, produzione dell'acciaio).

4.4.1. Calcestruzzo

Il calcestruzzo è una miscela composta da legante, acqua, inerti e, a seconda delle necessità, additivi. Parte del materiale utilizzato come inerte viene recuperato dalla fase di perforazione delle gallerie, utilizzando direttamente lo smarino trasportato presso i portali di accesso (si veda il paragrafo precedente). Per poterlo riutilizzare è prima necessario frantumarlo tramite un frantoio semovente a mascelle: per tale operazione, si sono state stimate emissioni pari a 2.628 t (tabella 4).

According to the resolution of the Provincial Council of Bolzano n° 3937 of 27.10.2008, the excavated material can be transported by truck for distances of less than 20 km. Beyond that distance, one must resort to alternative transport systems. Having identified concrete producers within 20 km, we can observe that their distance from the BBT sites is less than the average distance from the procurement quarries used by the former. From this, it follows that the contribution from the sale of excavated material (estimated as no more than 3% of the spoils) is considered as a reduction of the total CO_2 emissions: consequently, that amount has been neglected in the calculation.

4.4. Construction materials production and stabilisation of rock mass

Rock mass stabilisation includes the production of construction materials, their transport on site and application. When the tunnel is excavated using the conventional method, first a primary lining is dimensioned to ensure support for the duration of the construction phase, subsequently a final coating is added.

Primary coating is obtained through the application of a layer of sprayed concrete (shotcrete) of variable thickness, reinforced with steel in the form of metal or fibre wire net. The final coating, instead, consists of in situ concrete, with a variable thickness from 30 to 60 cm depending on the type of rock; concrete is armed only in the most critical stretches, mainly at the multifunction stations, halls and cross tunnels.

With the mechanised excavation, the primary lining of the tunnel can be done in the same way as just described, but prefabricated segments installed by the TBM are most frequently used. Reinforced concrete is the material that has greater CO_2 emissions. Knowing the amount of materials needed for its manufacture, to calculate CO_2 emissions from its production, the process is broken down in its various stages (aggregates grinding, cement production, batching plant, prefabricated concrete production, application of shotcrete, steel production).

4.4.1. Concrete

Concrete is a mixture of binder, water, aggregates and additives, as required. Some of the material used as aggregate is retrieved from the drilling phase of the galleries, using the spoils transported to access portals (see previous paragraph). For reuse, it must first be crushed using a self-moving jaw crusher: to perform this operation 2628 t of emissions were estimated (table 4).

The quantities used in the construction of the BBT amount to almost 6 Million m^3 ([33], [36]). Taking as reference the composition type for Rck 35 concrete, the most used in works of this kind, almost 2.4 million tons of cement are needed for its production.

TABELLA 4 – *TABLE 4*

CO_2 per la frantumazione dell'inerte
CO_2 for crushing of aggregates

Inerti per calcestruzzo *Aggregates for concrete* **[m³]**	**Potenza frantoio** *Crusher power* **[kW]**	**Alimentazione** *Power supply*	**Capacità frantoio** *Crusher capacity* **[t/h]**	**Densità inerti** *Aggregates density* **[kg/m³]**	**Capacità oraria frantoio** *Hourly capacity of crusher* **[m³/h]**	**Tempo funzionamento** *Operation time* **[h]**	**Consumo energetico** *Power Consumption* **[kWh]**	**Fattore di conversione** *Conversion factor* **[Kg/kWh]**	**CO_2 [t]**
(1)	(2)		(3)	(4)	$(5)=(3)/(4)\cdot10^3$	$(6)=(1)/(5)$	$(7)=(2)\cdot(6)$	(8)	$(9)=(7)\cdot(8)/10^3$
6.231.000,00	187	Elettrica *Electric*	250	1.857,00	134,63	46.283,87	8.655.083,32	0,304	**2.627,68**
(Fonte - Source: (2) (3): [35]; (4): [23]).									

Le quantità utilizzate nella costruzione del BBT ammontano a quasi 6 Mio m³ ([33], [36]). Prendendo a riferimento la composizione tipo per un calcestruzzo Rck 35, la più utilizzata in opere di tale natura, servono quasi 2,4 Mio t di cemento per la sua produzione.

Nei cantieri è utilizzato prevalentemente cemento pozzolanico (70% del cemento totale), ma una componente considerevole (30% del calcestruzzo totale) è rappresentata dal cemento Portland, utilizzato prevalentemente per la produzione dello spritzbeton. Il coefficiente di emissione del cemento è il risultato di una media ponderata, derivata dai rispettivi fattori di emissione dei due cementi. Dai calcoli riportati in tabella 5, per la produzione del cemento risulta necessaria una quantità totale di CO_2 pari a 1.561.007 t.

TABELLA 5 – *TABLE 5*

Emissioni di CO_2 per la produzione del cemento
CO_2 emissions for cement production

Calcestruzzo *Concrete* **[N/mm²]**	**Cemento in 1 m³ di cls tipo** *Cement in 1 m³ of standard concrete* **[kg/m³]**	**Calcestruzzo utilizzato** *Concrete used* **[m³]**	**Cemento utilizzato** *Used concrete* **[t]**	**Fattore conversione cemento portland (30%)** *Portland cement conversion factor (30%)* **[kgCO_2/t]**	**Fattore conversione cemento pozzolanico (70%)** *Pozzolanic cement conversion Factor (70%)* **[kgCO_2/t]**	**CO_2 produzione cemento totale** *Total CO_2 production rom cement* [t]
	(1)	(2)	$(3)=(1)\cdot(2)\cdot10^{-3}$	(4)	(5)	$(6)=[(4)\cdot0,3+(3)\cdot0,7]\cdot(3)/10^3$
Rck 35	400	5.972.260	2.388.904	622	576	**1.561.007,02**
(Fonte - *Source*: (4), (5): [21]).						

La produzione del calcestruzzo avviene prevalentemente in cantiere, attraverso la miscelazione tramite impianto di betonaggio. Utilizzando i dati tecnici ricavati direttamente presso il cantiere di Mules [37], questa fase comporta un'emissione complessiva di CO_2 pari a 2.213 t (tabella 6). Solo i conci prefabbricati utilizzati per la costruzione del cunicolo di Aica (400.000 t di calcestruzzo, pari al 7% del calcestruzzo totale) sono prodotti fuori opera. È stata stimata un'emissione complessiva di CO_2 pari a 13.084 t, sulla base dei dati forniti da misurazioni dirette, condotte dalla ditta produttrice (Ipa Precast SpA di Calcinate).

On construction sites Pozzolanic cement is primarily used (70% of total cement), but a considerable component (30% of the total concrete) is Portland cement, mainly used for the production of shotcrete. The emission coefficient of concrete is the result of a weighted average, derived from the respective emission factors of the two cements. From the calculations shown in table 5, a total quantity of 1.561.007 tons of CO_2 is necessary for the manufacture of cement.

Concrete production takes place mainly on site, by mixing using the batch plant. Using the technical data obtained directly from the Mules site [37], this phase involves a total emission of CO_2 equal to 2213 t (table 6). Only the precast segments used in the construction of the Aica tunnel (400.000 tons of concrete, equal to 7% of the total concrete) are produced off work. A total emission of CO_2 of 13084 t was estimated, based on data provided by direct measurements carried out by the manufacturer (Ipa Precast SpA in Calcinate).

The last step is the application of shotcrete, using the Sika - PM 500 machine. Equipped with a pump with a power of 37 kW, this machine is operated electrically, it has a maximum theoretical capacity of 30 m³/h and a regime of about 25 m³/h. Emissions from its use are 1638 t (table 7).

TABELLA 6 – *TABLE 6*

Emissioni di CO_2 dell'impianto di betonaggio
CO_2 emissions of the batching plant

Capacità *Capacity* **[m³/h]**	**Quantità cls per rivestimento definitivo** *Concrete quantity for final coating* **[m³]**	**Tempo funzionamento** *Operation Time* **[h]**	**Potenza** *Power* **[kW]**	**Alimentazione** *Power supply*	**Consumo energetico** *Power consumption* **[kWh]**	**Fattore conversione** *Conversion factor* **[Kg/kWh]**	**CO_2 [kg]**	**CO_2 [t]**
(1)	(2)	(3)=(2)/(1)	(4)		(5)=(3)·(4)	(6)		(7)=(5)·(6)/10³
100	5.563.810	55.638,10	131	elettrica	7.288.590	0,304	2.212.816	2.212,82

(Fonte - Source: *(1), (4): [37]).*

L'ultimo passaggio consiste nell'applicazione del calcestruzzo proiettato, tramite la macchina Sika – PM 500. Dotata di una pompa con 37 kW di potenza, tale macchina ha un funzionamento elettrico, una portata teorica massima di 30 m³/h ed una portata operativa di regime di circa 25 m³/h. Le emissioni derivanti dal suo utilizzo sono 1.638 t (tabella 7).

TABELLA 7 – *TABLE 7*

Consumo energetico per l'applicazione del calcestruzzo proiettato – sistema BBT
Energy consumption for application of shotcrete – BBT system

Portata *Capacity* **[m³/h]**	**Potenza pompa** *Power pump*	**Alimentazione** *Power supply*	**Quantità di cls** *Quantity of concrete* **[m³]**	**Funzionamento** *Operation* **[h]**	**Consumo energetico** *Power consumption* **[kWh]**	**Fattore conversione** *Conversion factor* **[Kg/kWh]**	**CO_2 [kg]**	**CO_2 [t]**
(1)	(2)		(3)	(4)=(3)/(1)	(5)=(2)·(4)	(6)	(7)=(5)·(6)	
25	37	elettrica	1.680.000,00	67.200,00	2.486.400,00	0,304	1.638.070,00	1.638,07

(Fonte - Source: *(1), (2): [38]).*

4.4.2. Acciaio

Note la quantità totale di calcestruzzo e le tipologie adottate, la quantità di acciaio contenuto sotto forma di fibre di acciaio, reti metalliche o centine è calcolata attraverso l'analisi di alcune sezioni trasversali tipo. Nelle tratte scavate in convenzionale sono utilizzati circa 20 ancoraggi radiali per metro di galleria, della lunghezza di 6 m e peso di 23,6 kg ciascuno [39], per un totale di 56.125 t di acciaio. Dove è necessario oltrepassare un fiume per accedere al portale di imbocco, vengono costruiti ponti di attraversamento (per il BBT, quattro) e richiedono l'utilizzo di 610 t di acciaio. Complessivamente, la quantità totale di acciaio utilizzata per la costruzione del sistema BBT (e comprendente armatura, ancoraggi, ponti) ammonta a circa 181.000 t, per i quali sono stimate emissioni di CO_2 pari a 358.555 t (tabella 8).

4.4.3. Trasporto materiale da costruzione

Nelle tratte di galleria dove sono utilizzati i conci prefabbricati, devono essere considerate anche le emissioni dovute al loro trasporto. Nel caso del cantiere di Aica, la prima parte del percorso comprende il tragitto dalla ditta di produzione, con sede a Calcinate (BG), fino al cantie-

4.4.2. Steel

Knowing the total amount of concrete and the different types adopted, the amount of steel contained in the form of steel fibres, wire mesh or centrings is calculated through the analysis of some standard type cross sections. About 20 radial anchors per metre of gallery are used in conventionally excavated sections, measuring 6 m and each weighing 23.6 kg [39], for a total of 56125 t of steel. Where a river must be crossed to access the entrance portal, crossing bridges are built (four, for the BBT) and require the use of 610 tons of steel. Altogether, the total amount of steel used in the construction of the BBT system (including armour, anchors, bridges) amounts to approximately 181.000 tons, for which CO_2 emissions of 358,555 t are estimated (table 8).

4.4.3. Building material transport

In the gallery routes where precast segments are used, emissions from transport should also be considered. In the case of the Aica construction site, the first part of the route includes the journey from the production company, headquartered in Calcinate (BG), up to the construction site. This contribution is estimated at 2,011 tons of CO_2. For other building lots this journey is not considered because the segments are produced directly on site. The second part of the transport takes place on site, via rail with shuttle trains from external deposits to the application site. According to the site manager of Aica during excavation, 20 daily round trips are performed (16 for the transport of the precast segments and 4 for maintenance). Assuming train

TABELLA 8 – *TABLE 8*

Emissioni di CO_2 derivanti dalla produzione di acciaio
CO_2 emissions from steel production

Acciaio per armatura *Reinforcement steel* [t]	**Ancoraggi radiali** *Radial anchors* [t]	**Ponti** *Bridges* [t]	**Totale acciaio** *Total steel* [t]	**Fattore conversione acciaio** *Steel conversion factor* [kg/t]	**CO_2** [kg]	**CO_2** [t]
(1)	(2)	(3)	(4)=(1)+(2)+(3)	(5)	(6)=(4)·(5)	
124.353	56.125	610	181.088	1.980	358.554.897	**358.554,90**
Nota (3): 1 MJ = 0,278 kWh						
(Fonte - Source: *(1): [40]; (2): [39], [41]).*						

re. Tale contributo è stimato in 2.011 t di CO_2. Per gli altri lotti di costruzione questo tragitto non viene considerato perché i conci sono prodotti direttamente in cantiere. La seconda parte del trasporto avviene in cantiere, su rotaia per mezzo di treni shuttle dai depositi esterni fino al luogo di applicazione. Secondo il direttore di cantiere di Aica, durante la fase di scavo, si effettuano quotidianamente 20 viaggi in andata e 20 in ritorno (di cui 16 per il trasporto dei conci prefabbricati e 4 di manutenzione). Ipotizzando un consumo del treno pari a un litro di carburante ogni 5 km, la CO_2 emessa per trasportare i conci prefabbricati utilizzati per la costruzione del sistema BBT è pari a 502 t.

4.5. Operatività delle gallerie

La fase di costruzione prevede l'installazione di un impianto di illuminazione, ventilazione e raffreddamento delle gallerie, per garantire agli operai le condizioni adeguate all'esecuzione dei lavori: anche esse concorrono alle emissioni di CO_2. Per analizzare tali componenti, è possibile distinguere la fase di costruzione grezza dalla fase di attrezzaggio: nella prima, vengono realizzati lo scavo delle gallerie, dei cunicoli e le lavorazioni relative all'opera grezza; nella seconda vengono realizzate le sovrastrutture ferroviarie, gli impianti elettrici e le componenti tecnologiche.

4.5.1. Illuminazione in galleria

Nelle gallerie è installato un sistema di illuminazione con lampade da 36W, posizionate ad un intervallo di 10 m lungo la parete del tunnel. Tale impianto è operativo 24 ore al giorno, per 351 giorni all'anno (viene considerata una interruzione dei lavori di due settimane).

Nella fase di costruzione grezza dell'opera, la lunghezza della tratta illuminata varia in funzione dell'avanzamento dello scavo: le emissioni dovute all'illuminazione (quantificate in 4.802 t) vengono calcolate considerando una lunghezza fissa riferita al punto medio di ogni componente. Per il cunicolo esplorativo e le finestre di accesso intermedio il valore stimato è pari a 2.026 t. In questo caso, si considera l'illuminazione non solo durante la fase di scavo, ma anche durante il loro funzionamento, per consentire le operazioni di costruzione delle altre componenti del sistema.

consumption equal to one litre of fuel every 5 km, the CO_2 emitted to transport the precast construction segments used to build the BBT System totalled 502 t.

4.5. Operability of galleries

The construction phase involves the installation of a lighting system, ventilation and cooling of tunnels, to guarantee workers adequate conditions to the completion of the work: they also contribute to CO_2 emissions. To analyse these components, the building phase can be distinguished from the tooling phase: in the first, the excavation of tunnels, burrows and processes regarding raw work is performed; in the second, the railway superstructures, the electrical systems and technological components are made.

4.5.1. Tunnel lighting

A lighting system is installed in the galleries with 36W lamps, located at an interval of 10 m along the wall of the tunnel. This system is operational 24 hours a day, 351 days a year (an interruption of work of two weeks is taken into account).

During the building of the raw work, the length of the illuminated section varies depending on the progress of the excavation: emissions due to lighting (quantified in 4802 t) are calculated on the basis of a fixed length referring to the midpoint of each component. For the exploratory tunnel and intermediate access windows the estimated value is equal to 2,026 tons. In this case, we consider not only lighting during the excavation phase, but also during their operation, to allow construction of the other system components.

During tooling, for which we assume an average duration of 3 years and 6 months, emissions are estimated at 6366 t. Altogether, therefore, for the lighting of the BBT system galleries, CO_2 emissions amounted to 13195 t.

4.5.2. Tunnel ventilation and cooling

As for the calculation of lighting, also in the case of ventilation and cooling the CO_2 emissions are distinguished between the rough construction phase and the tooling phase. In the case of ventilation, all work areas have to be provided with fresh air, which is passed through pipelines up to

Nella fase di attrezzaggio, per la quale si ipotizza una durata media pari a 3 anni e 6 mesi, le emissioni sono stimate in 6.366 t. Complessivamente, quindi, per l'illuminazione delle gallerie del sistema BBT, le emissioni di CO_2 risultano pari a 13.195 t.

4.5.2 Ventilazione e raffreddamento delle gallerie

Come per il calcolo dell'illuminazione, così anche nel caso di ventilazione e raffreddamento le emissioni di CO_2 vengono distinte tra la fase di costruzione grezza e la fase di attrezzaggio. Nel caso della ventilazione, tutte le zone di lavoro devono essere approvvigionate con aria fresca, che viene fatta passare attraverso condotte fino alla zona di scavo secondo i valori limite di quantità e velocità d'aria. Al contempo, l'aria viziata viene fatta fuoriuscire dal portale principale.

Per ottenere queste prestazioni, agli imbocchi della galleria sono installati ventilatori di grosse dimensioni, mentre sono previsti ventilatori ausiliari nei settori di avanzamento, nelle condotte, nelle paratie climatiche e nelle chiuse. Per il raffreddamento delle canne si impiegano macchine refrigeranti che sottraggono calore all'aria e la cedono all'acqua di raffreddamento. Condotte appositamente realizzate trasportano l'acqua calda usata per il raffreddamento degli impianti fuori dalla galleria, dove torri di raffreddamento garantiscono lo scambio di calore con l'aria esterna. Per la fase di costruzione grezza si fa riferimento al settore di cantiere più critico, ossia l'area di Ahrental, ipotizzando un consumo energetico unitario simile anche per gli altri due settori di costruzione (Mules e Wolf). Nella fase di costruzione grezza le emissioni di CO_2 per la ventilazione e il raffreddamento di tutto il sistema BBT ammontano a 77.132 t (tabella 9).

Infine, la fase di attrezzaggio delle gallerie è stata analizzata con un calcolo simile a quello di tabella 9. Conoscendo le potenze richieste dagli impianti per la ventilazione e il raffreddamento dell'intero sistema [42], le emissioni di CO_2 stimate risultano pari a 73.578 t. Complessivamente, quindi, le emissioni di CO_2 dovute alla ventilazione e al raffreddamento di tutto il sistema BBT nella fase di costruzione grezza e attrezzaggio risultano pari a 150.710 t.

4.6. Operatività dei cantieri

Le nove aree di cantiere sono localizzate presso gli imbocchi e gli accessi laterali al tunnel. Il lato italiano conta quattro cantieri: in corrispondenza dell'imbocco del cunicolo esplorativo di Aica, dell'attacco intermedio Mules, nella zona del sottoattraversamento dell'Isarco e presso la stazione di Fortezza ([16], [23], [24], [25], [41], [43], [44], [45]). Il lato austriaco prevede l'installazione di cinque aree: all'imbocco della finestra di accesso di Tulfes, Ampass, Ahrental e Wolf, e nei pressi della stazione di Innsbruck [45].

4.6.1. Impianto di illuminazione aree esterne, funzionamento di uffici e officine meccaniche

Il calcolo delle emissioni dovute all'illuminazione delle aree esterne, al funzionamento degli uffici e delle offi-

the excavation area according to the limit values of quantity and air speed. At the same time, stale air is forced out of the main portal.

To achieve these benefits, large fans have been installed at the tunnel entrances, while auxiliary fans are provided in the advancement areas, in the pipelines, in the weather bulkheads and in locks. Refrigeration machines are used for cooling pipes that remove heat from the air and release it to the cooling water. Specially made pipelines carry the hot water used for the cooling of equipment out of the tunnel, where cooling towers ensure the exchange of heat with the outside air. For the phase of rough construction reference is made to the more critical construction site sector that is the Ahrental area, assuming unit energy consumption also similar for the other two construction sectors (Mules and Wolf). In the rough construction phase CO_2 emissions for ventilation and cooling of the entire BBT system amounted to 77.132 t (table 9).

Finally, the tooling of the tunnels was analysed using a calculation similar to that of table 9. Knowing the power required by the ventilation and cooling systems of the entire plant [42], the estimated CO_2 emissions amounted to 73.578 tons. Overall, therefore, CO_2 emissions due to ventilation and cooling of the entire BBT system during rough construction and tooling amounted to 150.710 tons.

4.6. Operability of the construction sites

The nine areas of the site are located at the entrances and side entrances to the tunnel. The Italian side has four sites: at the entrance of the exploratory tunnel in Aica, the intermediate joint of Mules, in the Isarco underpass crossing area and at the station of Fortezza ([16], [23], [24], [25], [41], [43], [44], [45]). The Austrian side includes the installation of five areas: at the entrance of the access window of Tulfes, Ampass, Ahrental and Wolf, and near Innsbruck station [45].

4.6.1. Lighting of outdoor areas, operation of offices and workshops

The calculation of emissions from the lighting of the outer areas, the operation of offices and workshops is based on direct measurements carried out at the Unterplattner area of the AICA construction site (table 10). Using a current clamp the intensity of electric current of the lighting outside of the offices and the mechanical workshop was measured. It is thus possible to determine the energy consumption of the site (1.085 kWh/day), equal to 31.34 kWh/day per hectare of surface. The operating time of the lighting of the exterior areas of the construction site is a function of the hours of darkness at latitude 45 ° N = 4.321,35, whose annual average value is equal to 11.84 hours per day. Offices and workshops are in operation for 11 hours a day, from 7 to 18 hours.

TABELLA 9 – *TABLE 9*

Emissioni di CO_2 per la ventilazione e il raffreddamento nella fase di costruzione grezza
CO_2 emissions for ventilation and cooling in the rough construction phase

Ventilazione - settore Ahrental - ***Ventilation - Ahrental sector***			
Potenza richiesta dai ventilatori in fase di costruzione grezza (massima lunghezza di scavo) *Power required by the fans during rough construction (maximum excavation length)*	[kW]	(1)	4.369,00
Durata temporale fase costruzione grezza gallerie *Duration of the rough construction phase of galleries*	[a]	(2)	3,5
Durata temporale fase costruzione grezza gallerie *Duration of the rough construction phase of galleries*	[h]	(3)	29.484
Consumo energetico dei ventilatori *Power consumption of the ventilators*	[kWh]	(4)	53.990.170
Raffreddamento - settore Ahrental - ***Cooling - Ahrental sector***			
Potenza richiesta dall'impianto di raffreddamento in fase di costruzione grezza (massima lunghezza di scavo) *Power demand from the cooling system in the rough construction phase (maximum excavation length)*	[kW]	(5)	2.484
Durata temporale fase costruzione grezza gallerie *Duration of the rough construction phase of galleries*	[a]	(6)	3,5
Durata temporale fase costruzione grezza gallerie *Duration of the rough construction phase of galleries*	[h]	(7)	29.484
Consumo energetico dell'impianto di raffreddamento *Energy consumption of the cooling system*	[kWh]	(8)	30.696.174
Ventilazione e raffreddamento - tutto il sistema BBT - ***Ventilation and cooling - entire BBT system***			
Settori considerati: Ahrenal, Mules, Wolf *Sectors considered: Ahrenal, Mules, Wolf*	[n]	(9)	3
Fattore conversione CO_2 *CO_2 conversion factor*	[kg/kWh]	(10)	0,304
CO_2 totale ***Total CO_2***	**[t]**	$(7)=[(4)+(5)]\cdot(9)\cdot(10)\cdot10^{-3}$	**77.132,32**
Nota (3 e 7): il sistema è in funzione 24 ore al giorno, per 351 giorni su 365 *Note (3 and 7): the system is in operation 24 hours a day, for 351 days out of 365*			
Nota (4 e 8): consumo energetico stimato considerando l'avanzamento del fronte di scavo su intervalli temporali di 2 mesi *Note (4 and 8): energy consumption estimated considering the advancement of the excavation front of temporal intervals of 2 months*			
(Fonte - *Source:* (1), (5): [42]; (2), (6): [25]).			

cine meccaniche si basa su misurazioni dirette effettuate presso l'area Unterplattner del cantiere di Aica (tabella 10). Tramite una pinza amperometrica è stata misurata l'intensità di corrente elettrica dell'impianto di illuminazione esterna, degli uffici e dell'officina meccanica. È possibile così determinare il consumo di energia del cantiere (1.085 kWh/giorno), pari a 31,34 kWh/giorno per ettaro di superficie. Il tempo di funzionamento dell'impianto di illuminazione delle aree esterne di cantiere è funzione delle ore di buio alla latitudine 45° N = 4.321,35, il cui valore medio annuale è pari a 11,84 ore al giorno. Gli uffici e le officine meccaniche sono invece in funzione per 11 ore al giorno, dalle ore 7 alle ore 18.

I valori calcolati presso Unterplattner e riferiti al funzionamento di uffici e officine meccaniche sono stati considerati analoghi anche per gli altri cantieri. Per quanto riguarda l'illuminazione, invece, il consumo di

The values calculated at Unterplattner and referring to the operation of offices and engineering workshops have been considered similar also for the other sites. As for the illumination, however, the consumption of each site varies as a function of its extension. Whereas construction sites are in operation every day, 24 hours a day, for a total of 351 days out of 365, a total of 15.299 t of CO_2 were estimated (table 11).

4.6.2. Water treatment plant

In this phase we calculate the emissions produced to treat the water coming out from the galleries as a result of the excavation, before being pumped back into waterways: in all the steps described above, the suspensions produced during excavation and consolidation operations and the accidental loss of oil, are handled by special treatment plants for water purification [46].

TABELLA 10 – *TABLE 10*

Consumo energetico giornaliero dell'area di cantiere Unterplattner ad Aica
Daily energy consumption of the Unterplattner site area in Aica

	Intensità corrente ***Power load*** **[A]**	**Tensione elettrica** ***Voltage*** **[V]**	**Fasi** ***Phases*** **[n]**	**cosΦ**	**Potenza** ***Power*** **[kW]**	**Tempo funzionamento** ***Operation time*** **[h/d]**	**Consumo energetico** ***Power consumption*** **[kWh/d]**
	(1)	(2)	(3)	(4)	$(5)=(1)\cdot(2)\cdot(4)\cdot(3)^{(-1/2)}$	(6)	(7)=(6)·(5)
Illuminazione esterna *Outdoor lighting*	20	400	3	0,85	11,78	11,84	139,45
Uffici *Offices*	96	400	3	0,85	56,53	11	621,88
Officina meccanica *Engineering workshop*	50	400	3	0,85	29,44	11	323,89
Totale consumo energetico ***Total energy consumption***						[kWh/d]	**1.085,22**
Totale consumo energetico per ettaro di superficie ***Total energy consumption per hectare of area***						[kWh/d·ha]	**31,34**

ogni cantiere varia in funzione della sua estensione. Considerando che i cantieri sono in funzione tutti i giorni, 24 ore su 24, per un totale di 351 giorni su 365, sono state stimate complessivamente 15.299 t di CO_2 (tabella 11).

4.6.2. Impianto di trattamento delle acque

In questa fase si calcolano le emissioni prodotte per trattare l'acqua che fuoriesce dalle gallerie a seguito dello scavo, prima di essere reimmessa nei corsi d'acqua: in tutte le fasi precedentemente descritte, le sospensioni prodotte durante le operazioni di scavo e di consolidamento, nonché le perdite accidentali di oli, sono gestite da appositi impianti di trattamento per la depurazione dell'acqua [46].

La stima del consumo energetico si basa per via comparativa, a partire da misurazioni dirette effettuate dalla ditta BAUER AG nei cantieri di Armsteg, Faido ed Erstfeld per la Galleria di Base del Gottardo. Si assume una potenza richiesta dagli impianti di trattamento pari a 0,15 kW per m^3/h d'acqua(4). Le venute di acqua sono state calcolate da uno studio idrogeologico elaborato da GEOTEAM per conto di BBT SE, che fornisce le valutazioni sia per le portate ipotizzabili durante le fasi di scavo in regime transitorio (portata di picco), sia per le portate stabilizzate a distanza di mesi/anni dal termine dello scavo delle opere. Tali valori hanno natura cautelativa: nei cantieri di Aica e Mules sono state infatti registrate portate considerevolmente inferiori rispetto ai valori previsti. Le emissioni di CO_2 derivanti dall'utilizzo dell'impianto di trattamento delle acque del sistema BBT sono state quantificate in 15.911 t (tabella 12).

The energy consumption estimate is based on a comparison, from direct measurements carried out by BAUER AG on the construction sites of Armsteg, Faido and Erstfeld for the Gotthard Base Tunnel. A power demand of 0.15 kW per m^3/h of water(4) by the treatment facilities is assumed. The water coming is calculated from a hydrogeological study elaborated by GEOTEAM on behalf of BBT SE, which provides feedback both for the assumed flow rates during the excavation stages in transient regime (peak flow rate), and for the stabilised flows at a distance of months/years from the end of the excavation works. These values have a precautionary nature: in the Aica and Mules sites considerably lower flow rates that those expected are recorded. CO_2 emissions from the use of the water treatment plant of the BBt system were quantified in 15.911 t (table 12).

The water coming out of the exploratory and drainage tunnel and the main galleries reach the treatment plants by gravity. Only water coming from the excavation of the access windows require lifting equipment, for which additional CO_2 emissions of 1.171 tons are expected. Overall, therefore, CO_2 emissions due to water treatment plants amount to 17.080 tons.

5. Summary of CO_2 emissions and discussion of results

The amount of CO_2 emitted during the construction phase of the BBT is estimated a total 2.280.550 t (fig. 3,

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(4) Tali valori non tengono conto della potenza richiesta per l'eventuale sollevamento delle acque di drenaggio fino all'impianto di trattamento. Questo aspetto dipende dalla specifica disposizione degli impianti di ogni cantiere e da come le acque vengono convogliate alle vasche.

(4) *Such values do not take into account the power necessary for the possible raise of the drainage water up to the treatment plant. This aspect depends both on the specific plants arrangement in each single site and on the way to convoy the drainage water to the tanks.*

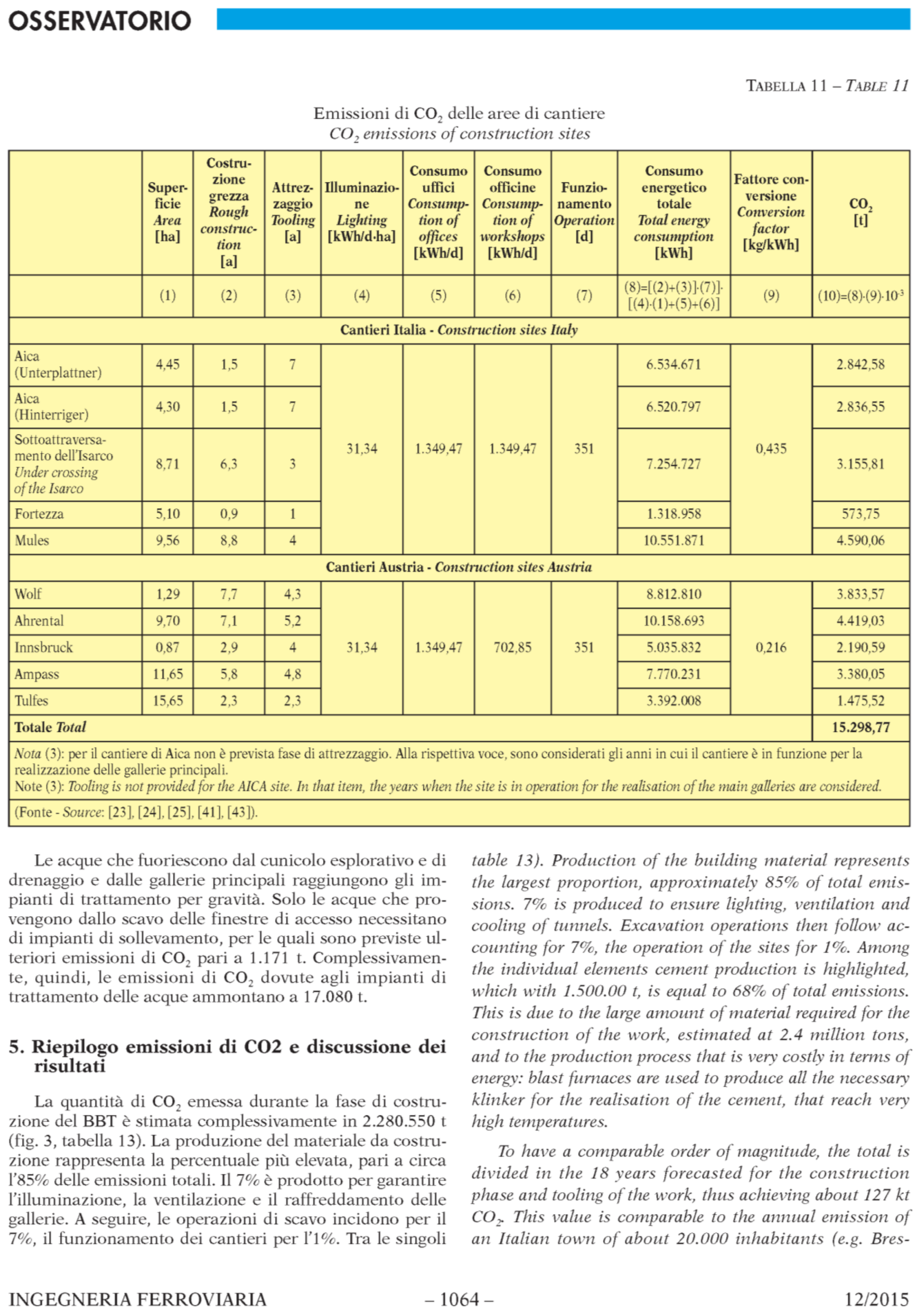

TABELLA 11 – *TABLE 11*

Emissioni di CO_2 delle aree di cantiere
CO_2 emissions of construction sites

	Superficie *Area* **[ha]**	**Costruzione grezza** *Rough construction* **[a]**	**Attrezzaggio** *Tooling* **[a]**	**Illuminazione** *Lighting* **[kWh/d·ha]**	**Consumo uffici** *Consumption of offices* **[kWh/d]**	**Consumo officine** *Consumption of workshops* **[kWh/d]**	**Funzionamento** *Operation* **[d]**	**Consumo energetico totale** *Total energy consumption* **[kWh]**	**Fattore conversione** *Conversion factor* **[kg/kWh]**	**CO_2 [t]**
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)=[(2)+(3)]·(7)]·[(4)·(1)+(5)+(6)]	(9)	(10)=(8)·(9)·10^{-3}
Cantieri Italia - *Construction sites Italy*										
Aica (Unterplattner)	4,45	1,5	7	31,34	1.349,47	1.349,47	351	6.534.671	0,435	2.842,58
Aica (Hinterriger)	4,30	1,5	7					6.520.797		2.836,55
Sottoattraversamento dell'Isarco *Under crossing of the Isarco*	8,71	6,3	3					7.254.727		3.155,81
Fortezza	5,10	0,9	1					1.318.958		573,75
Mules	9,56	8,8	4					10.551.871		4.590,06
Cantieri Austria - *Construction sites Austria*										
Wolf	1,29	7,7	4,3	31,34	1.349,47	702,85	351	8.812.810	0,216	3.833,57
Ahrental	9,70	7,1	5,2					10.158.693		4.419,03
Innsbruck	0,87	2,9	4					5.035.832		2.190,59
Ampass	11,65	5,8	4,8					7.770.231		3.380,05
Tulfes	15,65	2,3	2,3					3.392.008		1.475,52
Totale *Total*										**15.298,77**

Nota (3): per il cantiere di Aica non è prevista fase di attrezzaggio. Alla rispettiva voce, sono considerati gli anni in cui il cantiere è in funzione per la realizzazione delle gallerie principali.
Note (3): *Tooling is not provided for the AICA site. In that item, the years when the site is in operation for the realisation of the main galleries are considered.*

(Fonte - *Source*: [23], [24], [25], [41], [43]).

Le acque che fuoriescono dal cunicolo esplorativo e di drenaggio e dalle gallerie principali raggiungono gli impianti di trattamento per gravità. Solo le acque che provengono dallo scavo delle finestre di accesso necessitano di impianti di sollevamento, per le quali sono previste ulteriori emissioni di CO_2 pari a 1.171 t. Complessivamente, quindi, le emissioni di CO_2 dovute agli impianti di trattamento delle acque ammontano a 17.080 t.

5. Riepilogo emissioni di CO2 e discussione dei risultati

La quantità di CO_2 emessa durante la fase di costruzione del BBT è stimata complessivamente in 2.280.550 t (fig. 3, tabella 13). La produzione del materiale da costruzione rappresenta la percentuale più elevata, pari a circa l'85% delle emissioni totali. Il 7% è prodotto per garantire l'illuminazione, la ventilazione e il raffreddamento delle gallerie. A seguire, le operazioni di scavo incidono per il 7%, il funzionamento dei cantieri per l'1%. Tra le singoli

table 13). Production of the building material represents the largest proportion, approximately 85% of total emissions. 7% is produced to ensure lighting, ventilation and cooling of tunnels. Excavation operations then follow accounting for 7%, the operation of the sites for 1%. Among the individual elements cement production is highlighted, which with 1.500.00 t, is equal to 68% of total emissions. This is due to the large amount of material required for the construction of the work, estimated at 2.4 million tons, and to the production process that is very costly in terms of energy: blast furnaces are used to produce all the necessary klinker for the realisation of the cement, that reach very high temperatures.

To have a comparable order of magnitude, the total is divided in the 18 years forecasted for the construction phase and tooling of the work, thus achieving about 127 kt CO_2. This value is comparable to the annual emission of an Italian town of about 20.000 inhabitants (e.g. Bres-

Tabella 12 – *Table 12*

Emissioni di CO_2 degli impianti di trattamento delle acque
CO_2 emissions from water treatment plants

	Localizzazione *Localisation*	**Portata stabilizzata** *Stabilised capacity* **[m³/h]**	**Potenza** *Power* **[kW/(m³/h)]**	**Potenza** *Power* **[kW]**	**Tempo** *Time* **[a]**	**Tempo** *Time* **[h]**	**Consumo energetico** *Power consumption* **[kWh]**	**Fattore conversione** *Conversion factor* **[kg/kWh]**	**CO_2 [t]**
		(1)	(2)	(3)=(1)·(2)	(4)	(5)=(4)·8670	(6)=(3)·(5)	(7)	(8)=(6)·(7)·10^{-3}
Lato Austria - ***Austrian side***									
Finestra Wolf *Wolf Window*	Wolf	18,00	0,15	2,70	2,00	17.520	47.304	0,216	10,22
Finestra Ahrental *Ahrental Window*	Ahrental	82,80		12,42	1,33	11.651	144.703		31,26
Cunicolo *Burrow*	Innsbruck	374,40		56,16	6,00	52.560	2.951.770		637,58
Cunicolo e gallerie principali *Burrow and main galleries*	Innsbruck	1.116,00		167,40	6,00	52.560	8.798.544		1.900,49
Lato Italia - ***Italian side***									
Finestra Mules *Mules window*	Mauls	90,00	0,15	13,50	1,17	10.220	137.970	0,435	60,02
Cunicolo di Aica *Aica burrow*	Aica	514,80		77,22	1,50	13.140	1.014.671		441,38
Cunicolo *Burrow*	Aica	1.098,00		164,70	5,00	43.800	7.213.860		3.138,03
Cunicolo e gallerie principali *Burrow and main galleries*	Aica	2.826,00		423,90	6,00	52.560	22.280.184		9.691,88
Totale - ***Total***									**15.910,85**
(Fonte - Source: *[46], [47], [48]).*									

voci si evidenzia la produzione del cemento, che con 1.500.000 t, equivale al 68% delle emissioni totali. Questo è dovuto alla grande quantità di materiale necessario per la costruzione dell'opera, quantificato in 2,4 Mio t, e al processo produttivo molto dispendioso a livello energetico: per produrre tutto il clinker necessario alla realizzazione del cemento, sono impiegati altiforni che raggiungono temperature molto elevate.

Per avere un ordine di grandezza comparabile, il totale viene suddiviso nei 18 anni previsti per la fase di costruzione e di attrezzaggio dell opera, ottenendo così circa 127 kt CO_2. Questo valore è equiparabile all'emissione annua di un comune italiano di circa 20.000 abitanti (es. Bressanone), considerando un emissione media per abitante pari a 6,3 t CO_2 [49].

Inoltre, è interessante paragonare

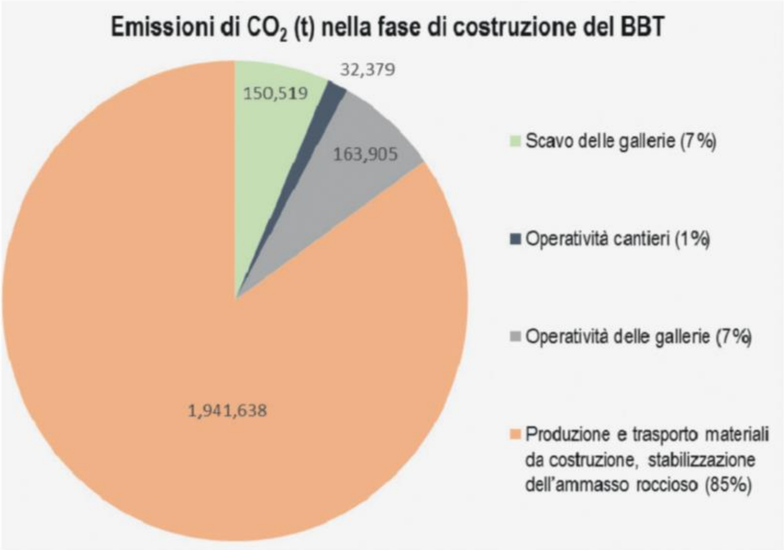

Fig. 3 - Emissioni di CO_2 nella fase di costruzione del BBT.
Fig. 3 - CO_2 emissions in the construction phase of the BBT.

TABELLA 13 – *TABLE 13*

Sintesi delle emissioni di CO_2 nella fase di costruzione del BBT
Summary of CO_2 emissions in the construction phase of the BBT

Macrofasi ***Macrophases***	**Fattori di calcolo** ***Calculation factors***	**CO_2 emessa** ***CO_2 emitted*** [t]	**Somme e percentuali** ***Amounts and percentages*** **[%]**
Scavo delle gallerie *Excavation of galleries*	Scavo meccanizzato *Mechanised excavation*	101.913	150.519 (7%)
	Produzione TBM *TBM production*	3.103	
	Trasporto TBM *TBM transport*	364	
	Scavo convenzionale *Conventional excavation*	17.680	
	Esplosione *Explosion*	7.012	
	Trasporto materiale di scavo (via camion) *Transport of excavated material (by truck)*	5.745	
	Trasporto materiale di scavo (via nastro) *Transport of excavated material (by conveyor)*	14.702	
Produzione e trasporto materiali da costruzione; stabilizzazione dell'ammasso roccioso *Production and transport of construction materials; stabilisation of the rock mass*	Frantumazione inerte *Crushing of aggregate*	2.628	1.941.638 (85%)
	Cemento *Cement*	1.561.007	
	Calcestruzzo prefabbricato *Precast concrete*	13.084	
	Impianto betonaggio *Batching plant*	2.213	
	Applicazione spritzbeton *Application of shotcrete*	1.638	
	Acciaio *Steel*	358.555	
	Trasporto materiale da costruzione (via trenino shuttle) *Transport of building material (via shuttle train)*	502	
	Trasporto materiale da costruzione cunicolo di Aica (via camion) *Transport of building material of AICA burrow (by truck)*	2.011	
Operatività delle gallerie *Operability of galleries*	Illuminazione gallerie *Tunnel lighting*	13.195	163.905 (7%)
	Ventilazione e raffreddamento *Ventilation and cooling*	150.710	
Operatività cantieri *Construction site operability*	Illuminazione aree esterne, funzionamento uffici e officine meccaniche *Lighting of outdoor areas, operation of offices and engineering workshops*	15.299	32.379 (1%)
	Trattamento delle acque *Water Treatment*	17.080	
Totale ***Total***			**2.288.441**

le emissioni di CO_2 prodotte durante la realizzazione del tunnel con quelle generate dal traffico stradale e ferroviario durante l'arco temporale di un anno. Considerato l'asse del Brennero, nella tratta da Kufstein a Verona, a seconda degli scenari con o senza tunnel e dell'anno di riferimento, le emissioni annue totali da traffico sono comprese tra circa 1,5 Mio t e 2 Mio t [8], un valore paragonabile (ancorché leggermente inferiore) alle emissioni totali prodotte per la realizzazione dell'opera. L'effettivo ri-

sanone), considering an average emission per capita of 6.3 t of CO_2 [49].

Also, it is interesting to compare the CO_2 emissions produced during the construction of the tunnel with those generated from road and rail traffic during the time span of one year. Considering the Brenner line, in the Kufstein to Verona stretch, depending on the scenarios with or without tunnel and on the reference year, the to-

sparmio ottenibile dal passaggio delle merci dalla strada alla rotaia e i tempi di compensazione dell'opera sono comunque un aspetto complesso, per i quali occorre considerare diversi scenari e politiche di accompagnamento alla messa in esercizio della linea AV/AC. In linea con uno scenario virtuoso, fatto di politiche di supporto alla nuova linea ferroviaria, è stato calcolato che la compensazione potrebbe avvenire dopo circa 19 anni dall'inizio dei lavori di costruzione [18]. È opportuno ribadire, comunque, che si tratta solo di uno degli scenari possibili, e che la sua realizzazione si verifica solo a determinate condizioni, rese possibili da una accorta politica dei trasporti.

Volendo infine valutare il contributo a scala locale [50], risulta che l'infrastruttura che ricade nel territorio altoatesino, ovvero la tratta Brennero-Fortezza e parte della linea di Accesso Sud che va da Fortezza fino a Salorno, comporta, per la sola fase di costruzione, emissioni pari a 1.855.000 t di CO_2. Tale quantità è pari a circa una volta e mezza le emissioni prodotte nel 2008 dal traffico stradale in Alto Adige [51].

6. Conclusioni

La metodologia proposta nel presente articolo consente di valutare in maniera quantitativa e sintetica le emissioni di anidride carbonica legate alla realizzazione di un grande tunnel ferroviario, colmando le lacune metodologiche riscontrate in letteratura. L'esplicazione puntuale del modello teorico e l'applicazione al caso studio del Brennero, consentono la trasferibilità dell'analisi ad infrastrutture di trasporto analoghe, anche a scala differente. L'approccio scelto (*Hybrid* LCA), ben si adatta ad opere estremamente complesse, articolate e la cui fase di realizzazione si protrae nel lungo periodo. Esso prevede una accurata fase di raccolta dei dati, sia durante la fase di progettazione, sia durante la fase di realizzazione, da farsi direttamente in loco e in stretta collaborazione con progettisti e ditte costruttrici, attraverso rilevazioni in cantiere, oltre alla ricerca di dati in letteratura il più possibile aderenti al contesto in esame. Questo permette di fornire indicazioni utili per quantificare l'impatto della fase di realizzazione dell'opera e di migliorare in itinere il processo nella direzione della sostenibilità ambientale.

Il metodo presentato è stato volutamente mantenuto semplice e non richiede l'utilizzo di particolari tecnologie, in modo tale da consentirne la replicabilità. Tale scelta, però, sconta al contempo la necessità di assumere nella fase di calcolo alcune ipotesi semplificative necessarie per agevolare il computo e di cui è necessario essere consapevoli in fase di valutazione dei risultati. Inoltre, poiché i tempi di costruzione di tali opere sono solitamente nell ordine dei decenni e conseguentemente la documentazione progettuale di riferimento per l'analisi si basa sullo stato di previsione, è necessario assumere ipotesi sulle scelte e sulle tecniche costruttive che saranno utilizzate. Tra i principali elementi di incertezza vi sono inoltre da annoverare quelli legati alla scelta dei fattori di emissione

tal annual emissions from traffic are between 1.5 million tons and 2 million tons [8], a value comparable (albeit slightly less) to the total emissions for the construction of the work. The actual savings achieved by the passage of goods from road to rail and compensation times of the work is still a complex issue, on which we must consider different scenarios and support policies for the commissioning of the HS/HC line. In line with a virtuous scenario, made of support policies to the new railway line, it was calculated that compensation could take place after about 19 years from the beginning of construction works [18]. It is worth repeating, however, that this is only one of the possible scenarios, and that its fulfilment only occurs under certain conditions, made possible by a wise transport policy.

Finally assessing the contribution at a local level [50], it appears that the infrastructure which falls within the South Tyrol territory, which is the Brenner-Fortezza stretch and part of the South access line from Fortezza to Salorno, involves, just for the construction phase, emissions equal to 1.855.000 tons of CO_2. This amount is equal to about one and a half times the emissions from road traffic in 2008 in South Tyrol [51].

6. Conclusions

The methodology proposed in this article allows evaluating, in a quantitative and synthetic manner, carbon dioxide emissions related to the construction of a large railway tunnel, filling methodological gaps identified in literature. The careful explanation of the theoretical model and its application to the Brenner case study, allow the transferability of the analysis to similar transport infrastructures, even at a different scale. The chosen approach (HybridLCA), is well suited to extremely complex and articulated works, whose progress continues in the long run. It provides an accurate data collection phase, both during the design process, and during the implementation phase, to be performed directly on site and in close collaboration with designers and construction companies, through surveys on site, in addition to data research in literature as much as possible pertinent to the context in question. This allows providing useful information to quantify the impact of the progress of the work and improve the ongoing process towards environmental sustainability.

The method presented has been deliberately kept simple and does not require the use of specific technologies, so as to allow its replicability. This choice, however, was affected by the need during the calculation to make simplification hypotheses necessary to facilitate calculation and which one must be aware of when evaluating the results. Moreover, because the timing of construction of such works is usually in the order of decades and consequently the reference design documentation for the analysis is based on forecasts, assumptions must be made on choices and construction techniques that will be used.

di CO_2. Mancando in letteratura un'armonizzazione di tali valori e dei metodi utilizzati per il loro calcolo, essi possono differenziarsi significativamente a seconda delle fonti utilizzate e della scala territoriale di riferimento, influenzando notevolmente i risultati finali. Le ipotesi introdotte possono portare in parte a sottostimare, in parte a sovrastimare i fattori di calcolo restituendo comunque nel complesso una stima attendibile delle emissioni di CO_2.

Nel caso del BBT, i risultati hanno permesso di fornire importati elementi utili per rendere più efficiente il processo di costruzione, individuando su quali voci intervenire per contenere le emissioni. Nello specifico, avendo individuato nella produzione del cemento la fase più impattante, la BBT SE ha potuto ridurre le emissioni di CO_2 nella produzione del calcestruzzo, sostituendo il cemento con scorie di altoforno e ceneri volanti fino ad una percentuale pari al 25%. Trattandosi di materiali di scarto, in particolare di particelle che derivano dalla combustione del carbone, esse non incidono sulle emissioni finali di CO_2. Inoltre sono stati ottimizzati gli interventi di costruzione, semplificando la struttura delle fermate di emergenza lungo la linea, costruendo rivestimenti a spessore unico nei tratti in cui le condizioni geologiche lo permettevano e annullando la costruzione del tunnel di accesso inizialmente previsto a Wolf Nord.

Infine, il metodo qui sviluppato può costituire un utile strumento per i decisori politici. Sulla base dei risultati ottenuti, infatti, si può monitorare il processo di costruzione, e si possono prevedere gli effetti di eventuali vincoli e norme prima di renderli operativi, in modo tale da stabilire in maniera precisa e collaborativa con i tecnici le condizioni migliori per contenere le emissioni nella fase di realizzazione delle opere. In una più ampia prospettiva, l'analisi diventa parte integrante di un processo di revisione metodologica, in grado di portare alla inclusione della CO_2 tra gli elementi da considerare in fase di pianificazione infrastrutturale [52], [53]. Tale processo è complesso e comprende diverse fasi. Alcune di esse hanno valenza operativa: la fase di esercizio [8], la valutazione dell impatto a scala nazionale [54], regionale [50]. Altre sono collegate all'attribuzione di un valore economico equo [55], [56], [57], [58]. Altre ancora, infine, riguardano il coinvolgimento di diversi attori [59], [60] e possono includere l'utilizzo di metodi di indagine [61], [62], [63] nel processo decisionale per costruire un percorso condiviso. Nel loro insieme, questi differenti approcci permettono di valutare quanto la realizzazione delle grandi infrastrutture di trasporto incida nel bilancio delle emissioni a diverse scale, integrandosi con altre analisi legate alla domanda o all'offerta di trasporto [64], [65], [66]. È così possibile stabilire concrete misure compensative e mitigative a favore del territorio, garantendo al contempo informazione e condivisione dell'operato. In questo modo i decisori politici hanno elementi utili per definire azioni vantaggiose a scala locale, e per contribuire ad una equa distribuzione di oneri e benefici che le grandi opere portano con sé nei territori attraversati.

Among the main elements of uncertainty there are also those related to the choice of CO_2 emission factors. Since harmonisation of these values and the methods used for their calculation are lacking in literature, they can differ significantly depending on the sources used and the reference territorial scale, greatly influencing the final results. The assumptions introduced can lead to partly underestimate, partly overestimate the calculation factors, however resulting in an overall reliable estimate of CO_2 emissions.

In the case of the BBT, the results have made it possible to provide important useful elements to help streamline the construction process by identifying the areas of intervention to contain emissions. Specifically, having identified the most impacting phase in cement production, the BBT SE was able to reduce CO_2 emissions in the production of concrete, replacing cement with blast furnace waste and flying ash up to a percentage equal to 25%. In the case of waste materials, in particular of particles that result from coal combustion, they do not affect the final emissions of CO_2. Construction work was also optimised, simplifying the structure of emergency stops along the line, building thick single coatings in stretches where geological conditions allowed doing so and eliminating the construction of the access tunnel initially planned at Wolf Nord.

Finally, the method developed here can be a useful tool for policy makers. Based on the results obtained, in fact, the building process can be monitored, and the effects of potential constraints and operational rules before making them operational, so as to determine with technicians precisely and in a collaborative manner the best way to curb emissions during the execution of works. In a wider perspective, the analysis becomes an integral part of a methodological revision process, which could lead to the inclusion of CO_2 between the elements to consider when planning infrastructures [52] [53]. This process is complex and includes several stages. Some of them have operational significance: the working phase [8], the assessment of the impact at national and [54], [50] regional level. Others are linked to the attribution of a fair economic value [55] [56] [57] [58]. Others, finally, concern the involvement of different actors [59], [60] and may include the use of methodologies [61] [62] [63] in the decision making process to build a shared path. On the whole, these different approaches allow assessing how the realisation of major transport infrastructures affect the balance of emissions at different scales, integrating with other analyses related to the demand or transport offer [64] [65] [66]. It is thus possible to establish important compensatory and mitigative measures in favour of the territory, ensuring information and sharing of the work at the same time. In this way, policy makers have useful elements to define favourable actions at local level, and to contribute to a fair distribution of burdens and benefits that great works carry with them in territories crossed.

Riconoscimento

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3.1.2. A new Method for forecasting CO_2 Operation Emissions along an Infrastructure Corridor

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A NEW METHOD FOR FORECASTING CO_2 OPERATION EMISSIONS ALONG AN INFRASTRUCTURE CORRIDOR

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Abstract

In evaluating the sustainability of a new transport infrastructure, an important aspect is the reduction of CO_2 emissions that might be produced due to the modal shift. To that end, this article proposes a model based upon the simulation method (in order to determine the specific consumption of the vehicles) and the scenario method (for the prediction of the future demand of traffic). The model has been tested on the case study of the Brenner Corridor. The evaluation is on how the new HC railway line will affect freight transport in various future scenarios relating to 2030, taking into consideration the consequences in terms of traffic redistribution on existing transport infrastructures (the historical railway line and the highway). If compared to the work not being realized (the "minimum" scenario), the results reveal that CO_2 emissions can increase of about 80 kt (the "trend" scenario), or decrease of approximately 230 kt (the "consensus" scenario) according to the political decisions that accompany the realization of the new line. In addition, the method makes it possible to determine the specific emissions that are necessary to transport one metric ton of freight along the entire corridor by the different transport modes. Finally, the transfer of freight from road to rail is quantified that is necessary to compensate the emissions originating from the construction of the work.

Keywords: operation phase, CO_2 emissions, scenarios, railway and road simulations, Brenner Corridor.

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1. Introduction

In transport planning, interest has grown in recent years in the evaluation of pollutants that are produced by an infrastructure system. Among the substances emitted by vehicles while traveling, carbon dioxide (CO_2) is considered among the most important indicators:

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it is one of the main causes of global warming, since it comprises more than 75% of greenhouse gas (GHG) emissions of human origin (IPCC, 2007).

Within that framework, means of transport are responsible for approximately 25% of total emissions (EC, 2005), and over the past two decades, there has been an increase of 27% with respect to the levels of 1990 (EC, 2009). At the European level, the attempt is being made to promote a more sustainable development in infrastructures by encouraging less polluting means of transport. For terrestrial transport, that coincides with the development of the railway network (Van Essen et al., 2003) and the public transport, including non-conventional and innovative systems (Cappelli, 2008). The TEN-T networks and the pan-European corridors have been designed with this specific aim. In order to measure the efficiency of such applications in terms of savings in emissions, it is necessary for the realization of such infrastructures to be preceded by an analysis capable of quantifying their impact.

The literature is lacking in comprehensive analyses of this type. In some cases (Liao et al., 2009; Italferr, 2010) the methodology is not described and only results are provided, thus not allowing the repeat in other contexts. In other cases (Tuchschmid, 2009), the scale is too broad and needs some oversimplifications that make the method not detailed enough. Finally, in some other paper (Cappelli, 2006, Kelly et al., 2009, Ou et al., 2010), the description is detailed but limited to a single transport mode. To face these issues, Nocera, Maino and Cavallaro (2012) propose a heuristic method for the calculation of a CO_2 balance for a new transport system: it included the construction and operation phases, allowing for a comparison between the system that is determined by the realization of the work and that, which is derived from its absence.

The present paper is a renovation of this approach, focussing on the operation phase of freight transport[2] and the consequences derived from different policies. The aim is the development of a new reiterable methodology, that helps to evaluate with more accuracy how CO_2 freight emissions can change after the introduction of a new transport infrastructure, considering also the main other infrastructures already existing. This study focusses in particular on the consequences that derive from the shifting of part of the transport demand from one transport mode to another. Finally, the method can determine the CO_2 emissions of a unitary quantity of freight transported by the different infrastructures.

In Section 2, a description is provided of the theoretical model that is adopted here. In Section 3, the model is tested on the case study of the Brenner Corridor. Finally, this is followed by concluding notes regarding strongpoints, critical components, and the possibility to repeat the method proposed here in other case studies.

2. The method for forecasting future CO_2 emissions in the operation phase

Figure 1 reports in summary form the totality of the operations necessary to quantify the future CO_2 emissions derived from the operation phase of an infrastructure system: the process is based upon the simulation method (described in Section 2.1) and upon the scenario method (Section 2.2). Also having an effect upon the emissions is the totality of the operations necessary to allow for the correct functioning of the infrastructure, that is,

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[2] Freight constitute the main critical component of transalpine traffic upon which the combined forces of the European Union and the individual countries are being concentrated in order to balance the transport modes (Economic Research - Policy Consultancy et al., 2011).

the operation of the infrastructure without freight or passengers. These operations are indicated as “idle operations” and have an effect upon the production of emissions primarily in the sections in tunnels, include lighting, ventilation, and the treatment of water that flows out of the tunnels themselves. Nevertheless, since their contribution does not exceed 1.5% (Ruffini et al., 2010), they may be considered minimal: this value is indeed lower than the total uncertainty of the method and is not considered in the calculation.

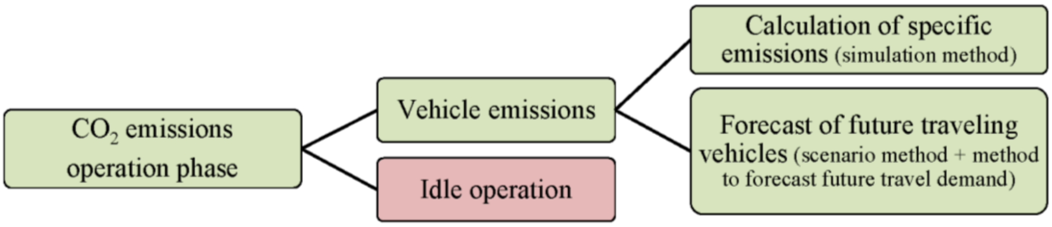

Figure 1: methodology for calculating CO_2 emissions from operation phase of a given infrastructure system

2.1 Simulation method

The “simulation method” bears this name because it is based upon the use of instruments capable of simulating the performance of a typical vehicle in terms of energy consumption and CO_2 emissions. This study refers to terrestrial long-distance traffic, and thus rail transport (Section 2.1.1) and road transport (Section 2.1.2) are analysed.

2.1.1 Rail-based simulation method

The rail simulation method permits the quantification of electrical energy consumption necessary for a train to travel a given route. It thus makes it possible to derive the related CO_2 emissions. To that end, some specific programs have been developed (Lukaszewicz, 2001; Jong and Chang, 2005; Lindgreen and Sorenson, 2005). Among these, the MOVEL software was developed by the company Atos Progetti.

The calculation is based upon the modelling of the infrastructure, that is, on its schematization for the purpose of providing the only input data that are necessary for the program. What is taken into consideration in the analysis is on one hand all of the characteristics of the route that influence the resistance to motion and which affect energy consumption, such as the presence of sections that are open or in a tunnel, the radius of the curves, and the slopes (positive or negative). Also taken into consideration on the other hand are the technical characteristics of the typical vehicle that is used, and in particular the resistances to motion. The literature summarizes the various resistances in a single equation as a function of velocity (Vicuna, 1986; formula 1):

$$R_j = a_j + b_j * V + c_j * V^2 \qquad 1)$$

where:
R is the resistance to the total motion;
j indicates the type of train analysed;
a represents the rolling resistance between the wheel and the track and the resistance due to the contact between the spindle and the bearing;

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b represents the resistance derived from the contact between the flange and the track, from the absorption of the vertical oscillations, from the structural characteristics of the vehicle, and from the conditions of the railroad tracks;
c represents the aerodynamic resistance;
V represents the velocity of the train.

With the technical characteristics of the railway infrastructure and of the typical vehicle as known quantities, a first simulation called the simulation of travel on the terrain (or train performance) determines the power at the pantograph of the train for the two directions of travel by step in terms of time or space. Normally the former is adopted to better compare the travel of trains in sequence both at a constant speed and at changing speeds. A series of printouts is obtained which, with scans in terms of time or space, provide the position of the train, the travel time since the start of the run, the progressive power absorbed, and the energy used in order to cover the entire route.

The train performance is followed by the electrical simulation, which serves to determine instant by instant (according to the step of a pre-established rate) the electrical energy that is absorbed at the primary point from the electrical substation (ESS) and the value of the voltage provided to the pantograph for every train along the route, including the presence of other trains according to the traffic. This simulation makes it possible to evaluate whether the electrical system is capable of supporting the envisioned traffic or not. In order to carry out this analysis, it is necessary to know the position of the ESS and the electrical characteristics of the lines and plants of the electrical propulsion in general.

In this way, the energy supplied by each ESS is determined as the output of the entire system: according to the relationship expressed in Formula 2, the energy that is actually required by the railway system is given by:

$$E_s = r \cdot E_p \tag*{2)}$$

where:
E_s is the energy absorbed by the electrical substations,
r is the efficiency of the entire electrical system,
E_p is the energy detected at the pantograph.

Finally, the use of the energy requirements yields the CO_2 emissions (formula 3) by means of the use of a suitable conversion factor (q_h). It is a function of the national energy mix or of the weighted average of the various national coefficients if the traffic flow takes place in more than one country.

$$E_{CO2} = \sum_h f_h \cdot q_h \tag*{3)}$$

where:
E_{CO2} is the emission of CO_2 derived to the energy requirement necessary to grant the circulation of trains;
h is the energy vector[3];

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[3] The means, equipment, or fluid which permit the transport of the energy for the exploitation of the energy sources. In a figurative sense, the vectors also include electricity, and thus electrical energy is at the same time considered to be both a vector and an energy source (Comini and Cortella, 2001).

f_h is the energy requirement for each energy vector;
q_h is the conversion factor in CO_2 emissions for each energy vector.

2.1.2 Road-based simulation method

In the case of road simulations, as well, the specific emissions of the typical vehicle are quantified utilizing specific software. In this case, the available models are more numerous, and the differences from a computational point of view are also greater. The first difference has to do with the supply of the fuel: some methods consider the entire process, from the phase of petroleum extraction up to the consumption of the fuel (the "well-to-wheel" approach); other methods limit the calculation to be from the fuelling by the user at the filling station up to the consumption (the "tank-to-wheel" approach). The other parameters being equal, the first approach obviously involves greater expenditures in terms of CO_2 emissions and also assumes a higher level of uncertainty. The second difference concerns the formulation of the methodology, that is, the totality of the variables that are considered in the modelling phase. Demir et al. (2011) distinguish six models in this connection:

- The *instantaneous fuel consumption model* is based upon the characteristics of the vehicle such as mass, energy, efficiency, and drag forces and fuel consumption associated with aerodynamic drag and rolling resistance. This model works at a microscale level, evaluating the fuel consumption per second. It has a higher performance for the estimations of the emissions that are derived from short trips: it indeed does not take into consideration the number of stops, dwelling instead upon acceleration, deceleration, cruise and idle phases.
- The *four-mode elemental fuel consumption model* includes the same parameters as the previous model, to which are added the initial and the final speed, and the parameters associated with the energy requirement. On one hand, the large number of parameters that are taken into consideration guarantees a higher degree of accuracy; on the other hand, though, it makes adoption difficult.
- The *running speed fuel consumption model* considers acceleration, deceleration, and cruise modes together in a single function. It is a method utilized in a large variety of traffic situations, including both short and long trips (although greater calculation difficulties are visible with the former); it does not take into consideration the phase in which the engine is operating at a minimum, whereas acceleration, deceleration and cruise modes are considered.
- The *comprehensive modal emission model* takes into consideration three parameters: fuel rate, power, and engine speed. This model is similar to that of the first group but more accurate because it requires additional information, such as the engine friction coefficient and the vehicle engine speed.
- The *methodology for calculating transport emissions and energy consumption model* is based upon the calculation of the specific factors of emissions from real-life experiments. It preliminarily considers conditions of typical traffic flow (class of roads, vehicles without loads) that are a function of the average velocity. From those initial values, depending upon the vehicle being considered, a series of corrections is carried out in order to take into consideration other factors, such as the slope of the road and the vehicle load. The initial values are measured by means of experiments and on-road measurements.

- The *computer program to calculate emissions from a road transport model*, just like the previous model, is based upon direct measurements but does not take into consideration the road gradient and the accelerations. Every class of vehicles is characterized by two ranges of velocity.

Even though the CO_2 emissions present a degree of accuracy that is generally superior with respect to other pollutant gases (Smit, 2010), the uncertainties relating to the calculation are nevertheless high and, as with all long-term forecasts, they expand with the time horizon (Parisa, 2012). It is therefore fundamental to choose the method as a function of the type of trip that is desired to be analysed, limiting the uncertainties to those that are endemic to the system and without introducing additional ones that relate to parameters not relevant to the analysis.

The process of calculating road emissions is similar to that adopted for rail emissions, but it is more simplified because the softwares directly provide the CO_2 values on the basis of the vehicle being examined and the road travelled.

Just as in the case with railways, the road simulation method also preliminarily requires infrastructure modelling, that is, the definition of the planimetric and altimetrical course of the road under consideration. First of all, it is necessary to assign the correct class (highway, urban road, suburban road) and the average travel velocity. Then the entire route is broken up into unitary kilometric spatial steps, distinguished by elevation (expressed in meters) and slope class (expressed as a percentage). These values are usually obtained from technical documentation, planimetries, or projects; in the absence of these, direct measurement can be used as well.

The emissions are associated with the characteristics of the typical vehicle: the parameters that have the greatest influence upon consumption are the weight hauled, the travel speed, the type of fuel supply, and the engine emission category (Sandberg, 2001). Other factors may be included in the analysis in order to refine the results: among those worthy of mention are the gross vehicle weight, unladen weight, theoretical load capacity, fill factor, freight quantity, maximum speed, fuel supply, and type of fuel used. The calculation of emissions is based upon the parameters that were just described, but another factor is taken into consideration: the type of emissions. Depending upon the vehicle's engine temperature, a distinction is usually made between "hot" emissions – that is, with the engine at full operating temperature and the catalytic converters at full function; "cold" emissions – that is, those that are generated during the warm-up phase of the engine; and evaporative emissions – that is, those derived from the evaporation of the fuel that is present in the vehicle's tank when the engine is off. The choice of the typology significantly affects the final specific value and must be carried out depending upon the type of trip that is analysed.

2.2 Scenario method

In order to determine the emissions along a certain infrastructure system, the combined road and rail emissions that were previously described must be multiplied by the number of vehicles that travel along the line during the time period being considered. If the reference year has already passed and the analysis reflects the past, then historical data are referred to. If, on the other hand, the year being considered is in the future, then the value is determined by means of the forecast of demand. In the field of transport engineering, this is one of the thematic areas that presents the greatest uncertainty in terms of final results and gives rise to incorrect evaluations regarding the feasibility or the dimensioning of a project (Flyvbjerg et al., 2006). The forecasting methods for future demand are different depending upon the time horizon that is taken into consideration.

If the forecast year is the next after the current one, and if an historical series is available that is sufficiently broad, then it is possible to extrapolate the data by means of the trend method, which determines the future value on the basis of the past trend. In this case, it is assumed that the economic and territorial variables remain constant over time and that therefore demand will evolve in the future according to the same manners that were observed in the past.

If, on the other hand, the time horizon is broader, it is preferable to adopt the scenario method. The scenario is not a forecast of future conditions, but rather a representation of possible future arrangements that is structured in a logical manner (EC, 2008). From a methodological viewpoint, the scenario is based upon certain hypotheses of growth which, when intersected with the available historical data, provide the logical consequences that the initial hypotheses imply.

The main value of this method lies in its versatility: indeed, different parallel scenarios can be developed, each with specific characteristics because it is based upon clear and distinct preliminary hypotheses. The construction of future demand scenarios in the field of transport may be based upon various models, of which the input-output model and the four step model are the strongest from a methodological viewpoint.

The input-output model (Leontief and Costa, 1996) is a macroeconomic model in which the transport demand depends upon a single variable (usually GDP) which summarizes and comprises all of the partial economic and territorial variables. These models have been demonstrated to be reliable for evaluations at the national scale, for which the predictions of the GDP trend in the future are available from reliable studies at both the national (e.g.: ISTAT, Bank of Italy, the national government, and the regional governments) and international (e.g.: research offices of the EU and the International Monetary Fund) levels.

The four step model (McNally, 2008) estimates the demand and the future modal split for a certain geographical area (defined in advance), taking into consideration four steps: generation, distribution, modal choice, and route assignment. The first two steps provide the total of the movements generated and attracted, respectively, by each individual zone during the preselected time horizon. These variations are a function of a series of parameters at the levels of socioeconomic, technological, and transport policy (different market rules, infrastructure and fiscal policies, prohibitions, and ordinances) and of the development of logistics systems. The third step distributes the movements that were calculated with the previous models among the various travel modes, while the fourth step specifies the route utilized to complete the movement.

The classic formulation of the method (Cascetta, 2006) is expressed in Formula 4):

$$s_{ij}(m,k) = G_i \cdot P(j \mid i) \cdot P\,(m \mid i,j) \cdot P(k \mid i,j,m) \qquad 4)$$

where:
s is the flow that is the subject of the analysis;
i and j are the origin and the destination of the journey, respectively;
m and k are the transport mode and the route adopted, respectively;
G is the generation of a certain flow;
P is the probability that the event will occur.

On the basis of the various initial hypotheses that are summarized in Cappelli and Nocera (2006) for freight and in Nocera (2010, 2011) for passengers, it is possible to construct different scenarios of demand growth that can be expressed both in terms of vehicles in the network and in terms of tons of freight transported, depending upon the values. In the case in which the analysis of the economic type provides the forecast tons of freight, the number of future vehicles in circulation along the infrastructures being considered is obtained by dividing the total quantity of freight by the net load capacity of the typical vehicle being considered. Finally, by multiplying the number of vehicles in circulation by the specific emissions as determined by the simulation method, the future CO_2 emissions are obtained.

The method presented in this section is tested on the case study of the Brenner Corridor.

3. The Brenner corridor

The Brenner Corridor is the main Alpine crossing that connects Germany to Austria and to Italy. It begins in Munich and ends in Verona, passing through the Lower Inn Valley (Kufstein-Innsbruck) and the Sill (Innsbruck-Brenner), Eisack/Isarco (Brenner-Bolzano), and Adige (Bolzano-Verona) valleys. Nevertheless, it often refers only to the section between Kufstein and Verona, in this way including only Austrian and Italian territory, because the section between Munich (520 m. above sea level) and Kufstein (497 m. above sea level) present characteristics that are different with respect to the remainder of the line so as to make it similar to a section on a plain. In this study, as well, this supposition has been adopted, taking into consideration only the section from Kufstein to Verona.

With almost 40% of the total Alpine traffic, the Brenner is the Alpine corridor that presents the greatest movement of freight. That is due primarily to three aspects: the central geographical position with respect to the Alps and to the countries that surround them, the limited elevation of the pass, and the presence of one single rise to be crossed in the entire section between Germany and Italy. Over the last thirty years, it has assisted in a constant increase in freight traffic: in 1990, approximately 15 million metric tons (mil. t) were transported, while in 2010, that figure grew to 43 mil. t (UFT, 2011). Analysing the transport modes in 2010 and intersecting that data with suitable considerations on the elasticity of the demand (Libardo and Nocera, 2008), it is deduced that the majority of the freight (29 mil. t) is transported by means of road traffic, while the railway transport is established at around 14 mil. t.

Starting out from these data, the quantity of future freight is first determined, delineating the reference scenarios (Section 3.1). The primary infrastructures that cross the corridor are then described in detail, as are the related CO_2 emissions produced by them. There are currently two of these infrastructures: the historical railway line and the highway. Starting in 2025, these will be joined by a high capacity (HC) railway line. Section 3.2 is dedicated to the description and calculation of the CO_2 emissions of the railway lines, while the highway is analysed in Section 3.3. Finally, the aggregate results along the entire corridor are evaluated (Section 3.4).

3.1 Future scenarios

ProgTrans (2007) worked out a detailed study for the Brenner axis up to 2030 based upon different hypotheses of socioeconomic growth and upon the introduction of various measures in support of transport systems. The output data of that study are the volume of origin/destination traffic that is relevant for transalpine traffic, the total passenger and freight traffic, and finally the modal split of the traffic volume (road and rail). Of the six scenarios originally developed by ProgTrans, three were not taken into account because they were not considered to be realistic: they in fact hypothesized the Gotthard Base Tunnel not being used, but it is currently in the advanced phase of realization and forecast to go into operation starting in 2017.

Therefore only three scenarios are used here[4], that is, that of the "minimum", which does not envision the construction of the Brenner Base Tunnel [BBT] and hypothesizes a transposition of the current transport policy to 2030; the "trend" scenario, which envisions a growth in continuity with the trend of the past decade (constant growth both in road and in rail traffic and the realization of the BBT); and finally the "consensus" scenario, which involves the realization of the tunnel and of a policy directed at favouring the rail development at the expense of the road development. The measures that were adopted in the various scenarios, subdivided into disincentive measures for road traffic and incentive measures for rail traffic, have been summarized in Appendix 1.

"Trend" and "consensus" are further subdivided into two subscenarios, indicated as "trend 1" and "trend 2" and as "consensus 1" and "consensus 2" on the basis of the split of railway freight traffic. While the total amount of freight transported and the split between road and rail does not change, there is a variation in the railway traffic split between the historical line and the new HC line. The "1" scenarios are based upon railway simulations carried out by the BBT that forecast 82% of the total traffic being concentrated on the HC line, while the remaining 18% is transported along the historical line. The "2" scenarios, on the other hand, envision the entire railway freight traffic along the new HC line[5]. Table 1 summarizes the quantities of freight transported between rail and road referring to the year 2030 taken as the reference year in this analysis, since train traffic at full capacity along the HC line can be hypothesized within that date.

Table 1: Freight transport along the Brenner corridor in 2030. Source: ProgTrans, 2007

FREIGHT ALONG THE BRENNER – YEAR 2030						
		MINIMUM	TREND1	TREND2	CONSENSUS1	CONSENSUS2
Historical railway line	Mil. t_{net}/year	19.5	-----	6.0	-----	6.6
HC railway line	Mil. t_{net}/year	-----	33.2	27.2	36.2	29.7
Highway	Mil. t_{net}/year	47.2	47.8	47.8	30.9	30.9

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[4] For a complete description of the scenarios, the interested reader may refer to Nocera and Cavallaro, 2011 and to Nocera et al., 2012.

[5] The theoretical operation capacity in that hypothesis has been verified by Atos Progetti (2009).

3.2 The Historical Railway Line and the HC Line

The historical Brenner railway line (Figure 2) coincides to a broad degree with the route that was realized during the period of the Austro-Hungarian empire (the last half of the nineteenth century). Its total length is 347 km, of which 112 km are in Austrian territory (Kufstein-Brenner) and 235 km are in Italian territory (Brenner-Verona). The highest point of the route is the Brenner station (1,370 m above sea level). The maximum slope is reached between Innsbruck and the national border (26‰), but the Italian section is also characterized by steep sections; near Waidbruck/Ponte Gardena, the maximum slope reaches peaks of 23‰. In order to reach those points without excessive wastes of time, numerous viaducts, bridges, and tunnels have been introduced in recent years. On the whole, the traffic in the south to north direction ("even" trains) has a total unfavourable elevation change of 1,100 m over approximately 100 km, while with regard to the north to south direction ("odd" trains), the elevation change is approximately 700 m over 50 km. Although the slopes are comparable in absolute value, the approach to the crossing on the Italian side is much more demanding and of a longer duration than that on the Austrian side.

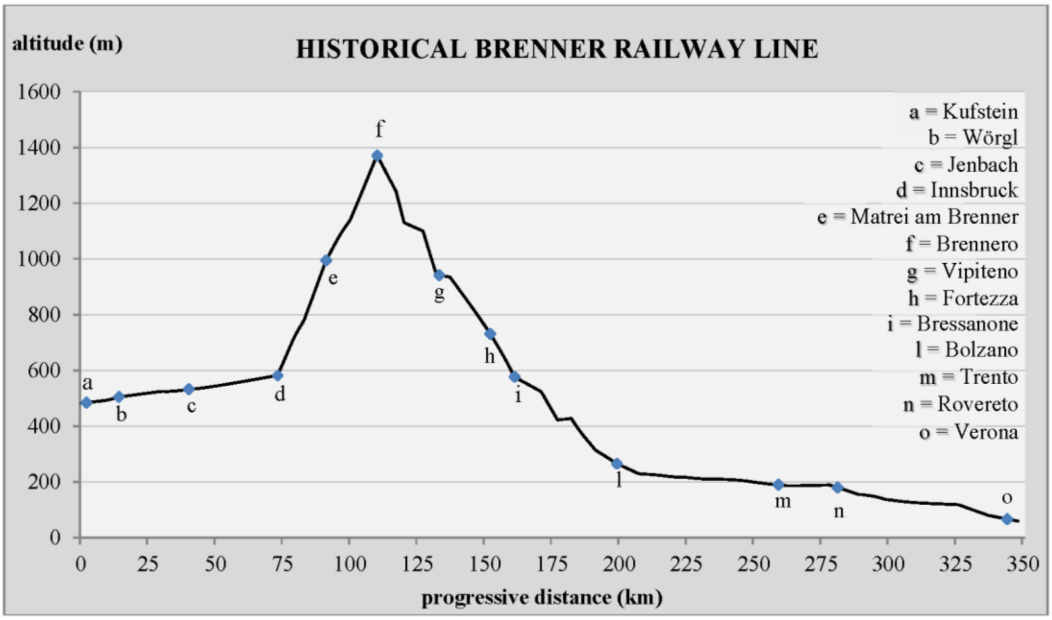

Figure 2: Historical Brenner railway line, profile of the Kufstein-Verona section

Certain technical characteristics of the existing railway route (high slopes, reduced radii of curvature, tunnels in rock that are difficult to enlarge) constitute some major limitations to the realization of a competitive line, and the recent modernizations do not eliminate the problem, especially in the Innsbruck-Brenner section, where the maximum velocity does not exceed 80 km/h and in some sections is even reduced to 40 km/h (ÖBB, 2009).

Beginning in the 1950s, the idea was already being disseminated to realize a base tunnel at Brenner in order to allow the realization of an HC line. Various studies and hypotheses followed one after another up to the actual project, which was proposed starting from the 1990s and is still in a phase of realization.

The Brenner HC line is traditionally subdivided into three sections (Figure 3):

- Northern access line: (Munich-Kufstein), Kufstein-Kundl, Kundl-Baumkirchen;
- Brenner Base Tunnel: Innsbruck-Franzensfeste/Fortezza and Innsbruck bypass;
- Southern access line: Franzensfeste/Fortezza-Waidbruck/Ponte Gardena, bypass of Bolzano and Trento, Verona.

The entire line is being realized in various phases. The work is in a phase of advanced realization for the northern access section, while it is still in a phase of project definition for the southern access. Finally, for the BBT, preliminary excavations were begun in 2008, while the primary work sites were inaugurated in April 2011 and will continue until 2025, the date at which the tunnel will become operational for all intents and purposes. Once it is in operation, the Brenner HC line will constitute the heart of the entire TEN-T no. 1 corridor, which will cover the approximately 2,200 km between Berlin and Palermo.

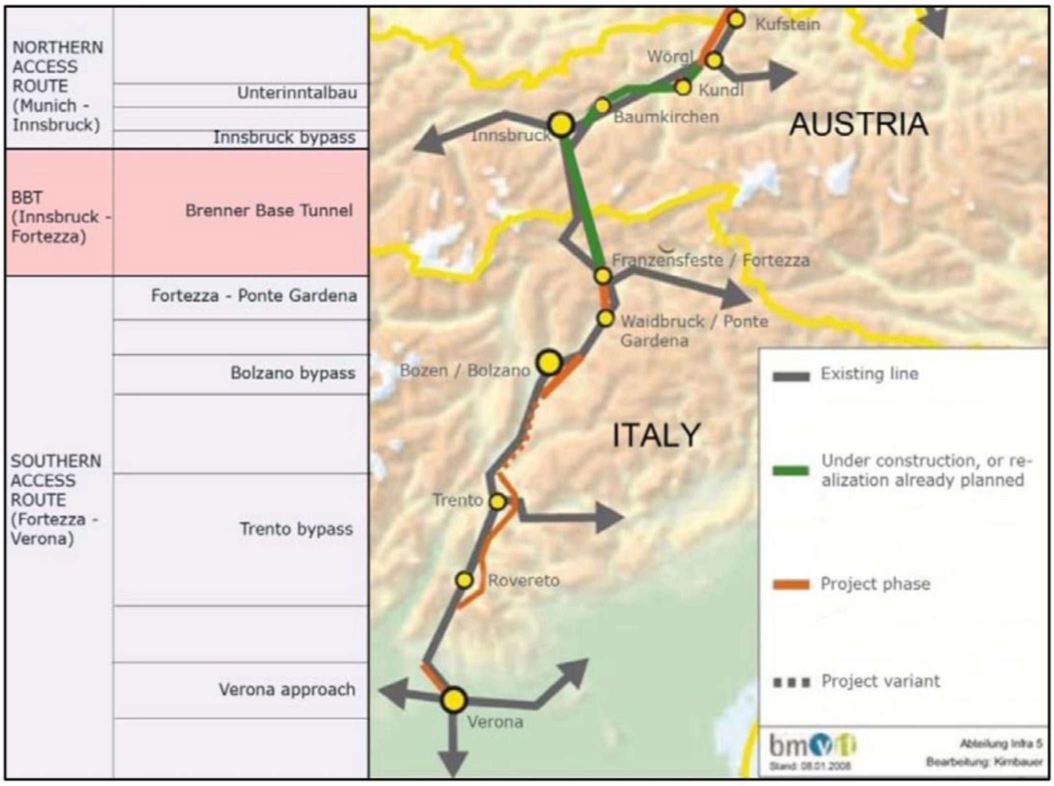

Figure 3: HC line Munich-Verona, Kufstein-Verona section. Source: BMVIT, 2008, modified

The infrastructure modelling takes place by means of existing data for the historical line and reconstructions on the basis of projects for the HC line (Italferr, 2003). This operation aims to determine all of the infrastructure characteristics that influence the resistance to motion. As was indicated in Section 2.1.1, the following parameters are considered: planimetric and altimetrical development, the presence of sections in tunnels, radii of curvature, slopes of the route, maximum travel velocity, and power supply systems. From the point of view of length, it is interesting to note that the two infrastructures differ by almost 35 km. The new HC line measures a total of 311 km, compared with the 345 km of the historical line, while with regard to the slopes, the maximum will be 6.7‰ from Kufstein to Brenner and 4‰ from Verona to Brenner.

What remains, finally, is to clarify the energy aspect: in the historical line, the power supply of the electrical propulsion is structured on the two national systems: the 3 kV DC in Italy and the 15kV 16 2/3 Hz AC in Austria, which provide energy by means of 22 ESS. The new HC line, on the other hand, will be electrified with two different propulsion systems: the 25 kV DC (in the 2x25 version) between Verona and Innsbruck, and the 15kV 16 2/3 Hz AC from Innsbruck to Kufstein. The energy will be completely provided by 13 ESS.

After the phase of infrastructure modelling, the selection of the train follows. The choice was made for a means of transport with a total weight equal to 1,200 gross metric tons (and thus including the locomotives, train cars, and freight), since trains of that weight can travel without distinction on both the historical line and the HC line. The travel takes place under different conditions. Among these is the number of locomotives necessary to transport the entire weight: the historical line requires double propulsion, while for the HC line, single propulsion is sufficient. Quantifying the unitary weight of a locomotive as 90 t, it follows that the HC line will allow for the freight transport in gross terms of 1,110 t, while the historical line is limited to 1,020 t. The determination of the net weight transported by the typical train is derived from the operation program worked out by BBT (BBT SE, 2008), in which the net/gross ratio is estimated at around 65%. An additional coefficient of reduction is also applied to this value, which, in a precautionary way, takes into consideration trains that travel without a full load, in this way providing a value close to 60%. That yields a net weight transported equal to 597 t and 664 t for the historical line and the HC line, respectively. Finally, the maximum theoretical travel speeds are assumed in both cases equal to 100 km/h, in accordance with international regulations for railway travel. A summary of the technical characteristics of the typical trains is provided in Table 2.

Table 2: Technical characteristics of the typical trains

TECHNICAL CHARACTERISTICS OF TYPICAL TRAINS						
Railway line	Type of train	Locomotives	Max speed	Total weight	Freight (gross)	Freight (net)
		n.	km/h	t	t	t_{net}
Historical line	LS train	2	100	1,200	1,020	597
HC line	HC train	1	100	1,200	1,110	664

Taking into consideration the typical trains and the modelling of the line, it is possible to launch the travel simulation over terrain and to determine the energy at the pantograph that is required in order to travel over the entire route. The graphs indicated in Figures 4 and 5 show the power required at the pantograph at every moment for the historical line and for the HC line in the sections of Verona-Kufstein (even track). The major difference that exists between the two infrastructure lines has been highlighted. The continuous variations in absorption are primarily due to the large slopes, to which is added the presence of numerous curves, including those with a tight radius, and the variations in velocity along different sections of the line. The most technically interesting aspect has to do with the peaks of absorbed power on the historical line (approximately 100% more than the new line) which, although they are supported by the system, are an indicator of potential inefficiencies. The slightest disturbance in travel can bring about the simultaneous presence of peaks along the line. For the historical line, and in particular for the Italian side electrified at 3 kV DC, that can cause untimely tripping of breakers at the ESS which increases the level of overall disturbance.

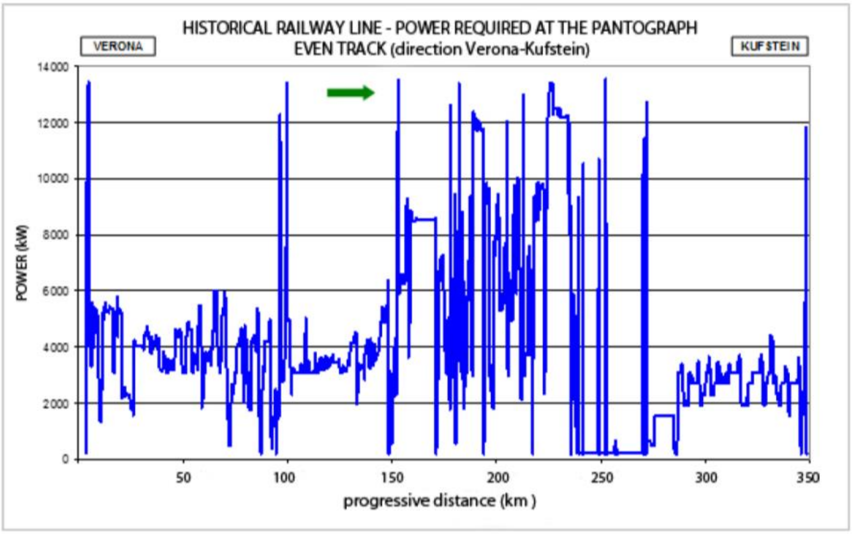

Figure 4: Power required by a typical train for the historical line. Source: Atos progetti, 2009

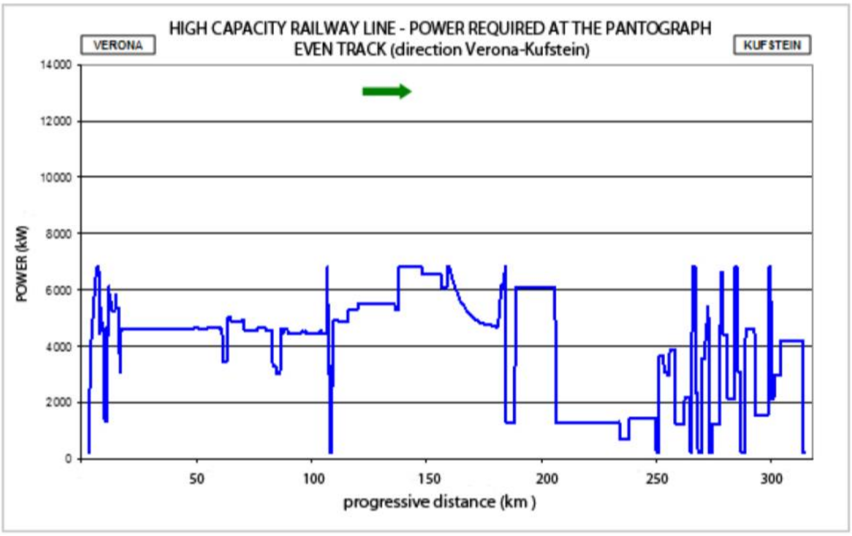

Figure 5: Power required by a typical train for the HC lines. Source: Atos progetti, 2009

The energy required at the pantograph is the value, expressed in kWh, which makes it possible to satisfy the power that was previously described. In the case of the historical line, that is equal to 15,190 kWh and 11,728 kWh, depending upon the direction of travel (in the south-north or north-south direction, respectively). Those values decrease to 13,251 kWh and 10,979 kWh in the case of the HC line (Table 3), with a reduction equal to 13.0% and 7.5%. As was previously mentioned, the consumption in the even direction is greater because the slopes to be overcome in ascent are higher.

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Table 3: Energy consumption of typical trains

ENERGY CONSUMPTION OF TYPICAL TRAINS						
	HISTORICAL LINE			HC LINE		
Direction	*Consumption*	*Freight*	*Distance*	*Consumption*	*Freight*	*Distance*
	kWh	t_{net}	km	kWh	t_{net}	km
Even (S-N)	15,190	597	345	13,251	664	311
Odd (N-S)	11,728	597	345	10,979	664	311

The values expressed in this way describe the consumption of energy by typical trains. That data then has to be intersected with that which relates to future demand, thus going back to the values expressed in Table 1. Once the quantity of annual freight in the various scenarios has been predicted and the tonnage of freight that can be transported by a single typical train has been recalled (Table 2), the number of trains can be established immediately that are necessary in order to satisfy the transport demand. The split along the even or odd line is carried out in accordance with the phase of operation that was hypothesized by BBT SE (2008), which envisions 56% of the freight traveling in the north-south direction and 44% in the south-north direction. The results are provided in Table 4, rows 1-3.

These values can then be intersected with those relating to the unitary energy at the pantograph that were previously calculated and provided in Table 3. In this way, the total energy at the pantograph that is necessary to make all of the freight trains travel along the line can be determined.

This value, expressed by Table 4, row 6, still does not represent the real energy requirements, because the efficiency of the system also has to be included, that is, the energy that is lost in the passage between the electrical substation and the recording at the pantograph.

In order to calculate that value, the behaviour of the typical train was studied by having it travel in sequence at intervals of 7 minutes and 30 seconds and inserting one InterCity Express (ICE) train every hour. The simulation was then brought up to speed, extending the operation to a time frame of approximately 8 hours. For the historical line, the efficiency was equal to 92%. For the HC line, that percentage grows to 98.5%. In this way, it is possible to determine the energy that is actually required to make the trains that are envisioned travel along the line. For the "minimum" scenario, that value is equal to approximately 472.05 GWh. For the "trend" scenarios 1 and 2, it equals 608.06 and 643.08 GWh, while for the "consensus" 1 and 2, it increases to 662.82 and 702.45 GWh, respectively (Table 4, row 7).

Finally, to calculate the CO_2 emissions, the electrical consumptions are multiplied by a suitable conversion factor which is the weighted average of the energy mixes of Austria and Italy and which is related to the length of the route that is developed in the respective countries. The majority of the electrical energy in Italy is produced using fossil fuel sources, causing a CO_2 production equal to 0.435 kg per kWh of electrical energy consumed (Terna, 2009). In Austria, on the other hand, the hydroelectric component is greater and consequently the production of energy in 2008 led to a lower unitary emission of CO_2, equal to 0.216 kg/kWh (Terna, 2009). The final value, which takes into account the distances travelled by the train in each country, is 0.36492 kg of CO_2/kWh for the historical line and 0.35835 kg of CO_2/kWh for the HC line. Since it is extremely complicated to predict the evolution of those mixes over the course of years, the decision was made to act conservatively and use the current values for the entire period 2010-2030.

This establishes annual emissions of CO_2 equal to 172.26 kilotons (kt) in "minimum", 217.90 kt and 231.39 kt in "tendency 1" and "tendency 2", respectively, and 237.52 kt and 262.75 kt in "consensus 1" and "consensus 2", respectively (Table 4, row 8).

Table 4: Brenner line, energetic consumption and CO_2 emissions from railway freight, year 2030

RAILWAY SIMULATION METHOD – SUMMARY TABLE

SCENARIO			MINIMUM	TREND1	TREND2		CONSENSUS1	CONSENSUS2	
		U.M.	Historical line	HC line	Historical line	HC line	HC line	Historical line	HC line
1	*Total number of trains*	n.	32,750	50,000	10,050	40,975	54,500	11,000	44,750
2	*Even trains*	n.	14,500	22,000	4,425	18,025	24,000	4,750	19,750
3	*Odd trains*	n.	18,250	28,000	5,625	22,950	30,500	6,250	25,000
4	*Energy consumption: even trains*	MWh	220,255	291,500	67,216	238,831	318,024	72,152	261,707
5	*Energy consumption: odd trains*	MWh	214,036	307,440	65,981	251,991	334,859	73,300	274,475
6	*Total energy consumption at pantograph*	MWh	434,291	598,940	133,197	490,822	652,883	145,452	536,182
7	*Total energy consumption*	MWh	472,055	608,061	144,779	498,297	662,826	158,101	544,347
8	CO_2	kt	172.26	217.90	52.83	178.56	237.52	57.69	195.06

In order to be able to compare the new system with the HC line and the existing situation, the rail emissions are analysed together with the values relating to the road emissions, the topic which is the subject of the next section.

3.3 The Highway

In the section between Kufstein and Verona, the Brenner Highway extends for 343 km. The Austrian part, which connects Kufstein (497 m above sea level) with the Brenner Pass (1,366 m above sea level) is 109 km long and comprises the highways A12 and A13. The Italian part (highway A22) connects the Brenner Pass and Verona (58 m above sea level) by means of a divided highway with two lanes in each direction which is 234 km long. The planimetric and altimetrical profile of the infrastructure is represented in Figure 6.

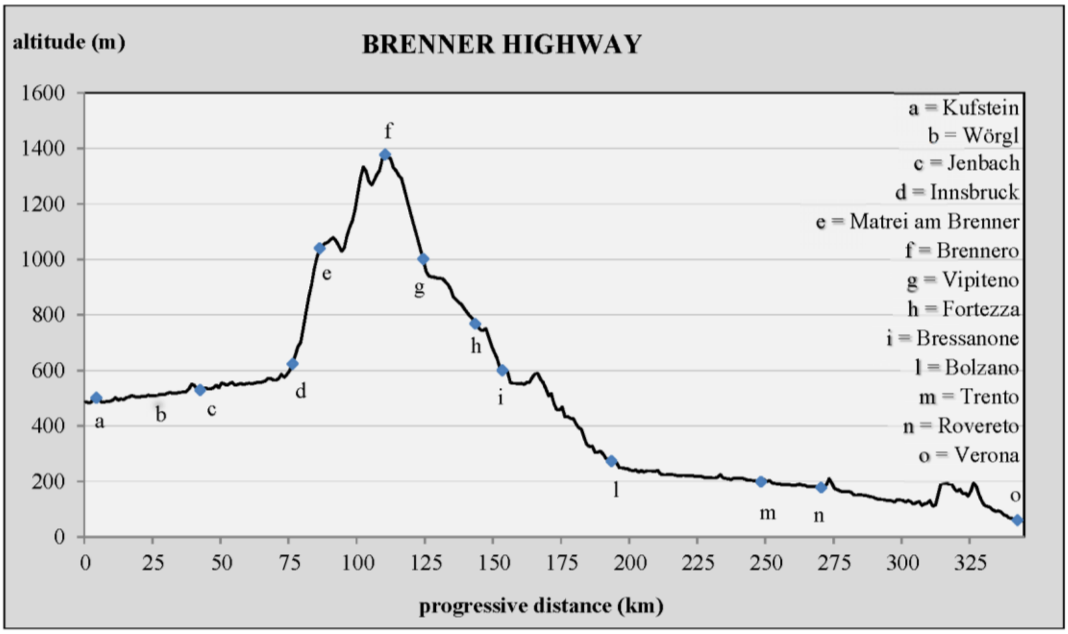

Figure 6: Profile of the Brenner highway

In order to calculate the CO_2 emissions due to vehicular traffic, it is first of all necessary to quantify the specifics of a typical vehicle for the entire route. In the case of highway freight traffic, in which the trips are generally of medium to long range and a constant velocity is maintained, it is advisable to adopt a method that is based upon the direct measurement of the values (thus belonging to the methodology for calculating transport emissions and energy consumption models, as was described in Section 2.1.2), disregarding the aspects relating to the stop and the restart that are typical of short or urban routes. For this purpose, one of the softwares that performs the best is the Infras emissions handbook (Infras, 2010), which was also already used in other studies on the future emissions of a section of Swiss highway (Hueglin et al., 2006) and of the Gubrist Tunnel (Colberg et al., 2005). In reference to the type of emissions, only the hot emissions are considered: since the highway travel of a freight vehicle usually does not constitute either the origin or the destination of a trip, the presence is excluded of both cold emissions and evaporative emissions that are typical of the departure and of the phase following the engine being shut off, respectively.

Just as with the railway network, in order to calculate CO_2 emissions in 2030 caused by road vehicles, reference is made to one typical vehicle, which in this case is a semitrailer with a total weight equal to 32 t, a theoretical load capacity equal to 23 t_{net}, and powered by diesel with a Euro 6 engine (Iveco, 2008). The maximum velocity is equal to 80 km/h. A fill factor is hypothesized equal to 0.6, which also takes into consideration empty trips and trips with partial loads. That establishes a real load equal to 13.8 t_{net} (Table 5).

Table 5: Characteristics of the typical vehicle for road transport

TECHNICAL CHARACTERISTICS OF THE ROAD TYPICAL VEHICLE						
	Gross vehicle weight	*Load capacity*	*Quantity of freight*	*Maximum speed*	*Fuel supply*	*Class*
	t	t_{net}	t_{net}	km/h		
Typical vehicle	32	23	13.8	80	Diesel	Euro 6

In addition to the parameters relating to the typical vehicle that were previously indicated, a fundamental role is played by the slope of the route. Seven different classes of slope have been introduced that range from -6% to +6%. The respective unitary specific emissions vary from 0 g/km to 3,457.57 g/km (Infras, 2010; Table 6).

Table 6: Specific CO_2 emissions of a typical vehicle according to slope. Source: Infras, 2010

SPECIFIC CO_2 EMISSIONS OF A ROAD TYPICAL VEHICLE								
	U.M.							
Classes of slope	[%]	6	4	2	0	-2	-4	-6
CO_2 emissions	g/km	3,457.57	2,504.52	1,591.48	627.67	41.10	1.26	0.00

The route of the entire highway is subdivided into the seven classes that were previously described, surveying the elevation corresponding to every kilometre of the route using satellite instrumentation. The difference in elevation between a given point and the next one determines the slope class of the given kilometre. It is therefore sufficient to assign to every kilometre the relative specific emissions in order to determine the CO_2 emissions of a typical vehicle from Kufstein to Verona and vice versa, equal to 235.25 kg and 275.10 kg of CO_2, respectively. As in the case of the railway, the values are higher in the case of south-north travel because the approach to the pass from the Italian side is more demanding.

Having taken note of the CO_2 emissions that are produced by a typical vehicle in order to travel the entire route, and by analysing the future demand of the road traffic, the annual emissions can be obtained. In reference to the ProgTrans (2007) scenarios that were previously described, the quantity of freight forecast for the year 2030 is equal to 47.2 mil. t_{net} for the "minimum" scenario, 47.8 for "trend", and 30.9 for "consensus" (Table 1), which determines the number of typical vehicles in the various scenarios expressed in Table 7, row 1. Reintroducing then the same coefficient of the subdivision of traffic that was adopted for the railway (56% in the north-south direction and 44% in the south-north direction), the annual vehicles traveling from Kufstein to Verona and vice versa are obtained (Table 7, rows 2 and 3). These last values, when multiplied by the unitary emissions, determine the values of the CO_2 emissions derived from road traffic. These are equal to approximately 865 kt in the "minimum" scenario, 876 kt in "trend", and 566 kt in "consensus" (Table 7, row 6).

Table 7: CO_2 emissions from freight railway transport along the Brenner line, 2030

ROAD SIMULATION METHOD – SUMMARIZING TABLE							
		U.M.	MINIMUM	TREND1	TREND2	CONSENSUS1	CONSENSUS2
1	*Total vehicles*	n	3,420,290	3,463,768	3,463,768	2,239,130	2,239,130
2	*Vehicles N – S*	n	1,915,362	1,939,710	1,939,710	1,253,913	1,253,913
3	*Vehicles S – N*	n	1,504,928	1,524,058	1,524,058	985,217	985,217
4	*CO_2 total emissions N-S*	kt/y	450.61	456.34	456.34	295.00	295.00
5	*CO_2 total emissions S-N*	kt/y	414.00	419.26	419.26	271.03	271.03
6	*CO_2 total emissions*	kt/y	864.61	875.60	875.60	566.03	566.03

3.4 Results and discussion

The sum of the road and rail CO_2 emissions described in Sections 3.2 and 3.3 provides the impact in 2030 of the freight traffic along the Brenner Corridor. In the “minimum” scenario, the CO_2 emissions are equal to approximately 1,037 kt, of which 865 are generated by road vehicles and 172 by freight trains along the historical line. The emissions increase to 1,094 kt in the case of “trend 1” and 1,107 kt in “trend 2”, while they decrease slightly both in the case of “consensus 1” and in the case of “consensus 2” (Table 8, Figure 7).

Table 8: Total CO_2 emissions in “minimum”, “trend 1”, ”trend 2”, “consensus 1” and “consensus 2” scenarios, 2030

TOTAL CO_2 EMISSIONS ALONG THE BRENNER CORRIDOR – YEAR 2030			
SCENARIO	*INFRASTRUCTURES*	*AMOUNT OF FREIGHT* Mil. t_{net}/year	*CO_2 EMISSIONS* kt/year
Minimum	Highway	47.2	865
	Train (historical line)	19.5	172
	Total	66.7	1,037
Trend 1	Highway	47.8	876
	Train (HC line)	33.2	218
	Total	81.0	1,094
Trend 2	Highway	47.8	876
	Train (historical line)	6.0	53
	Train (HC line)	27.2	179
	Total	81.0	1,107
Consensus 1	Highway	30.9	566
	Train (HC line)	36.2	238
	Total	67.1	804
Consensus 2	Highway	30.9	566
	Train (historical line)	6.6	195
	Train (HC line)	29.7	58
	Total	67.1	819

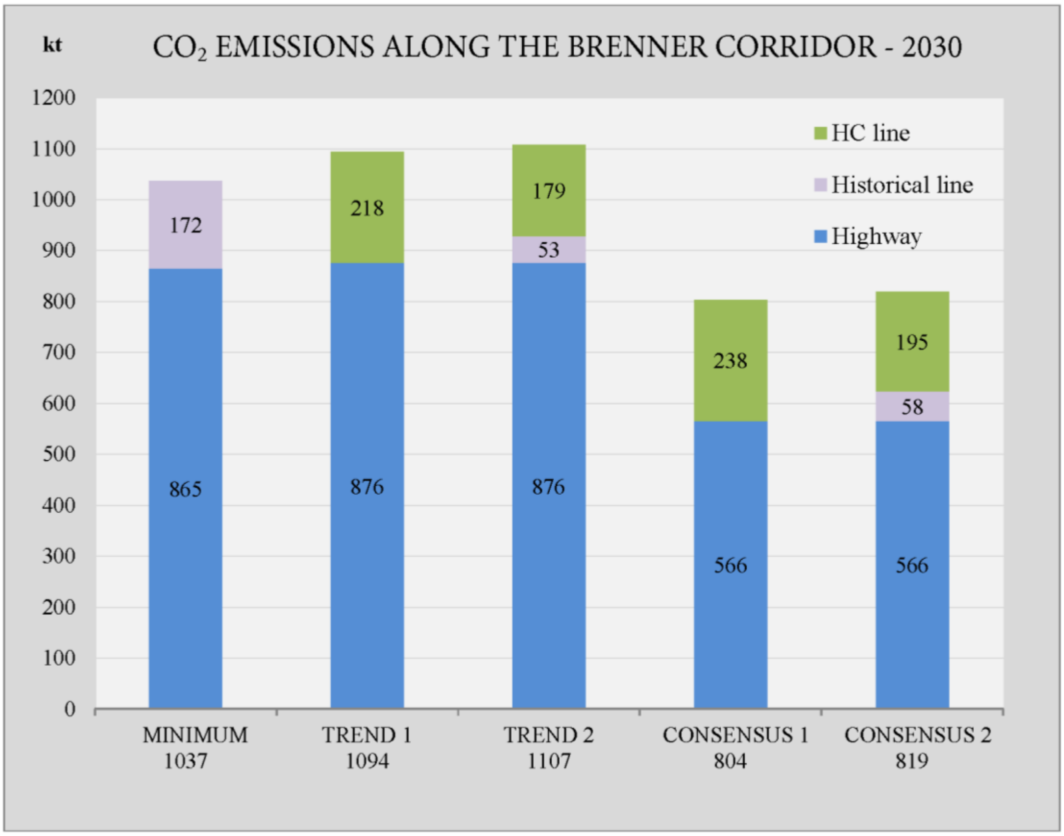

Figure 7: CO_2 emissions along the Brenner corridor, 2030

If compared to the absence of the realization of the HC railway line ("minimum"), then the savings of CO_2 that are allowed by "consensus 2" are equal to approximately 218 kt. That value is equivalent to approximately 79% of the current annual emissions due to the mobility of the inhabitants of the city of Bolzano, which in 2007 was equal to 272 kt (Sparber et al., 2010). If all of the freight traffic forecast on rail in 2030 is routed to the new line ("consensus 1"), the savings in CO_2 grows even further, leading to approximately 233 kt (85% of the annual CO_2 emissions due to the mobility of the city of Bolzano in 2007). If, on the other hand, measures of support for railway traffic are not introduced, then the transport demand grows without regulation, generating an additional increase in emissions in comparison with the minimum scenario: 57 kt and 80 kt in the case of trend 1 and trend 2, respectively.

In reference to the specific emissions, it is possible to estimate the savings in CO_2 that can be attained in transport for one ton of freight by means of the HC line with respect to the historical railway line or to the road. The average emissions associated with the transport of one net ton of freight are equal to 18.3 kg in the case of road transport, 8.8 kg in the case of the historical line, and 6.6 kg in the case of the HC line. This means that with respect to the road, the routing of one ton of freight on the historical railway line permits a savings in emissions equal to 48.2%, a value that rises to 62.5% in the case of the HC line (Table 9).

Table 9: CO_2 emissions per ton of freight along the HC, historical railway line and road, 2030

BRENNER CORRIDOR - CO_2 EMISSIONS PER TON OF FREIGHT (2030)

Mode	*Infrastructure*	*CO_2 specific emissions*	*Variation*
		kg CO_2 / t_{net}	%
Road	Highway	18.3	----
Rail	Historical line	8.8	-48.2%
	HC line	6.6	-62.5%

Finally, the values indicated in Table 9 are useful for establishing the theoretical volume of freight to be transferred from road to rail in order to compensate for the emissions produced during the construction phase of the BBT, equal to 2,280.35 kt of CO_2 (Nocera et al., 2012).

From the comparison between the CO_2 emissions per ton of freight transported on the HC line and that on the road, a savings results equal to 11.7 kg of CO_2; what follows from this is that the compensation is achieved for the transfer of 195 mil. t. This quantity corresponds to approximately four and a half times the volume of freight that was moved by means of the approach to Brenner in 2010 (41.9 mil. t_{net} of freight including both road and rail modes; 2011). If in addition to the BBT, the emissions produced for the southern access from Brenner to Bolzano are taken into consideration, equal to 886.59 kt of CO_2 (Ruffini et al., 2010), then the volume of freight to be transferred from the road to the HC line in order to obtain a positive balance in the CO_2 emissions grows to approximately 271 mil. t, seven times the total freight traffic which crossed the Brenner Pass in both directions in 2010.

4. Conclusions

Quantifying the future emissions of carbon dioxide that are generated by one or more infrastructures is a fundamental task for evaluating the sustainability of transport modes. Nevertheless, scientific uncertainty (Clarkson and Deyes, 2002) makes the evaluation difficult. The greater difficulties lie both in hypothesizing the future technological evolution (the knowledge of how a modernization of the fleet of vehicles can influence the specific emissions, the knowledge of the technologies adopted in order to realize new vehicles, and the evolution of the national energy mix) and in determining the future transport demand. These uncertainties are endemic and therefore cannot be eliminated; they can only be minimized.

To that end, a new methodology has been developed in this article based upon simulations of vehicle performance and scenarios of future demand growth. With respect to studies provided by the literature, the proposed methodology considers a broader set of parameters, which also takes into consideration the variation in the transport demand and its modal split as a consequence of the adoption of different policies. Taking into consideration one single vehicle traveling along the line, the aspect relating to the vehicle fleet was disregarded because it was not essential to the goals of this study. Nonetheless, the topic of the modelling of operation, in particular in the railway case (Malavasi and Ricci, 2005), could be integrated in a future study for the purpose of also making the results of this present analysis, in addition to being significant from the viewpoint of CO_2 emissions, compatible with a real model of operation and with respect to the problems of traffic management (Corman et al., 2011).

Nevertheless, this paper proposes a model to evaluate the CO_2 emissions produced by the freight transport along the Brenner Corridor with a sufficient degree of detail, comparing the hypothesis of the realization of an HC line (the scenarios of "trend" and "consensus") with the lack of its realization (the "minimum" scenario). The results show that if it is not supported by adequate policies, the realization of the HC line can lead, just for the year 2030, to an increase in absolute emissions (of 80 kt). Conversely, if it is accompanied by adequate measures, it can assist in a reduction greater than 230 kt. Furthermore, it has been possible to evaluate the difference in terms of emissions with the variation of the traffic split between the various infrastructures and to calculate how much freight has to be moved along the new HC line in order to compensate for the emissions derived from the realization of the work itself (approximately 270 mil. t).

The evaluations expressed relate only to the freight transport, which is recognized as the main critical component of the transalpine traffic, and consider the Brenner corridor as territorial scale. However, the method is generalizable to all the corridors that includes rail and road infrastructures, provided that their technical characteristics are known and a reliable forecast of future transport demand is available. Furthermore, with a specific evaluation of the parameters to be considered, the method can also be extended to passenger traffic, even if in this case the analysis requires more detailed information about the real model of operation.

Finally, the method presented here can be the basis for future development, related to three main issues: the transport modes, the substances considered and the economic evaluation of the emissions. Regarding the first point, in this paper only the terrestrial transport has been considered, but with the adequate modifications, the analysis can be extended to other transport modes. Secondly, further studies can be carried out, which deepen not only CO_2, but also other GHGs. Thirdly, the method can be adopted to estimate the monetary value of CO_2 emissions (Nocera and Cavallaro, 2012 and 2013); this last point makes it possible to forecast the economic impact of a new infrastructure and the related political choices (Cappelli et al., 2013), as far as the global environmental aspects are concerned.

With the method proposed here, it has been possible in this way to evaluate the efficacy of the construction of a new infrastructure from the viewpoint of environmental sustainability, integrating the traditional techniques of evaluation based primarily on cost-benefit analyses. Moreover, the basis is presented for a more general reflection centred upon policies and on the choices to be adopted for the purpose of seeing realized that which the report on transport, as early as the beginning of the century (EC, 2001), considered an inescapable element for obtaining sustainable growth: the rebalancing of transport modes to reduce the emissions of polluting substances.

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6. Appendix 1

Description of the three scenarios developed by ProgTrans (2007). Source: Nocera and Cavallaro, 2011

MEASURES ADOPTED IN "MINIMUM", "TREND" AND "CONSENSUS" SCENARIOS			
	MINIMUM	TREND	CONSENSUS
MEASURES TO DISCOURAGE THE USE OF ROAD TRANSPORT			
Road costs per km	Current costs	Current costs	+30% in comparison with other scenarios
Road tolls (passengers)	No tolls related to the covered distance; no urban tolls	No tolls related to the covered distance; no urban tolls	No tolls related to the covered distance. Introduction of urban tolls. General costs +15% in comparison with other scenarios
Road costs (freight)	Highway tolls lower than infrastructure costs up to 2015	Highway tolls at the same level as infrastructure costs up to 2015	Highway tolls higher than infrastructure costs (+15% in comparison with "Trend"); harmonisation of tolls over the entire Alpine region
Road traffic ban	No ban along Brenner highway, maintenance of Sunday and night time bans, use of traffic density control systems	No ban along Brenner highway, maintenance of Sunday and night time bans, use of traffic density control systems	Implementation of social and safety regulations, no ban along Brenner highway, maintenance of Sunday and night time bans, use of traffic density control systems
Speed-limits	No changes	No changes	More controls, reduction of 8%
Tax on petroleum	Uniform tax rate in all EU countries based on current value	Uniform tax rate in all EU countries based on current value	Uniform tax rate in all EU countries higher than current value; introduction of an eco-tax
Road construction	Completion of highways (but not along Alps)	Completion of highways (but not along Alps)	Investments only for national programmes or for TEN-T to reduce bottlenecks
MEASURES TO ENCOURAGE THE USE OF RAIL TRANSPORT			
Intermodality	Improvement, reduction of technical and administrative barriers	Considerable improvement, reduction of technical and administrative barriers	Considerable improvement, reduction of technical and administrative barriers, optimisation of railway services
Rolling highway	At 2004 level	At 2004 level	At 2003 level
Railway charges	Slight reduction (-5% for freight)	Slight reduction (-5% for freight)	Considerable reduction
Subsidies	Reduction for non-profitable transport modes	Reduction for non-profitable transport modes	Slight reduction, but not related to non-profitable transport modes. Railway transport receives higher funds
Railway traffic market rules	Slight liberalisation and broad privatisation of freight and passenger transport	Liberalisation and broad privatisation of freight and passenger transport	Liberalisation and broad privatisation of freight and passenger transport
Railway lines construction	Completion of Gotthard, Moncenisio and Lötschberg base tunnels	Completion of Brenner, Gotthard, Moncenisio and Lötschberg tunnels. TEN-T corridors fully realised by 2025	Completion of Brenner, Gotthard, Moncenisio and Lötschberg tunnels. TEN-T corridors fully realised by 2025
Telematics	Introduction of ERTMS systems for HC lines by 2025	Introduction of ERTMS systems for HC lines by 2025	Introduction of ERTMS systems for all HC lines by 2015
Average rail speed	Slight changes in comparison with current speeds	In comparison with current speeds: +3% up to 2015, additional + 2% up to 2025	In comparison with "Trend": +3% up to 2015, additional + 2% up to 2025

3.2. Economic valuation: CO_2 and GHG meta-analysis

Section 2.2 has discussed the importance of a fair economic valuation of CO_2 emissions and the related methodological difficulties. The articles presented in this section aim at reducing the scientific and economic uncertainties, by adopting alternative approaches.

The article "*A methodological framework for the economic evaluation of CO_2 emissions from transport*" (Nocera and Cavallaro, 2014a) contains a preliminary analysis of the methods available in the literature and their characteristics. The literature review reveals that avoidance costs are more reliable for short and medium term analyses and for practical purposes, because policy goals in terms of CO_2 abatement are stated up to the same date at the international level, thus reducing the uncertainty about future emission levels. On the other hand, damage costs are preferred when it comes to long-term analyses and when a more robust scientific comparison with other environmental externalities has to be made. In continuity with the two case studies presented in 3.1, this double temporal horizon is adopted to assess the economic impacts of CO_2 emissions that derive from the realization of the Brenner corridor.

A vast uncertainty affects the adoption of the damage costs, which can determine a range of values up to six orders of magnitude (Nocera and Tonin, 2014). Many factors concur to determine such condition. A comprehensive meta-analysis could allow a correct understanding of the significant variables and provide values that are more reliable. A meta-analysis can be defined as "a systematic method that uses statistical techniques for combining results from different studies to obtain a quantitative estimate of the overall effect of a particular intervention or variable on a defined outcome; it produces a stronger conclusion than can be provided by any individual study" (Segen, 2002). Fischer and Morgenstern (2003) and Kuik et al. (2008) provided useful preliminary information about meta-analyses of carbon estimations, emphasizing the need to explain the cost differences according to the choice of the selected variables. Tol (2008) tried to address this issue, by analysing several values derived from studies pertaining to the cost of carbon emissions. However, Tol's work only assesses studies carried out with PAGE, FUND and DICE, while the list of the IAMs includes several other models, thus making the statistical analysis non-exhaustive (Ackerman, 2009). Even in the latest version of the database (Tol, 2013), where the sample was broadened, the same issue remained.

In the article "*The Economic Impact of Greenhouse Gas Abatement through a Meta-Analysis: Valuation, Consequences and Implications in terms of Transport Policy*" (Nocera et al., 2015a) a comprehensive meta-analysis of GHG estimations has been provided, based on a wide number of observations (699) deriving from the literature. For each of them, the study provides information about the following main components:

- General information: the name and year of the study, its nature and the economic value in 2010.
- Scenario considered: type of model adopted, reference scenario, characteristics in terms of temperature increase, concentration, temporal horizon and geographic scale.
- Economic impacts: GDP variation, discount rate, equity weights, damage function and other economic parameters that influence the final price.
- Physical impacts considered, among the macro-groups proposed by Watkiss et al. (2005) and reported in Table 1.
- Specifications: other relevant aspects.

The meta-analytic regression model adopted in the model has the generic expression presented in formula 7):

$$\ln(\cos t2010) = a + b_i X_i + u_i \tag{7}$$

Where: the dependent variable is the natural log of cost emission; *i* is the number of observations, *a* is the constant term, *b* is the coefficient of the vector of explanatory variables *X* and *u* is a vector of residuals.

This generic formula is further specified according to the variables considered in our model, thus obtaining the formula (8):

$$\begin{gathered}\ln(\cos t2010) = 9.60 + 1.09 \cdot fiam + 0.69 \cdot cge + 0.40 \cdot ew - 0.006 \cdot ypub - 0.47 \cdot peer\_rev - 0.60 \cdot prtp + \\ - 0.26 \cdot comb + 0.03 \cdot geogsc + 0.13 \cdot temp + 0.001 \cdot ppmv + 0.22 \cdot adaptation\end{gathered} \tag{8}$$

Where: *fiam, cge*, *ew, adaptation,* are dummy variables denoting if the study uses, respectively a fully IAM, a Computable General Equilibrium[3], equity weighting and adaptation. *Peer_rev* and *geogsc* are dummy variables for peer reviewed studies and studies assessing global impacts (1 = yes); *ypub* is the year of the publication of the study; *prtp* is the Pure Rate of Time Preference; *comb* indicates the number of macro groups considered in the damage function; *temp* and *ppmv* are the future temperature and concentration of GHGs.

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[3] See section 2.2.

This model is used in the article to evaluate the GHG potentialities of several European transport policies up to the year 2050, by providing for each of them a specific economic value.

An alternative approach to determine the price of CO_2 emissions is based on the Multiple Agent Multi Criteria Decision Making (MAMCDM). The article "*On the Perspective of using Multiple Agent Multi Criteria Decision Making for determining a fair Value of Carbon Emissions in Transport Planning*" (Nocera et al., 2014) describes this approach. MAMCDM is the combination of an evaluation method, the Multi Criteria Analysis, and the Multi Agent System, which models the interactions of agents (or groups of agents) in a given environment. Differently from the approaches previously described, this estimation process does not rely only on an ex-post mediation of different technical approaches. Indeed, the process results from a deeper analysis, which aims at understanding the different frames and redefining them through a shared approach. The carbon MAMCDM process is presented, with a first explicative example that illustrates the potentials of this model in determining a fair price for CO_2 emissions. The method is conceptually very different in comparison with the technical valuation previously illustrated. It is founded on a procedure, which implies the dynamic human interactions and decisions taken before the production of a final value. Conceptually, this approach is strictly related to the frame reflection theory elaborated by Schön and Rein (1994): rather than proposing a univocal solution, the final value is the synthesis of different points of view, which takes into account the actors' values and mental conception of the world. This is an alternative vision in line with social sciences, rather than the so-called "hard sciences".

3.2.1. A Methodological Framework for the Economic Evaluation of CO_2 Emissions from Transportation

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A methodological framework for the economic evaluation of CO_2 emissions from transport

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SUMMARY

As the main cause of the global warming, CO_2 emissions are a relevant externality in the transport sector. However, feasibility assessments do not always take these effects into adequate account, because a number of scientific and economic uncertainties make it difficult to determine a reliable estimate for a unitary CO_2 cost.

This paper first analyses the methods generally used to determine the cost of CO_2 emissions, showing that market-based prices are not always suitable for this aim. Avoidance and damage cost methods are then thoroughly discussed, evaluating their pros and cons, including an extensive review of previous studies of methods for comparing costs. To determine the most reliable values, a method based on both avoidance and damage costs is proposed here.

This method is then applied to the case study of the Brenner Base Tunnel, comparing the outcomes of three different scenarios: 'minimum' suggests the maintenance of the 'do-nothing' option (no tunnel realisation), whereas 'trend' and 'consensus' both imply the construction of the tunnel with different political choices, namely, a complete market liberalisation in trend and sustainable interventions in consensus. Results up to 2035 reveal that, in comparison with the do-nothing option, the enlightened transport policy shown in consensus could bring about a CO_2 economic saving of up to around €331m for the community, whereas a simple liberalisation (trend) increases the costs derived from global warming by about €228m. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: CO_2 economic evaluation; damage cost; avoidance cost; transport; Brenner base tunnel

1. INTRODUCTION

Carbon dioxide (CO_2) represents the major component of unsustainability with respect to global warming, and, among all greenhouse gases (GHGs), it can be considered the main parameter to be taken into account in economic evaluations. This assumption is mainly sustained by three aspects: firstly, CO_2 accounts for almost 90% of global GHG emissions [1] and for about 96% of the emissions in the transport sector [2]. Secondly, traditional mitigation measures have an effective impact on CO_2 levels, but not on other polluting GHGs [3]. Thirdly, the economic value of other GHGs suffers from a time horizon problem: some gases (e.g. CH_4) have a very short lifetime in the atmosphere compared with CO_2, resulting in a rather high economic value in the short term but considerably lower over the long term. Such differing values would be difficult to aggregate. Therefore, specific analyses based on the single pollutant seem still the most efficient solution for estimating GHGs economically. In this framework, CO_2 emissions obviously play the main role [4,5].

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CO_2 is detrimental neither to the environment nor to health if it does not exceed a threshold of 350 ppmv (parts per million by volume) [6]. However, its concentration has grown by over 25% in the last 150 years, passing from 288 ppmv in 1850 to 390 ppmv in 2010 [7]. At this concentration, CO_2 now constitutes one of the main causes of global warming. Transport is considered to be significantly responsible for this increase, because in the last 20 years transport emissions have grown about 30% (Figure 1), thus making this the only sector not to provide a reduction in comparison with 1990 [8,9].

Global warming and CO_2 emissions have generated much research and political interest, especially from 1988 on, when the Intergovernmental Panel on Climate Change (IPCC) was established to assess the scientific, technical and socio-economic information related to climate change. Following the introduction of the Kyoto Protocol [10] and the further development of acts and measures to reduce the emissions of polluting gases in most countries, transport planners are now required to evaluate the feasibility of any new infrastructure, not only in strict economic terms but also in view of the overall impact of the development on a specific area as well as on a global scale. Improvements in terms of CO_2 emission sustainability may include the development of less polluting transport systems, such as railways and shipping for terrestrial and maritime modes [11,12] or advanced traffic demand management schemes [13].

Even if the understanding of the physical climate system has progressed rapidly, the use of this knowledge to support transport decision-making, manage risks and engage stakeholders still seems inadequate [14]. Indeed, placing an actual monetary value on global warming would require us to provide a consistent estimation of the effects of the increase in temperature, including interactions between terrestrial, atmospheric and hydrologic systems, as well as social, political and economic systems. Climate change experts are faced with numerous uncertainties and disagree on the magnitude, distribution and time frame of global warming impacts, making the evaluation of CO_2 externality particularly complex [15–17].

This paper focuses on the quantification of CO_2 impacts arising from the introduction of a new infrastructure. In Section 2, we present a method for the economic evaluation of CO_2 emissions in transport; in Section 3, we apply this method to the case study of the Brenner Base Tunnel (BBT); we finish the paper with some concluding remarks.

2. NATURE AND EVALUATION OF CO_2 EXTERNALITY

To internalise CO_2 emission costs, monetisation is the most frequently adopted technique [18,19]. Monetisation is the process of putting additional costs and benefits that are not already directly expressed as monetary expenditures and revenues onto the same monetary scale. During this process, the substances emitted are first quantified, that is to say they are usually measured in tonnes of carbon

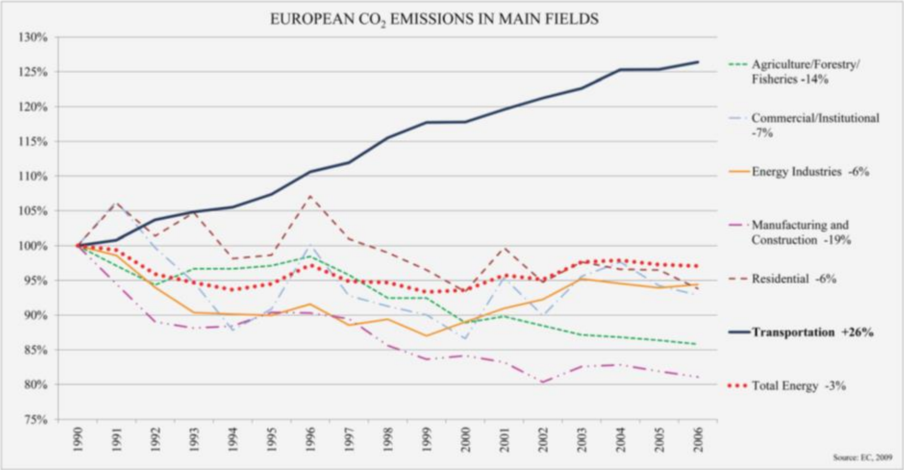

Figure 1. European CO_2 emissions in main fields. Source: EC [9].

(tC) or in tonnes of carbon dioxide (tCO_2).[1] This value is then converted into monetary terms by multiplying the quantity by a unitary price. Costs of carbon dioxide are thus generally expressed in dollar ($), pound (£) or euro (€) per tCO_2.

Several methods can be adopted to determine a unitary economic value for CO_2: some of these are the result of political choices, whereas others derive from scientific analyses. A *carbon trading cost* derived from the European Union emissions trading system [20] or a *carbon tax cost* [21] would belong to the first group, being the result of governmental measures stated at national and international level. Because these measures are largely related to single jurisdictions, the prices will tend to fluctuate [22] and therefore, be inherently unsuitable for long-term forecasts [23]. For these reasons, scientific analyses are normally preferred; these consist of two alternative methods, namely *damage cost* and *avoidance cost*, which will be described in detail in following Sections 2.1 and 2.2.

2.1. *Damage cost*

The damage cost method assesses the future physical impacts of climate change and links them with their effects on the economy and society. It is based on a cost-benefit analysis that determines the optimal policies to adopt on the basis of the environmental, social and economic consequences expected, and then, evaluates whether the benefits are likely to exceed the costs.

The aim is to establish the so-called marginal social cost of carbon, defined as the net present value of climate change impacts over the next 100 years of one additional tonne of CO_2 emitted to the atmosphere today [24].

Determining CO_2 impacts on future climate and physical changes is the real challenge of this method, because the most important consequences (Table I; [24]) are not easy to predict, because of the lack of certainty about their precise relationship with the increase in CO_2 emission levels. To face this issue, specific Integrated Assessment Models (IAMs) have been developed recently to determine the externalities of endogenous greenhouse warming and to monetise them. Dynamic Integrated Climate-Economy model of the Economics of Global Warming (DICE) was one of the first models to be introduced [25]: it forecasts future population growth and per capita income and estimates the appropriate tax at a given time horizon to optimise pollution control, trading off the economic costs of consequences due to GHGs [25,26]. In the first versions of DICE, the function that links damages to temperature does not consider the rate of change in temperatures. This is a great oversimplification, and it is also a critical aspect of the model if it is to be used to provide detailed forecasts. Hence, Policy Analysis for the Greenhouse Effect (PAGE) and Climate Framework for Uncertainty, Negotiation and Distribution (FUND) have subsequently become the preferred reference IAMs.

PAGE is based on future climate scenarios as defined by IPCC [27], modelling both economic and non-economic parameters, and determining the damage they cause in the event of temperature increases [28]. A few major climatic events deriving from CO_2 emissions are also considered, whereas socially contingent effects, such as the social and political costs that cause migration from disadvantaged areas, are not taken into account. Hence, the results could be considered to be slightly underestimated. The ultimate time horizon of PAGE is 2200, but emissions are considered constant after 2100 due to the lack of adequate climate analyses. Consequently, reliable results are provided only up to 2100. PAGE's outcomes are probability distributions of the marginal impacts of reducing CO_2, providing 5%, mean and 95% values.

FUND is a more comprehensive model, because its input includes demographic, economic, technological, carbon cycle, climate and climate change impacts. It covers about 350 years, from 1950 to 2300. Past periods are essential to initialise climate change impacts, whereas the period 2100–2300 is based on simple extrapolations [29]. The mean and the median values are provided, which are higher than those of PAGE, because FUND includes values for the impact on human life as well. However, the FUND increase rate is lower, because it does not take into consideration major climatic events that are presumed to have greater impact, mostly in the long term.

Both models are sensitive to the discount rates and time horizons adopted, which must be chosen with the utmost attention (Section 2.3). FUND and PAGE can also be compared, thus obtaining a mean value of the marginal social cost of carbon [24].

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[1] $1\,tC = 3.664\,tCO_2$ [32].

Table I. Main environmental impacts of CO_2.

GROUP	IMPACTS
1) Sea level rise	- costs of additional protection measures - loss of dry land, wetland loss - increased likelihood of storm surges - landward intrusion of salt water, risk for coastal ecosystems - social and economic effects for inhabitants of small islands and/or low-lying coastal areas
2) Energy use	- migration based on socially contingent effects - summer increase due to air conditioning - winter decrease in demand for heating
3) Agricultural impacts	- changes in temperature and rainfall - changes in cultivated areas and yields - choice of crops - development of new cultivars and other technical changes such as irrigation
4) Water supply	- changes in rates of precipitation and evapotranspiration - demand changes, affected by various climatic factors such as temperature and humidity - exacerbation of water shortages in water scarce areas
5) Health impacts	- increase in summer heat stress - reduction in winter cold stress - extension of the area amenable to parasitic and vector borne diseases - socially contingent damage to health caused by 1, 2, 3, 4 - threats in lower income populations, mostly in (sub)tropical countries
6) Ecosystems and biodiversity	- alteration of ecological productivity and biodiversity - risk of extinction of some vulnerable species. - risk for some isolated systems, including unique and valuable systems (e.g. coral reefs) - acidification of the oceans, impacts on marine ecosystems - impact on fluxes of gases between ocean and atmosphere
7) Extreme weather events	- heat waves, drought, floods and potentially storms, tropical cyclones and even super typhoons (even if the correlation with CO_2 emissions is not clear) - climate variability
8) Major events	- loss of the West Antarctic ice sheet and the Greenland ice sheet; methane outbursts, instability or collapse of the Amazon Forest; changes in the thermohaline circulation, Indian monsoon transformation; change in stability of Saharan vegetation; Tibetan albedo change

Source: Watkiss *et al.* [24], modified

The rapid development of IAMs has encouraged many analyses in the last 15 years based on the damage cost method; in the following notes, a list of the most important studies is analysed. To facilitate comparison, all values originally expressed in dollar ($) and pound (£) have been converted to euro (€) values by adopting historical rate changes [30,31].

Some studies summarised in IPCC [32] were pioneering. Because of their oversimplifications, these studies are not shown here.[2] However, collected values suggested a reference price between €1.43/tCO_2 and €46.56/tCO_2, using year 2000 exchange rates. This range has to be considered only as the interval between the highest and the lowest values expressed, and not as a confidence interval.

The External Costs of Energy (ExternE) project [33] tried to define a specific CO_2 monetary value, rather than a range. Several reports were developed annually, with cyclical updates. In 2005 a value of €9/tCO_2 was proposed, though considered very conservative by the authors themselves. To obtain fairer values, a return to the avoidance cost approach was suggested (Section 2.2).

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[2] Interested readers may refer to Clarkson and Deyes [44].

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Tol [34] summarised the state of the art, analysing studies of CO_2 monetisation by using a statistical approach. The analysis revealed that for the CO_2 economic value, the mode is €0.44/tCO_2, the median €2.80/tCO_2, the mean €18.60/tCO_2 and the 95th percentile €95.52/tCO_2. Indeed, grey literature has been found to provide higher CO_2 values [35–38]. Hence, Tol concluded that marginal damage costs of CO_2 emissions were unlikely to exceed €12/tCO_2.

HEATCO [39] also provided a review of the most relevant European studies to use a cost-benefit analysis approach. Lower, central and upper values of CO_2 economic value have been determined. The range in the central value varied from €22/tCO_2 (in the year 2000) to €83/tCO_2 (in the year 2050), not including the major climatic and socially contingent effects.

Watkiss *et al.* [24] adopted both PAGE and FUND models, applying a discount rate suggested by the Green Book[3] and a time horizon up to 2060. The PAGE model returned a mean value of €18/tCO_2 for the year 2001, whereas the FUND model, €26/tCO_2. The average of these two values (€22/tCO_2) was considered by the authors as the reference value for the damage cost method. However, the authors suggested cross-tabulating this value with that derived from the avoidance cost analysis in order to obtain a more robust value.

Stern [40] adopted the PAGE method, describing several different scenarios up to 2050. By that year, the CO_2 value is €25/tCO_2 if the concentration is stabilised at 550 ppmv; conversely, if the level decreases to 450 ppmv, the cost is expected to be €71/tCO_2.

Finally, in a more comprehensive range varying from €0.70//tCO_2 to €71.50/tCO_2, National Research Council [41] suggested that the value of non-climate damage starts from €21.50/tCO_2.

Results of the most important damage cost studies are summarised in Table II; in order to make them comparable, they have been converted to 2010 € values using the European harmonised indices of consumer prices [42].

2.2. *Avoidance cost*

The avoidance cost approach (also known as *mitigation* or *control cost*) quantifies the money required to avoid an increase of CO_2 levels, to reduce such emissions and to remove CO_2 from the atmosphere. The method is strictly related to the development of policy targets that aim at lowering emissions for a fixed time horizon. The most common targets—e.g. the 'Kyoto Protocol' [10] or European '20-20-20' targets [43]—are defined in terms of reducing CO_2 concentrations (ppmv) or in arresting temperature increases (°C).

Avoidance cost is based on a cost-effectiveness analysis focused on expressing the optimum price to achieve the targets. Because it compares the costs of alternative ways of producing the same or similar outputs, it can be considered a relative measure. In economic terms, the value to be found is the least cost option to achieve a required reduction level of GHG emission (Figure 2). The optimum emission level is determined as the intersection between the curves of the marginal avoidance costs and the marginal social damage curves. In other words, emissions are at their optimum level when the incremental social costs of additional abatement (i.e. reducing emissions by 1 tonne) are equal to the additional social benefits of avoided damage [44].

The MARKet ALlocation (MARKAL) model, adopted by the British Department of Trade and Industry (DTI) [45] for long-term forecasts in the energy sector, is still one of the leading reference programmes for such analyses. The model referred to the UK and indicated that a cost equal to 0.5–2% of the gross domestic product is required to reduce CO_2 emissions by 60% by 2050.

Other methods of this category referred to the medium term: in the following notes, a list of the most important studies is analysed. To facilitate comparison, all those values originally expressed in $ and £ have been converted to € values, by adopting historical rate changes [30,31].

Maibach *et al.* [46] focused on the transport sector, developing a study for the International Union of Railways. A shadow value of €135/tCO_2 was estimated here, derived from the average between the lower value of €70/tCO_2 and the upper value of €200/tCO_2.

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[3] The Green Book [70] is the UK treasury guidance for central government, setting out a framework for the appraisal and evaluation of all policies, programmes and projects.

Table II. Damage cost method, list of main studies on the economic value of CO_2.

Study	Year	Reference	Lower value	Central value	Upper value	Lower value	Central value	Upper value
			(€/tCO_2)*	(€/tCO_2)*	(€/tCO_2)*	(€$_{2010}$/tCO_2)§	(€$_{2010}$/tCO_2)§	(€$_{2010}$/tCO_2)§
IPCC	1995	[32]	1.43		46.56	2.25		60.49
Tol	—	[34]	0.44	2.80	18.60	0.51	3.25	21.58
ExternE	2005	[33]		9			10.44	
Watkiss	2005	[24]	18†	22	26‡	20.88	25.52	30.16
DLR	2006	[82]	15	70	280	17.05	79.58	318.30
HEATCO	2005	[39]	22		83	25.52		96.28
Stern review	2006	[40]	25		71	28.42		80.71
NRC	2009	[41]	0.70	21.50	71.50	0.74	22.70	75.48

Notes:
Exchange rates taken from Bundesbank [30] and Bankenverband [83].
IPCC, Intergovernmental Panel on Climate Change; ExternE, External Costs of Energy; NRC, National Research Council (NRC); PAGE, Policy Analysis for the Greenhouse Effect; FUND, Framework for Uncertainty, Negotiation and Distribution.
*The value date is indicated in column 'year'.
†Adopting PAGE model
‡Adopting FUND model.
§Conversion to 2010 € values based on EC [42]

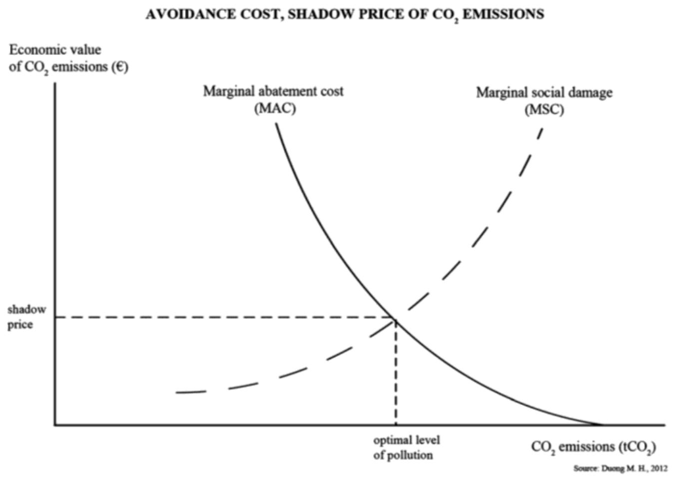

Figure 2. Shadow price of CO_2 emissions as the intersection between marginal abatement costs and social damage curves. Source: Duong [84].

The Real Cost Reduction of Door-to-door Intermodal Transport project [47] was based on the target proposed by the Organisation for Economic Co-operation and Development under the Kyoto Protocol for the short term and the IPCC target for the long term. The study provided respectively €37/tCO_2 and €135/tCO_2 as reference values.

The target fixed by the Kyoto Protocol was also chosen by other studies, determining a CO_2 economic value of €20/tCO_2 [48] or slightly lower [49]. Maibach *et al.* [50] also adopted this value for the short term, fixing the value for the long term at €140/tCO_2.

The value adopted in the ExternE project [33] was only slightly lower (19 €/tCO_2), because it also took into account the price of the tradable CO_2 permits in 2005, which varied between €18/tCO_2 and €24/tCO_2. Nonetheless, ExternE clearly highlighted that the values could be very different if other targets were adopted: in particular, €95/tCO_2 would be required to limit temperature increase to only 2°C in comparison with the pre-industrial age.

The Commission of the European Communities (CEC) [51] adopted two different models, namely the Prospective Outlook on Long-term Energy Systems (POLES) and General Equilibrium Model for Economy–Energy–Environment (GEM-E3). POLES [52] is a dynamic partial equilibrium model. It provides CO_2 emission marginal abatement cost curves from 2005 to

2050 by region and/or sector, as well as emission trading systems analyses under different market configurations and trading rules. GEM E3 [53] is a general model that covers the interactions between energy, economy and the environment: the internalisation of environmental externalities is conveyed either through taxation or through global system constraints. It is extended up to 2030 with a 5-year time step. By using these two models, the scenario adopted aimed at reducing emissions by a good 25% by 2050.[4] Prices increased from €15/tCO_2 (2010) to €65/tCO_2 (2030, the last year of analysis). Extrapolating results up to 2050, the value grew up to €120/tCO_2.

The target fixed by Kuik *et al.* [29] was even more ambitious: restricting CO_2 values to 350 ppmv by 2050. The costs for this challenge were quantified between €74/tCO_2 and €227/tCO_2 by 2025 and between €132/tCO_2 and €381/tCO_2 by 2050.

Results of the most important damage cost studies are summarised in Table III; in order to make them comparable they have been converted to 2010 € values using the European harmonised indices of consumer prices [42].

2.3. CO_2 *uncertainties as the main cause of indefiniteness*

Avoidance and damage costs are based on several operative differences: the former aims at determining the optimum level of emissions, whereas the latter evaluates the difference related to a 1 tonne change in the present and the consequences of this change in the future. It follows that the mean values are not comparable either. Litman [54] estimates that avoidance costs range between €15.09/tCO_2 and €37.72/tCO_2; on the other hand, damage costs range from €14.33/tCO_2 to about €678.88/tCO_2, but in some cases negative values have also been proposed (e.g. [34]). This would imply that CO_2 emissions can generate benefits for society, when considering only the short-term effects.

Obviously the range is vast, involving up to almost four orders of magnitude (Tables II and III): this is mostly due to the presence of uncertainty. The topic has been extensively treated in Clarkson and Deyes [44], in which two main groups of uncertainty are indicated, namely the scientific and the economic.

2.3.1. *Scientific uncertainty*

Scientific uncertainty includes four main aspects. The first concerns the evaluation of future CO_2 emission levels. Because this value is strictly connected with hard to predict parameters such as socio-economic and technological developments, future forecasts suffer from a great degree of uncertainty, which can be tackled by the adoption of different scenarios. A scenario is defined as a ‘representation of visions/images of the future and courses of development organised in a systematic and consistent way’ [55]. The methodology is based on using hypotheses to generate outcomes, which are then cross-tabulated with the initial situation to predict the future sequences of events that are implied by the hypotheses. The scenario method does not solve the uncertainty problem, but provides rational answers under certain hypotheses [56]. In particular, two aspects are especially critical: firstly, to predict future technologies in propulsion systems and secondly, to forecast future travel demand. As far as the first point is concerned, the development of hybrid-electric vehicles and battery-electric vehicles (BEVs) may lead to a transport system, which has a lower impact on the environment. However, it is currently very difficult to forecast future sales of these vehicles, because their price break-even point is still somewhere in the future, and, with regard to the BEVs, decades may be required before they become competitive [57]. It follows that the car fleet for the next few years at least is expected to be mainly based on oil, but we have no precise knowledge as to how this will evolve. The determination of future travel demand is the main cause of errors in transport planning, because it leads to an underuse or overuse of the single infrastructures that generates consequent problems in the whole mobility network [58]. Also in this case, no definitive answers can be provided, but the error can be

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[4] The baseline scenario shows an increase in emission by 86% up to 2050 in comparison to current levels.

Table III. Avoidance cost method, list of main studies on the economic value of CO_2.

Study	Year	Source	Lower value	Central value	Upper value	Lower value	Central value	Upper value
			(€/tCO_2)*	(€/tCO_2)*	(€/tCO_2)*	($€_{2010}/tCO_2$)§	($€_{2010}/tCO_2$)§	($€_{2010}/tCO_2$)§
INFRAS	2000	[46]	70	135	200	90.94	175.39	259.84
IPCC	2001	[27]		20			25.29	
RECORDIT	2001	[47]	$37^{\dagger}$		$135^{\ddagger}$	45.50		166.00
UNITE	2003	[48]	5	20	38	6.03	24.13	45.84
INFRAS	2004	[50]	$20^{\dagger}$		140	23.66		165.65
ExternE	2005	[33]	19		95	22.04		110.20
CEC	2007	[51]	15**	$65^{\ddagger\ddagger}$	$120^{§§}$	16.70	72.38	133.63
Kuik	2008	[29]	$74^{\dagger\dagger}$		$132^{§§}$	78.97		140.87
			$227^{\dagger\dagger}$		$381^{§§}$	242.25		406.60

Notes:
IPCC, Intergovernmental Panel on Climate Change; RECORDIT, Real Cost Reduction of Door-to-door Intermodal Transport; ExternE, External Costs of Energy; CEC, Commission of the European Communities.
*The value date is indicated in column "year".
†Short term value
‡Long term value
§Conversion to 2010 € values based on EC [42]
**Year 2010
††Year 2025
‡‡Year 2030
§§Year 2050

controlled by adopting specific forecasting methods, such as the 'four stage model' [59,60] and the 'input–output' model [61].

The second issue of scientific uncertainty is determining a link between emissions and atmospheric concentration: not all CO_2 emissions increase the atmospheric concentration, as there is some sequestration by the oceans and vegetation. The uncertainty lies in determining the amount of future emissions that could be absorbed in this way.

The third issue is related to the assessment of the consequences of CO_2 on climate changes. The most important relationships have been outlined in Table I, but no general agreement can be guaranteed. Furthermore, disaggregating and analysing them at regional level is very difficult.

The fourth issue is the measurement of the physical impacts of climate change. In other words, this means determining the consequences that climate change produces on a given region in terms of variations in the landscape. The risk here lies mainly in making allowances for, or overestimating or underestimating certain aspects. Because the relationship between climate change and actual consequences for the environment is not clearly understood, very different approaches are used: for example, several studies include catastrophic events (e.g. human deaths, loss of the Gulf Stream as well as the Greenland ice sheet), whereas other studies exclude them, considering only consequences such as sea level rise, energy use, agricultural impacts, water supply, health impacts, ecosystems and biodiversity[5] (Table I).

2.3.2. *Economic uncertainty*

Determining economic uncertainty is even more problematic. The lack of specific analyses related to the context of climate change is an issue, which is still far from reaching a satisfactory solution [62,24]. It involves two principal aspects: the first aspect is to determine the CO_2 unit cost. The measure of economic climate change impacts is not the money itself, but the money equivalent of the utility [63]. The wealth of a given nation is very influential on the monetisation of the impacts: an emission of a single tonne of CO_2 does not have the same economic impact on every country, because both the willingness to pay to avoid the consequences and the willingness to pay to accommodate the consequences are driven by the respective gross domestic products of the countries. Earlier studies did not include this aspect in their analyses [64,65], because regional impacts were quantified

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[5] Interested readers may refer to Litman [54] for further details.

in local currencies, converted to dollars and then totalled. To avoid these differences, the concept of *equity weight* has been introduced [66], whose formula could be expressed as

$$D_w = \sum_{i=1}^{n} \left(\frac{c_w}{c_i}\right)^{\varepsilon} \cdot d_i \tag{1}$$

where

D_w is the global damage derived from CO_2 emissions;
c_w is the world average per capita consumption;
c_i is the average per capita consumption of a given nation i;
ε is the elasticity of marginal utility;
d_i is the damage derived from CO_2 emissions in country i.

The equity weight is based on the assumption that countries with consumption above the world average receive a low weight and vice versa. In Equation (1), c_w is used to normalise the values, assuming a world based on fair rules. The parameter ε plays a main role in quantifying the global damage [67]. First, it expresses the kind of welfare function, determining the measure of aversion to inequality between regions; second, it is the expression of inequality between different time periods; and third, it takes into account the risk aversion of the decision maker if the uncertainty is also considered in the analysis. CO_2 estimates that adopt equity weighting are substantially higher than the others, but the parameter is neither universally accepted nor determined [68]. The consequence is that estimates can differ even by two orders of magnitude due to the equity weight, depending on the region considered [69].

The second aspect of economic uncertainty is determined by the choice of the discount rate used to monetise future emissions. Discounting is a technique used to compare costs and benefits that occur in different time periods. It is a separate concept from inflation, and it is based on the principle that people generally prefer to receive goods and services now rather than later and prefer to pay their bills as late as possible. The discount rate is used to convert all costs and benefits to present values, so that they can be compared [70]. Some trustworthy critics voice concerns with the fundamentals of this method: Chichilnisky [71], for example, considers discounting as a dictatorship of the present generation over the future, whereas Daly and Cobb [72] are convinced that discounting is a method for converting future large numbers into present small ones. Nevertheless, this method still continues to be adopted worldwide.

Higher discount rates lead to lower values and vice versa. Normally, the rate lies between 1% and 3%, but the variation of the unitary cost is very high in this range. In Watkiss *et al.* [24], for example, the value decreases from €67.85/tCO_2 to €27.93/tCO_2 when the 1% and 3% discount rates are considered, respectively.

Different uncertainties can overlap, making them not necessarily cumulative. It follows that the global uncertainty could be much higher, but also much lower in comparison with the single uncertainty described earlier. Considering the sum of all the uncertainties, the emission cost per tonne of CO_2 could have up to three orders of magnitude, passing from negative values (including benefits in the analysis) to more than €1000/tCO_2 [54]. Obviously, this range is too large and prohibits the determination of a reliable economic value for CO_2 emissions.

2.4. *The choice of the most appropriate economic value of CO_2*

As a result of the issues described in Section 2.3, a method partly based on avoidance costs and partly on damage costs seems to work better to minimise the uncertainty and to determine the most appropriate economic value of a tonne of CO_2 in transport [73]. In the remainder of this paper, avoidance costs are considered to be more reliable and are consequently chosen for the medium term up to 2020 [74]: policy goals and measures in terms of CO_2 abatement are stated at international levels up to the same date, thus reducing the uncertainty about future emission levels.

On the other hand, damage costs are preferred for the longer term (up to 2035 and over): first, this is the method most often adopted in other environmental analyses of external costs as well, making the results comparable. Second, long-term policy goals and measures have yet to be decided, thus making the use of avoidance costs more difficult to evaluate.

Hence, a technique based on both damage and avoidance costs is adopted here to determine a robust CO_2 monetary value. Three different monetary trends are considered, namely, the lower, the central and the upper levels. The values provided here are taken from different studies, as described in detail in the following paragraphs. All the values have been converted to 2010 prices by using the European harmonised indices of consumer prices [42]; the analytical reconstruction of the final prices, as listed in Table IV, is elaborated in Appendix 1.

Lower values are derived from Watkiss *et al.* [24]. In their analysis, the authors calculate the damage value as an average of the results provided by the PAGE and FUND models, referring to two of the most relevant IAMs. Because these programmes underestimate CO_2 emission costs in comparison with other methods (Section 2.1), the lower economic trend adopted by Watkiss *et al.* is also chosen as a reliable reference for the lower value in the present study. Originally expressed in £/tC, the values have been converted to €/tCO_2 using historical exchange rates referenced to 2005, as provided by the Bank of Italy [31] and then adjusted to 2010 exchange rates. The value grows from €19.45/tCO_2 in 2010 to €37.68/tCO_2 in 2035.

Central CO_2 economic values are based on ExternE [33] for the short term (2010–2020) and CEC [51] for the long term (2021–2035): both projects have been developed under the supervision of the European Union and recognised for the attention that they pay to the environmental sector. Furthermore, a yearly review of the values is provided, including a constant update of results. Undoubtedly these two aspects constitute a robust control of the choice of the most accurate CO_2 values. Significantly, in the year 2020 ExternE and CEC give a very similar economic value (about €46/tCO_2), thus showing a convergence in the medium term. In the year 2010, the central value was evaluated at €23.14/tCO_2, a cost that rises to €92.08/tCO_2 by the year 2035.

Finally, the upper values are included in a range between €50.43/tCO_2 (for the year 2010) and €129.05/tCO_2 (for the year 2035), according to Maibach *et al.* [73]. The quantification of these values takes into account the author's clearly stated wish for the study to be used as a 'guideline at the European level' to encourage strong policy-making aimed at reducing CO_2 emissions. Using

Table IV. CO_2 prices (€/tCO_2) adopted here for the years 2010–2035. Lower, central and upper values.

Year	Lower value (€/tCO_2)	Central value (€/tCO_2)	Upper value (€/tCO_2)
2010	19.45	23.14	50.43
2011	19.93	25.46	53.23
2012	20.42	27.77	56.03
2013	20.90	30.08	58.83
2014	21.39	32.40	61.63
2015	21.88	34.71	64.43
2016	22.36	37.03	67.23
2017	22.85	39.34	70.04
2018	23.33	41.66	72.84
2019	23.82	43.97	75.64
2020	24.31	46.28	78.44
2021	25.04	47.59	81.80
2022	25.77	50.75	85.16
2023	26.49	53.90	88.52
2024	27.22	57.06	91.89
2025	27.95	60.22	95.25
2026	28.68	63.37	98.61
2027	29.41	66.53	101.97
2028	30.14	69.69	105.33
2029	30.87	72.85	108.69
2030	31.60	76.00	112.06
2031	32.81	79.22	115.98
2032	34.03	82.43	117.29
2033	35.25	85.65	121.21
2034	36.46	88.87	125.13
2035	37.68	92.08	129.05

DOI: 10.1002/atr

the methodology adopted in this section, the values derive from both the avoidance and damage cost methods, in the short and long terms, respectively. For these reasons, the highest values expressed in Maibach's report are also considered reliable as the upper CO_2 economic values in the present study.

All the CO_2 economic values, expressed in € (calculated from 2010 rates), are listed in Table IV. They have been slightly increased here (+5%) in comparison with the reference studies. This choice is determined by the specific CO_2 transport trend, which, as shown in Section 1, has been steadily growing since the 1990s and is thus not contributing to the aim of reducing atmospheric CO_2.

The increase in CO_2 unitary prices implies that the policies adopted will also affect the future impacts of emissions: if a greater increase in emissions is seen, a greater negative economic consequence can be anticipated for the community, whereas a reduction in CO_2 concentrations provides for greater savings.

Finally, it has to be noted that the values proposed here are the result of an analysis made mostly at the European level. For this reason, the values expressed previously should be limited to European countries only. Their use for other developed countries, especially if some care is taken to check with national policies, should be possible as well. The method could also be applied to developing countries. However, in this case, the values of CO_2 emissions should be carefully adapted to local conditions by adopting an appropriate equity weighting value. To achieve this aim, a separate analysis has to be carried out, which should also include the lower incidence of transport in their current global emissions of CO_2 [5] and their contribution to past emissions: these states consider themselves as relatively new CO_2 emitting nations, and thus would expect to pay a lower price in comparison with developed countries, which have been producing CO_2 emissions since the 19th century without paying any fees.

In conclusion, results have to be carefully distinguished according to the aim and the geographical areas considered in the study. The values given in this section refer only to the transport sector and only to Europe and are thus consistently suitable for the case study presented in the next section, namely, the Brenner Base Tunnel.

3. CASE STUDY: THE BRENNER BASE TUNNEL

3.1. The new Munich–Verona high-speed line and Brenner Base Tunnel

The Brenner Corridor is the central sector of Line 1 of the Trans-European Transport Network that links Berlin and Palermo with a 2200 km long high-speed (HS) railway line. The Corridor, whose length is about 450 km, is commonly divided into the following three sections (Figure 3):

(1) Northern access route: Munich–Kufstein, Kufstein–Kundl and Kundl–Baumkirchen;
(2) Brenner Base Tunnel: Innsbruck–Fortezza/Franzensfeste with the Innsbruck bypass;
(3) Southern access route: Fortezza/Franzensfeste–Ponte Gardena/Waidbruch, Bolzano bypass, Trento bypass and Verona approach.

The Alpine stretch runs from Kufstein, a town close to the Austrian–German border, to Verona: as it is a mountainous region, it is generally considered the most critical area. In particular, the Brenner Pass, located between the Austrian and the Italian border, is characterised by steep gradients (Figure 4). In this stretch, the existing line is not adequate for maintaining constant speeds and avoiding bottlenecks: gradients of 26 per thousand between Innsbruck and Brenner and 23 per thousand between Brenner and Fortezza/Franzensfeste, tight curve radii as well as stone tunnels that are difficult to enlarge do not meet the minimum requirements for a high-speed line (i.e. a constant speed not lower than 250 km/h).

Thus, in 1990 a new tunnel through the base of the Brenner was planned between Innsbruck (Austria) and Fortezza/Franzensfeste (Italy). The BBT is a 55 km-long railway tunnel, due to be completed by 2025,[6] which will enable the entire route from Munich to Verona to be a HS line. Furthermore, it will bring about time savings of up to 150 min along the stretch: an intercity train will take only 3 h to cover the entire distance compared with the current 5 h and 30 min [75].

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[6] In a first phase, the tunnel was scheduled for completion in 2022.

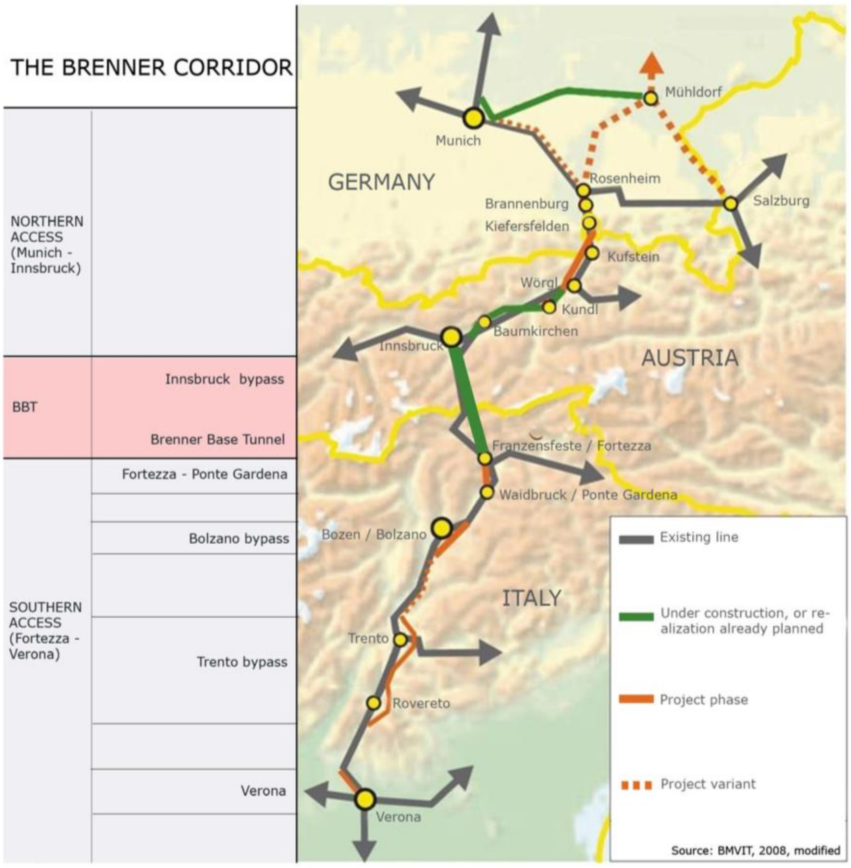

Figure 3. Munich–Verona high-speed railway line. Source: BMVIT [85], modified.

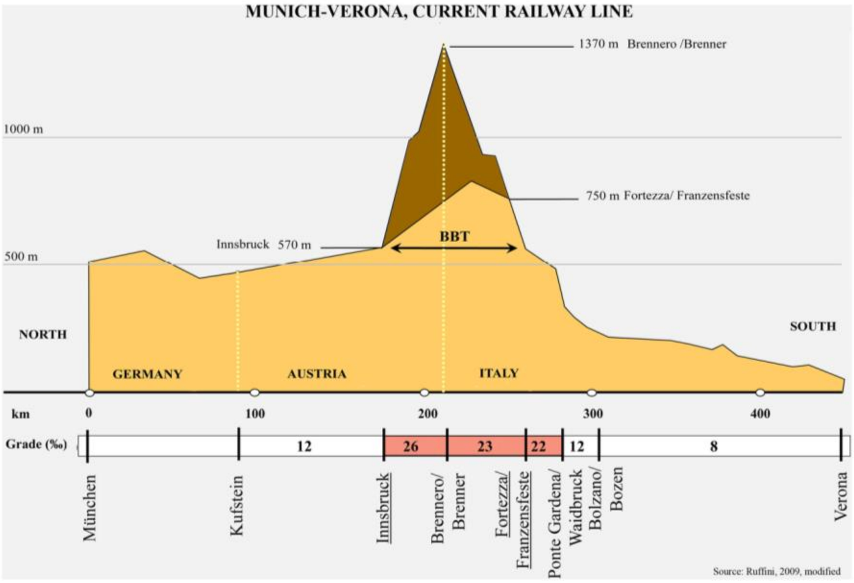

Figure 4. Munich–Verona, current railway line. Source: Ruffini [86], modified.

In general, the impacts that an infrastructure produces on a given territory involve many aspects [19]: several are merely related to transport engineering (changing travel times, modal split, traffic generated, etc.), others involve the land use (e.g. shift of population to more accessible locations or to ex-urban areas, development of city centres, variation in market prices and in density), whereas others imply social and environmental aspects. The methodology presented in this section tries to quantify and monetise CO_2 emissions, which, as stated in Section 2, is one of the most important among the environmental aspects. Two main steps are required to settle this problem: determining future CO_2 emissions (Section 3.2) and monetising them (Section 3.3). Subsequently, we will discuss the economic consequences produced by the BBT on the community as far as CO_2 emissions are concerned (Section 3.4).

3.2. Future CO_2 emissions

To quantify future CO_2 emissions along the Brenner corridor deriving from the realisation of the BBT project, the balance method is adopted. A balance applied to an infrastructure project is based on the development of two groups of scenarios: the former considers the realisation of the infrastructure project, whereas the latter implies the do-nothing option. In short, the process goes as follows: the incoming and outgoing CO_2 emissions of the first group are evaluated both in the construction and operational phases and then, compared only with the operational phases generated by the do-nothing scenario. The balance is positive if the overall emissions of the first group are lower than those of the second, thus determining the CO_2 effectiveness of the infrastructure. In the following sections, the scenarios adopted in this analysis are first described (Section 3.2.1), and then the values of CO_2 emissions are calculated during the construction (Section 3.2.2) and the operational phases (Section 3.2.3). Finally, the results are compared (Section 3.2.4).

3.2.1. Scenarios

The balance is based on a comparison between three different scenarios, labelled minimum, trend and consensus. These scenarios take into account the traffic forecasts along the Brenner Corridor up to 2030, as elaborated by ProgTrans AG [76]. The minimum scenario considers no new construction: it is a simple do-nothing scenario. Both the trend and consensus scenarios involve the completion of the BBT. Table V describes in detail the most important measures adopted in each of the three scenarios.

Minimum is very conservative, because it implies few changes for the next 25 years in comparison with the current situation. It transposes the present transport policy to the year 2035, slightly liberalising and privatising passenger and freight transport on the railways. Changes in costs per kilometre are not considered, nor toll variations for either heavy goods vehicles (HGVs) or cars, nor changes in railway and road speeds. There is provision for further improvement of highways linked with Alpine roads. The subsidies for transport are granted for profitable modes only, whereas multimodality is empowered on main high-capacity corridors.

Trend is based on the ‘business-as-usual’ rules: on the one hand, the market liberalisation boosts road traffic; on the other hand, political measures encourage the development of rail transport (which also includes here the completion of the Munich–Verona HS railway line and the BBT). It follows that the highest amount of overall traffic is generated in this scenario, due to the presence of measures that favour the use of the railways and the absence of measures to discourage the use of road vehicles. Future evolution of prices and transport demand are based on the trends of recent years: a 5% cost reduction and a 3% to 5% average speed growth for freight transport by rail are considered up to 2035. The Austrian railway fares and transport subsidies are also substantially reduced, whereas the highway tolls are at the same level as the infrastructure costs.

Consensus fulfils a sustainable transport policy by adopting several measures to internalise all the external costs. Referring to tax policies, the most important measures are the subsidies of rail transport, along with some toll increases (Austrian tolls are assumed to reach Swiss levels) for all types of vehicles. Moreover, an ecotax for mineral oil is introduced, and the reduction of transport subsidies is forecast. In terms of infrastructure policy, the HS railway line and ‘rolling highway’ (combined truck and rail transport) are improved; new materials are also introduced, thus reducing travel times and increasing comfort for passengers. Furthermore, only the most

Table V. Measures adopted in 'minimum', 'trend' and 'consensus' scenarios.

	Minimum	Trend	Consensus
Measures to discourage the use of road transport			
Road costs per kilometre	Current costs	Current costs	+30% in comparison with other scenarios
Road tolls (passengers)	No tolls related to the covered distance; no urban tolls	No tolls related to the covered distance; no urban tolls	No tolls related to the covered distance, introduction of urban tolls, and general costs +15% in comparison with other scenarios
Road costs (freight)	Highway tolls lower than infrastructure costs up to 2015	Highway tolls at the same level as infrastructure costs up to 2015	Highway tolls higher than infrastructure costs (+15% in comparison with trend); harmonisation of tolls over the entire Alpine region
Road traffic ban	No ban along Brenner highway, maintenance of Sunday and night time bans and use of traffic density control systems	No ban along Brenner highway, maintenance of Sunday and night time bans and use of traffic density control systems	Implementation of social and safety regulations, no ban along Brenner highway, maintenance of Sunday and night time bans and use of traffic density control systems
Speed limits	No changes	No changes	More controls, reductions of at least 8%
Tax on mineral oil	Uniform tax rate in all EU countries based on current value	Uniform tax rate in all EU countries based on current value	Uniform tax rate in all EU countries higher than current value; introduction of an ecotax
Road construction	Completion of highways (but not along Alps)	Completion of highways (but not along Alps)	Investments only for national programmes or for TEN-T to reduce bottlenecks
Measures to encourage the use of rail transport			
Intermodality	Improvement, reduction of technical and administrative barriers	Considerable improvement, reduction of technical and administrative barriers	Considerable improvement, reduction of technical and administrative barriers, and optimisation of the railway services
Rolling highway	At 2004 level	At 2004 level	At 2003 level
Railway charges	Slight reduction (−5% for goods)	Slight reduction (−5% for goods)	Considerable reduction
Subsidies	Reduction for non-profitable transport modes	Reduction for non-profitable transport modes	Slight reduction, but not related to non-profitable transport modes; railway transport receives higher funds
Railway traffic market rules	Slight liberalisation and broad privatisation of freight and passenger transport	Liberalisation and broad privatisation of freight and passenger transport	Liberalisation and broad privatisation of freight and passenger transport

(*Continues*)

Table V. (Continued)

	Minimum	Trend	Consensus
Measures to encourage the use of rail transport			
Railway lines construction	Completion of Gotthard, Moncenisio and Lötschberg base tunnels	Completion of Brenner, Gotthard, Moncenisio and Lötschberg base tunnels. TEN-T corridors fully realised by 2025	Completion of Brenner, Gotthard, Moncenisio and Lötschberg base tunnels. TEN-T corridors fully realised by 2025
Telematics	Introduction of ERTMS systems for HS lines by 2025	Introduction of ERTMS systems for HS lines by 2025	Introduction of ERTMS systems for all HS lines by 2015
Average rail speed	Slight changes in comparison with current speeds	In comparison with current speeds: +3% up to 2015, further + 2% up to 2025	In comparison with trend: +3% up to 2015, further + 2% up to 2025

Source: Nocera and Cavallaro [78]
EU, European Union; TEN-T, Trans-European Transport Network; ERTMS, European Railway Traffic Management System; HS lines, high-speed lines.

critical road bottlenecks are resolved (no further construction of sections of road between the Alpine highways). In operation, these measures lead to 30% growth of the cost per kilometre for heavy goods vehicles (HGVs) and cars by 2025. In comparison with trend, consensus implies an increase of the highway tolls (15%) and of railway speed (5%) as well as a reduction of speed along roads (−8%).

CO_2 emissions are then calculated in the three scenarios. In trend and consensus, this value is equal to the sum of the emissions produced during the construction phase (Section 3.2.2) and operational phase (Section 3.2.3) of the infrastructure, whereas, self-evidently, in minimum, only the latter phase is considered, because no construction of the tunnel is foreseen. To this end, two different spatial scopes were used: construction-related emissions refer to the realisation of the BBT, whereas operation-related emissions consider the transnational impact of the tunnel and its effects on the entire Alpine section of the line, namely the section between Kufstein and Verona.

3.2.2. *Construction phase*

The *construction phase* quantifies the amount of CO_2 emitted during the realisation of the BBT. Four main process elements are identified: drilling, transportation of the spoil, production of the construction materials and fitting out. Each of these processes is the sum of several sub-elements, as listed in Table VI.

The overall CO_2 emissions produced by the construction of the BBT are estimated to be about 2280 kt (kilotons), of which more than 85% (about 1940 kt) derives from the production of construction materials (concrete and steel); 188 kt are expected to be emitted during the fitting out operations, 130 kt during the drilling and finally 20 kt during the transportation of the spoil.[7]

3.2.3. *Operational phase*

The *operational phase* aims at determining the CO_2 emissions to 2035 of four transport means, namely cars, HGVs, passenger trains and freight trains. For each of these, a traffic demand growth rate is provided, referring to different scenarios along the Brenner Corridor [76]. These values are then cross-tabulated with the historical data to determine the yearly future transport demand up to 2035 [77].

Once this value is known, the future CO_2 emissions in a given year are obtained by multiplying the amount of each mean by the yearly specific emissions and the distance covered, according to Equation (2):

$$p_i = d_i \cdot c_i \cdot n_i \tag{2}$$

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[7] The methods and the parameters adopted to determine these values are fully explained in Nocera *et al.* [79].

Table VI. CO_2 emissions in the construction phase of Brenner Base Tunnel.

Main process elements	Sub-process elements	CO_2 (kt)
Drilling	Conventional excavation	17.68
	Mechanical excavation	101.91
	Manufacturing of TBMs	3.10
	Transportation of TBMs	0.36
	Rock blasting	7.01
	Subtotal	130.07
Transportation of the spoil	Transportation using conveyor belt	14.70
	Transportation using trucks	5.74
	Subtotal	20.45
Production of the construction materials	Concrete	1580.37
	Steel	358.55
	Transportation of the construction materials using trucks	2.51
	Subtotal	1941.44
Fitting out	Ventilation and cooling of the tunnels	150.71
	Water treatment plants	14.26
	Running the offices and the machine shops	1.48
	Lighting the tunnels	8.75
	Lighting the external areas	13.19
	Subtotal	188.39
Total		2280.35

Source: Ruffini *et al.* [77]

where

p_i stands for the national CO_2 emissions for the transport mode i in a given year;
d_i is the distance covered from the transport mode i;
c_i is the average consumption of the standard vehicle of the transport mode i in the year considered[8]; and
n_i is the overall number of vehicles of the transport mode i in the year considered.

To obtain the overall yearly CO_2 emissions in a given scenario, Equation (2) must be summed for the transport mode (index i) and for the country (index j), as indicated in (3):

$$CO_{2k} = \sum_{j=1}^{2} \left(\sum_{i=1}^{4} p_i \right)_j \tag{3}$$

where

CO_{2k} represents the amount of emissions of carbon dioxide in a given scenario in the year k; and
p_i is defined as the former definition;
i is the modal index ($i = 1$ for cars; $i = 2$ for HGVs, $i = 3$ for passenger trains; and $i = 4$ for freight trains); and
j is the national index ($j = 1$ for Italy and $j = 2$ for Austria).

These formulas are then iterated for each year in the period of time considered and then summed [78]. Overall CO_2 emissions deriving from the operational phase are provided in Table VII: the lowest values (about 43 150 kt) are forecast in consensus, followed by minimum and trend, with about 46 700 kt and 48 800 kt respectively.

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[8] In this analysis, standard trains are powered by electricity and standard road vehicles by diesel technology. According to Cappelli and Pozzi [87] and to Weiss *et al.* [57], alternative sources such as BEVs can be considered economically competitive only after a few decades, and thus are not considered here.Specific emissions are calculated adopting Tremove [88] and Infras [89] for train and road emissions, respectively. Interested readers may refer to Nocera *et al.* [79], where a detailed description of the values and the methodology is provided.

Table VII. CO_2 emissions related to road and rail transport.

Year	Minimum (kt)	Trend (kt)	Consensus (kt)
2010	1535	1535	1500
2011	1555	1555	1502
2012	1581	1581	1510
2013	1608	1608	1518
2014	1635	1635	1526
2015	1663	1663	1534
2016	1690	1696	1542
2017	1715	1726	1565
2018	1741	1762	1589
2019	1767	1801	1615
2020	1793	1840	1643
2021	1805	1866	1659
2022	1817	1889	1670
2023	1829	1913	1681
2024	1840	1937	1695
2025	1852	1963	1709
2026	1873	1998	1733
2027	1885	2017	1740
2028	1897	2036	1748
2029	1909	2055	1755
2030	1921	2074	1763
2031	1934	2094	1772
2032	1946	2114	1780
2033	1959	2135	1788
2034	1972	2155	1797
2035	1984	2176	1805
Total	46 706	48 822	43 139

Source: Nocera *et al.* [79]

3.2.4. *Emissions in future scenarios*

Once the emissions in both construction and operational phases are determined, it is necessary to sum these values in those scenarios, which include the completion of the BBT, thus determining future overall emissions. As shown in Tables VI and VII, trend provides emissions equal to about 51 100 kt (2280 kt+ 48 800 kt), whereas consensus limits CO_2 to 45 400 kt (2280 kt + 43 150 kt). Finally, because in this scenario the BBT is not realised, emissions in minimum remain at 46 700 kt (Figure 5).

Consequently, the construction of the BBT does not necessarily imply a reduction in CO_2 emissions; indeed, the tunnel might even generate a significant increase, as evidenced by trend, which yielded

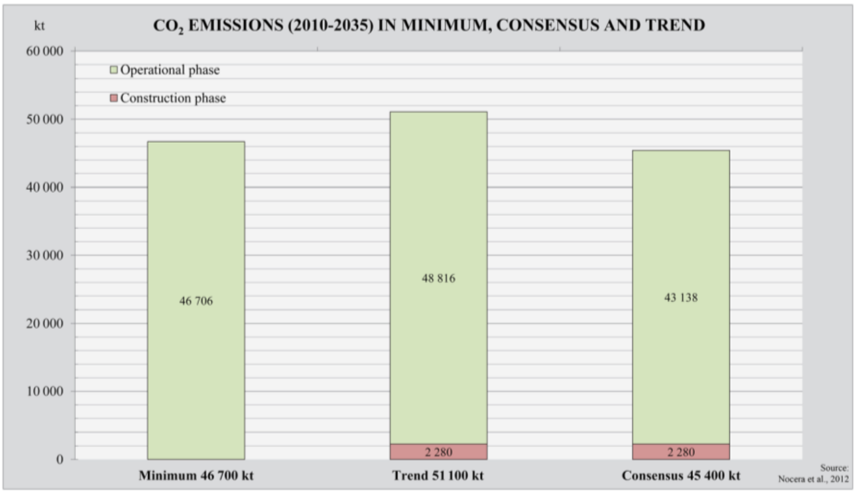

Figure 5. CO_2 emissions in ‘minimum’, ‘trend’ and ‘consensus’ for the years 2010–2035. Source: Nocera *et al.* [79].

Table VIII. CO_2 economic values in different scenarios adopting different unitary values.

	Unitary economic value		
Scenario	Lower (million EUR)	Central (million EUR)	Upper (million EUR)
Minimum	1275	2635	4188
Trend	1341	2788	4416
Consensus	1175	2424	3857

4400 kt CO_2 in excess of the do-nothing position expressed by minimum. Only when supported by a policy that favours rail and discourages road transport can the tunnel help cut CO_2 emissions (consensus, −1300 kt).

3.3. CO_2 emission costs

To quantify the external costs deriving from CO_2 emissions along the BBT, unitary costs are cross-tabulated with the emissions calculated in the previous section. The yearly economic value in a given scenario is provided by multiplying the emissions for a given year (Table VII) by the corresponding unitary CO_2 price, selecting from the lower, the central and the upper values listed in Table IV. These values must be chosen according to the policy decided by the authorities: the lower value implies more precautionary reduction strategies, whereas the upper level allows a more sustainable approach. Hence, the overall CO_2 emissions in a given scenario are the sum of the single yearly values, as expressed in Equation (4):

$$E_{CO_2} = \sum_{k=i}^{n} CO_{2k} \cdot u_{hk} \tag{4}$$

where

E_{CO2} are the economic cost of CO_2 emissions in a given scenario;
n is the last year considered in the analysis;
CO_{2k} are the CO_2 emissions in the year k;
u_{hk} is the discounted unitary price of CO_2 emitted and considered in each of the values h in the year k; and
h is the index that indicates the value considered: $h = 1$ refers to lower value, $h = 2$ refers to central value and $h = 3$ refers to upper value.

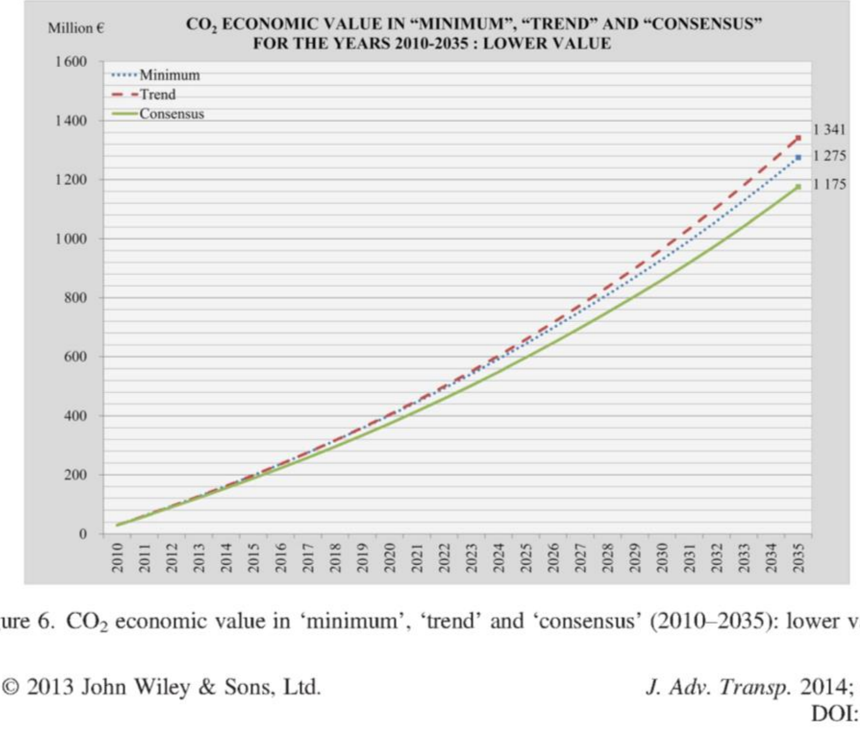

Figure 6. CO_2 economic value in 'minimum', 'trend' and 'consensus' (2010–2035): lower value.

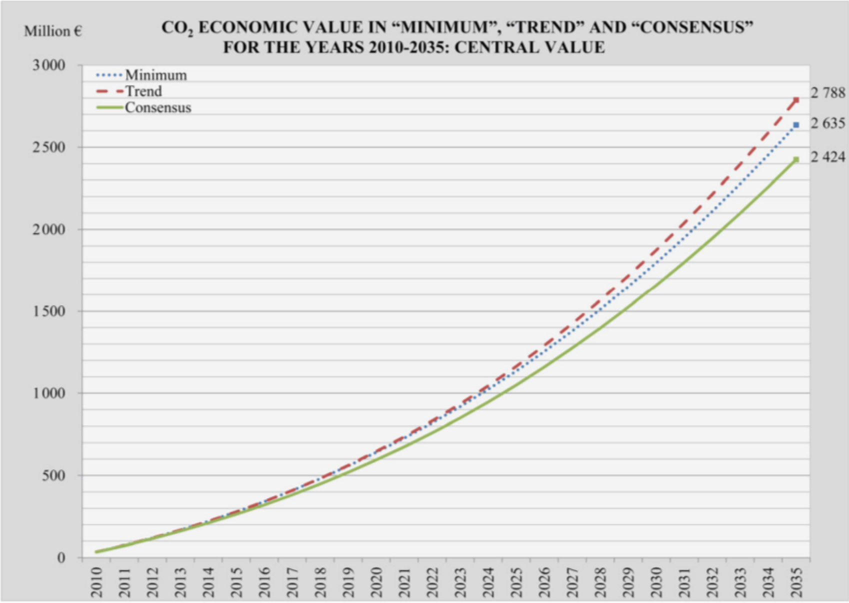

Figure 7. CO_2 economic value in 'minimum', 'trend' and 'consensus' (2010–2035): central value.

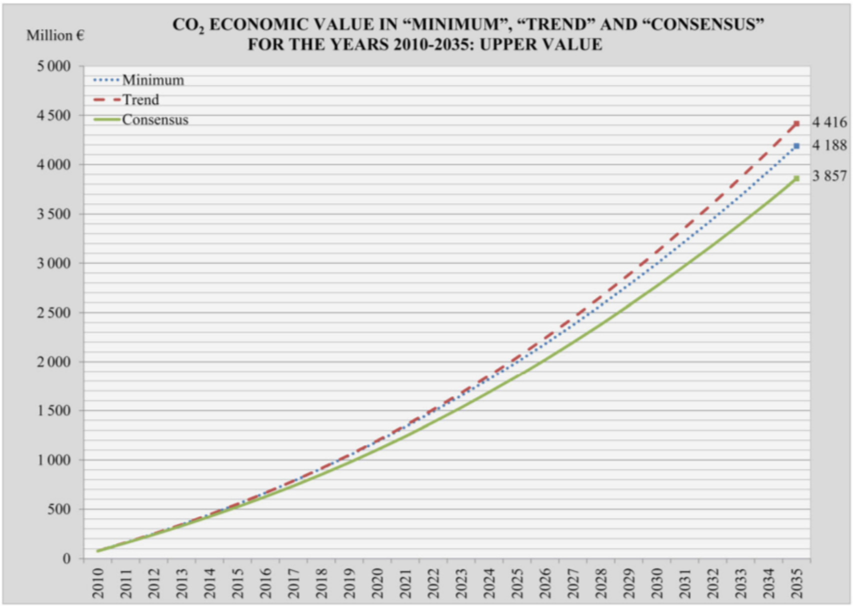

Figure 8. CO_2 economic value in 'minimum', 'trend' and 'consensus' (2010–2035): upper value.

Reiterating this formula for each of the three scenarios and for each of the three unitary prices gives rise to a 3×3 matrix, which provides the economic value of CO_2 emissions from 2010 to 2035 in different scenarios (Table VIII). As far as the lower unitary value is considered, minimum determines an economic impact of about €1275m. This value rises to €1341m in trend and lowers to €1175m for consensus (Figure 6).

The central unitary values determine a CO_2 economic cost of about €2635m in minimum, increasing to €2788m in trend and reducing to €2424m in consensus (Figure 7).

Finally, adopting the upper unitary value (Figure 8), the economic impact of CO_2 is quantified at €4188m when using the minimum scenario. The value rises to €4416m in trend, and lowers to €3857m in consensus.

Table IX. CO_2 economic values related to the emissions in different scenarios.

	Policies adopted	Emissions (2010–2035)	Emission difference	Economic value		Economic difference
Scenario		kt	kt	million EUR		million EUR
Minimum	Present transport policies extended to the year 2035. No BBT realisation	46 700	—	lower: central: upper:	1275 2635 4188	— — —
Trend	Continuation of the trend of the last decade, encouraging railway (realisation of BBT) and road traffic	51 100	+4400	lower: central: upper:	1341 2788 4416	+66 +153 +228
Consensus	Fulfilment of a sustainable transport policy, encouraging railway traffic (realisation of BBT) and discouraging road traffic	45 400	−1300	lower: central: upper:	1175 2424 3857	−100 −211 −331

BBT, Brenner Base Tunnel.

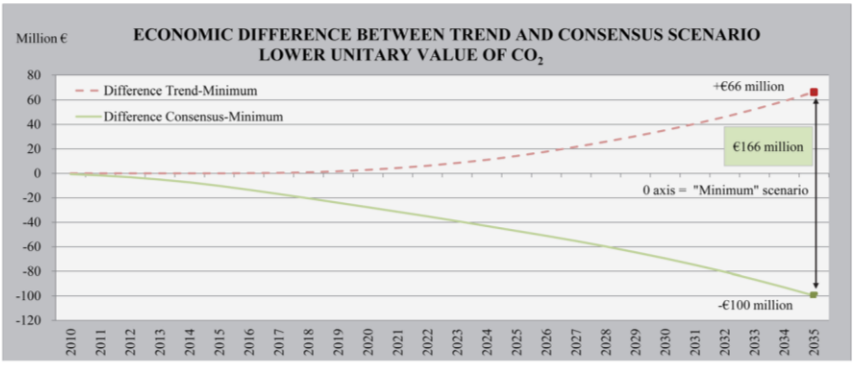

Figure 9. Economic difference between ‘trend’ and ‘consensus’: lower unitary value of CO_2.

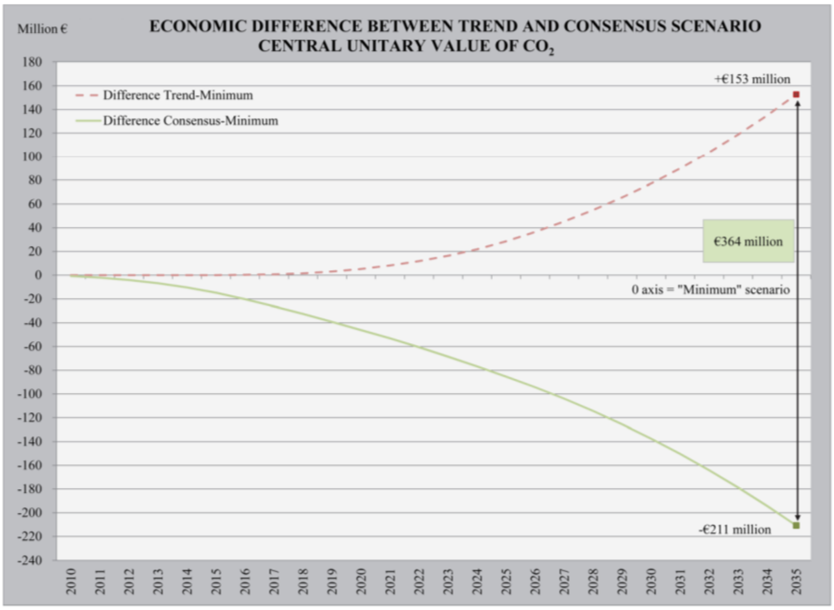

Figure 10. Economic difference between ‘trend’ and ‘consensus’: central unitary value of CO_2.

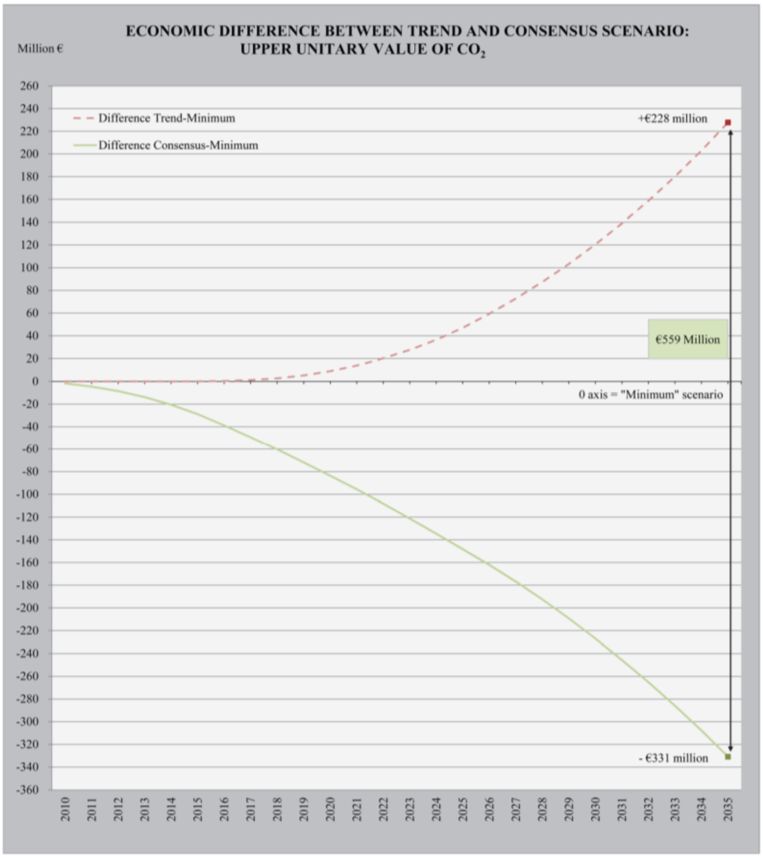

Figure 11. Economic difference between 'trend' and 'consensus': upper unitary value of CO_2.

3.4. *Discussion of the results*

The results shown in the previous section were as anticipated, according to the outcomes expressed in Nocera *et al.* [79]. It is important here to underline once more that minimum is a do-nothing scenario, in which the lowest number of measures undertaken in comparison with current conditions cannot carry over to the overall lowest amount of emissions and therefore of global costs. However, a policy aimed at transferring a consistent amount of demand into less polluting modes by internalising the external costs (consensus) shows a noticeable saving in terms of CO_2 emitted (respectively a reduction of about €100m, €211m or €331m if the lower, central or upper value is considered; Table IX). Conversely, a policy such as that expressed by trend causes a large increase in costs, because it encourages the growth of both railway and road travel demands, without providing a sustainable solution. Consequently, the CO_2 economic impact is also higher when compared with minimum (respectively an increase of about €66m, €153m or €228m, if the lower, central or upper value is considered; Table IX).

It follows that the difference between trend and consensus is respectively €166m, €364m, or €559m if the lower, central or upper value is considered (Figures 9, 10, and 11). These values are the range that quantifies the effectiveness of a policy, which favours rail and discourages road transport (consensus) compared with a policy simply based on the liberalisation of the market (trend). In other words, the only use of so-called 'pull-measures'[9] seems ineffective if not also supported by 'push measures'[10] in reducing CO_2 emission costs.

This finding is relevant, because on the one hand it confirms that a combination of push and pull measures provide optimal results in terms of CO_2 reduction [80]; on the other hand, it warns the community that the simple realisation of less polluting infrastructures cannot be enough. It follows that

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[9] Pull measures can be defined as measures implemented to discourage the use of road transport by improving the attractiveness of existing alternatives.

[10] Push measures can be defined as measures imposed on travellers and freight operators in order to influence individual decisions. They can be divided into financial instruments (e.g. taxes, charges and tolls) and technical and regulatory constraints (e.g. orders and bans).

the backing of a solid policy—here including local and national legislation, voluntary agreements, graduated vehicle taxes, fiscal measures and consumer information—is necessarily required if a lower cost of CO_2 emissions is to be achieved.

4. CONCLUSIONS

Some of the leading climate scientists claim that global GHG emissions need to be slashed below present levels if humans wish to avoid significant climate change. But such a drastic emission reduction is at odds with the world's growing energy needs.

Researchers do not agree about what the economic costs of climate change will be over the coming decades, as they are not a mere economic value, but a more complex parameter that tries to quantify the negative environmental consequences deriving from the rise in temperature levels. Such consequences are cumulative, and ever greater effects are expected from the progressive increase in CO_2 concentrations. It follows that future emissions cannot be monetised by simply adopting the current CO_2 market value and discounting it, unless a very short time horizon (i.e. with no substantial changes in CO_2 concentration) is considered.

This could be very critical within transport planning, when the feasibility assessment of an infrastructure deals with long-term forecasts (up to 20 years and over). Using these time horizons, avoidance cost and damage cost methodologies generally provide more robust results for economic CO_2 emission values. However, the unitary CO_2 value is not easy to determine by adopting these methods, because it includes several scientific and economic uncertainties, as well as ethical and political aspects, which should be clearly stated before the quantification of the value itself.

This paper proposes a framework of CO_2 prices up to 2035, adopting an avoidance cost evaluation for the medium term and damage cost assessment for the long term. Three values are given, according to different enforceable policies used to reduce CO_2 emissions: lower values may be adopted in conservative strategies, whereas upper values are preferred in more resolute approaches. Finally, central values are suitable in adopting long-term measures, according to the international agreements on CO_2 reduction. Based both on literature reviews previously undertaken and on political choices specifically foreseen for the transport sector, this approach has reduced the range of values from four orders of magnitude found in literature to two orders.

These values have then been adopted to evaluate the economic impact of CO_2 of a major infrastructure such as BBT up to 2035. The values calculated in Section 3 demonstrate that realising a new and less polluting infrastructure does not necessarily induce an overall reduction of the CO_2 emission costs. Indeed, when compared with the maintenance of the status quo, a sustainable policy that aims at the internalisation of external costs might bring about a saving of up to about €331m by 2035. On the other hand, a policy based simply on the liberalisation of the market would generate an increase in costs up to about €228m. It means that when hypothesising the realisation of the BBT, political transport decision-making could determine an economic saving for the community equal to about €559m, only considering CO_2 emissions.

More detailed studies should be carried out in order to limit the range further, to minimise the uncertainties and to define a more accurate economic value for CO_2. Nevertheless, with the caveat specified in Sections 2.3 and 3.4, the method presented here may be usefully adopted by the whole transport planning sector to determine further benefits and costs that early feasibility assessments might not take into account and can also be included in a more comprehensive assessment of the economic evaluation of all external impacts of an infrastructure through a multi-criteria evaluation [81]. For these reasons, we believe that this method constitutes a helpful tool for planners and decision-makers on the road to transport sustainability.

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APPENDIX A. THE ANALYTICAL DETERMINATION OF CO_2 ECONOMIC VALUES.

	Lower value							Central value		
Year	Starting values[§]	Unitary value of C[*]	Unitary value of CO_2[†]	$HICP_1$	Unitary value of CO_2	5% increase	Final values	Starting values[**]	$HICP_2$	Unitary value of CO_2
	£2005/tC	€2005/tC	€2005/tCO_2		€2010/tCO_2	€	€2010/tCO_2	‡		€2005/ tCO_2
	(1)	(2) = (1)* 1.4624245	(3) = (2)/ 3.664	(4)	(5) = (3)*(4)	(6)	(7) = (5)*(6)	(8)	(9)	(10) = (8)*(9)
2010	40.00	58.50	15.97	1.16	18.52	0.93	**19.45**	19.00	1.00	19.00
2011	41.00	59.96	16.36	1.16	18.98	0.95	**19.93**	20.90	1.00	20.90
2012	42.00	61.42	16.76	1.16	19.45	0.97	**20.42**	22.80	1.00	22.80
2013	43.00	62.88	17.16	1.16	19.91	1.00	**20.90**	24.70	1.00	24.70
2014	44.00	64.35	17.56	1.16	20.37	1.02	**21.39**	26.60	1.00	26.60
2015	45.00	65.81	17.96	1.16	20.83	1.04	**21.88**	28.50	1.00	28.50
2016	46.00	67.27	18.36	1.16	21.30	1.06	**22.36**	30.40	1.00	30.40
2017	47.00	68.73	18.76	1.16	21.76	1.09	**22.85**	32.30	1.00	32.30
2018	48.00	70.20	19.16	1.16	22.22	1.11	**23.33**	34.20	1.00	34.20
2019	49.00	71.66	19.56	1.16	22.69	1.13	**23.82**	36.10	1.00	36.10
2020	50.00	73.12	9.96	1.16	23.15	1.16	**24.31**	38.00	1.00	38.00
2021	51.50	75.31	20.56	1.16	23.84	1.19	**25.04**	40.70	0.96	39.07
2022	53.00	77.51	21.15	1.16	24.54	1.23	**25.77**	43.40	0.96	41.66
2023	54.50	79.70	21.75	1.16	25.23	1.26	**26.49**	46.10	0.96	44.26
2024	56.00	81.90	22.35	1.16	25.93	1.30	**27.22**	48.80	0.96	46.85
2025	57.50	84.09	22.95	1.16	26.62	1.33	**27.95**	51.50	0.96	49.44
2026	59.00	86.28	23.55	1.16	27.32	1.37	**28.68**	54.20	0.96	52.03
2027	60.50	88.48	24.15	1.16	28.01	1.40	**29.41**	56.90	0.96	54.62
2028	62.00	90.67	24.75	1.16	28.71	1.44	**30.14**	59.60	0.96	57.22
2029	63.50	92.86	25.34	1.16	29.40	1.47	**30.87**	62.30	0.96	59.81
2030	65.00	95.06	25.94	1.16	30.09	1.50	**31.60**	65.00	0.96	62.40
2031	67.50	98.71	26.94	1.16	31.25	1.56	**32.81**	67.75	0.96	65.04
2032	70.00	102.37	27.94	1.16	32.41	1.62	**34.03**	70.50	0.96	67.68
2033	72.50	106.03	28.94	1.16	33.57	1.68	**35.25**	73.25	0.96	70.32
2034	75.00	109.68	29.93	1.16	34.72	1.74	**36.46**	76.00	0.96	72.96
2035	77.50	113.34	30.93	1.16	35.88	1.79	**37.68**	78.75	0.96	75.60

$HICP_1$, Harmonised indices of consumer prices adjusted to 2010 values [42]; $HICP_2$, Harmonised indices of consumer prices adjusted to 2005 values [42]. Bold defines the values that have been considered in the paper to determine the economic unitary values of CO_2 emissions.

*1 £ = 1.4624245 € [31]

[†] 1 tC = 3.664 tCO_2 [32]

[‡] €2005/tCO_2 for years 2010–2020; €2007/tCO_2 for years 2021–2035

[§] Watkiss *et al.* [24]

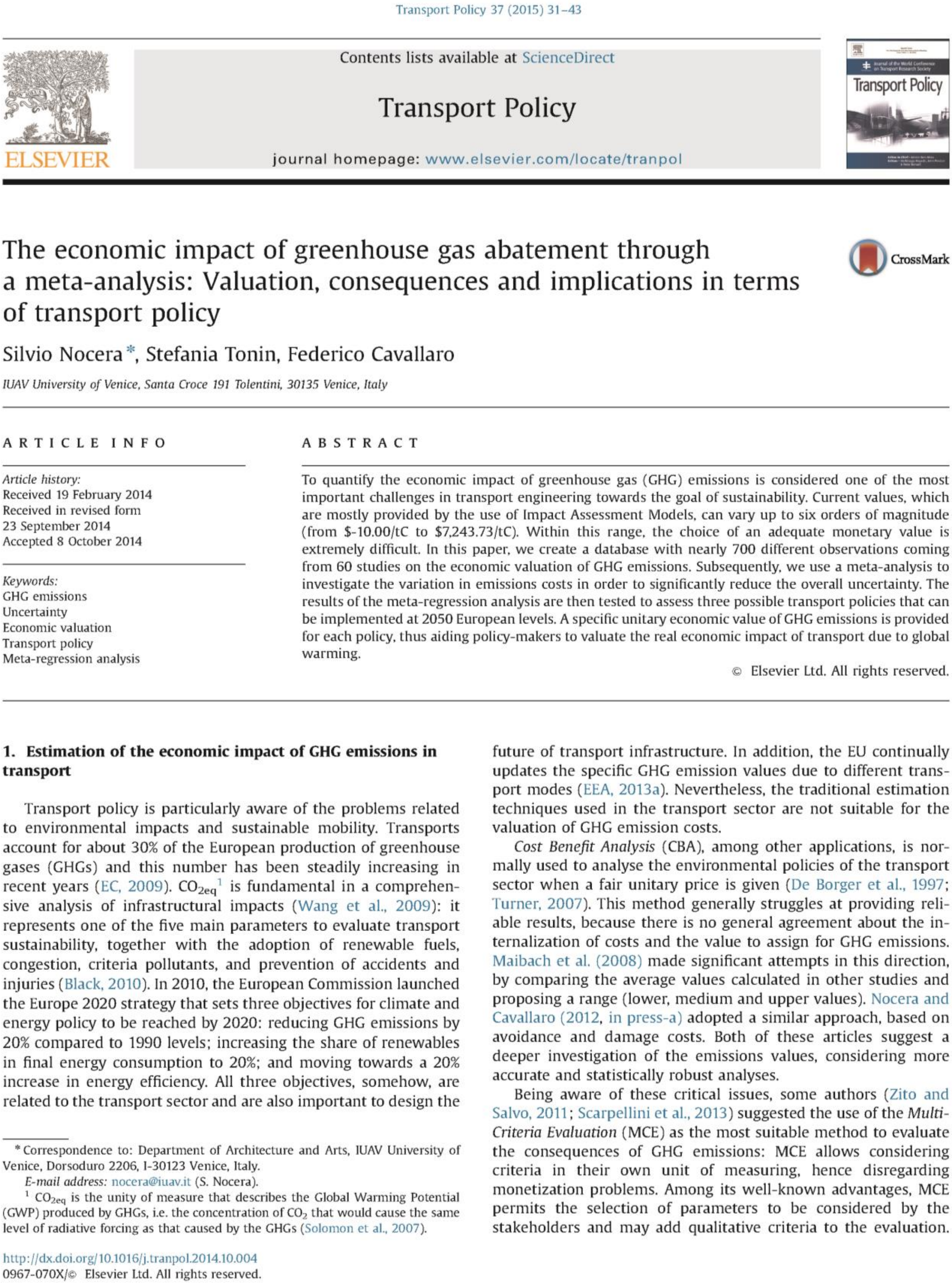
**ExternE [33] for the years 2010–2020; CEC [51] for the years 2020–2035

[††] Maibach *et al.* [73]

APPENDIX A. Continued.

Central value				Upper value						
HICP$_1$	Unitary value of CO$_2$	5% increase	Final values	Starting values††	HICP$_2$	Unitary value of CO$_2$	HICP$_1$	Unitary value of CO$_2$	5% increase	Final values
	€$_{2010}$/tCO$_2$	€	€$_{2010}$/tCO$_2$	€$_{2008}$/tCO$_2$		€$_{2005}$/tCO$_2$		€$_{2010}$/tCO$_2$	€	€$_{2010}$/tCO$_2$
(11)	(12) = (10)* (11)	(13)	(14) = (12)* (13)	(15)	(16)	(17) = (15)* (16)	(18)	(19) = (17)* (18)	(20)	(21) = (19)* (20)
1.16	22.04	1.10	**23.14**	45.00	0.92	41.40	1.16	48.02	2.40	**50.43**
1.16	24.24	1.21	**25.46**	47.50	0.92	43.70	1.16	50.69	2.53	**53.23**
1.16	26.45	1.32	**27.77**	50.00	0.92	46.00	1.16	53.36	2.67	**56.03**
1.16	28.65	1.43	**30.08**	52.50	0.92	48.30	1.16	56.03	2.80	**58.83**
1.16	30.86	1.54	**32.40**	55.00	0.92	50.60	1.16	58.70	2.93	**61.63**
1.16	33.06	1.65	**34.71**	57.50	0.92	52.90	1.16	61.36	3.07	**64.43**
1.16	35.26	1.76	**37.03**	60.00	0.92	55.20	1.16	64.03	3.20	**67.23**
1.16	37.47	1.87	**39.34**	62.50	0.92	57.50	1.16	66.70	3.34	**70.04**
1.16	39.67	1.98	**41.66**	65.00	0.92	59.80	1.16	69.37	3.47	**72.84**
1.16	41.88	2.09	**43.97**	67.50	0.92	62.10	1.16	72.04	3.60	**75.64**
1.16	44.08	2.20	**46.28**	70.00	0.92	64.40	1.16	74.70	3.74	**78.44**
1.16	45.32	2.27	**47.59**	73.00	0.92	67.16	1.16	77.91	3.90	**81.80**
1.16	48.33	2.42	**50.75**	76.00	0.92	69.92	1.16	81.11	4.06	**85.16**
1.16	51.34	2.57	**53.90**	79.00	0.92	72.68	1.16	84.31	4.22	**88.52**
1.16	54.34	2.72	**57.06**	82.00	0.92	75.44	1.16	87.51	4.38	**91.89**
1.16	57.35	2.87	**60.22**	85.00	0.92	78.20	1.16	90.71	4.54	**95.25**
1.16	60.36	3.02	**63.37**	88.00	0.92	80.96	1.16	93.91	4.70	**98.61**
1.16	63.36	3.17	**66.53**	91.00	0.92	83.72	1.16	97.12	4.86	**101.97**
1.16	66.37	3.32	**69.69**	94.00	0.92	86.48	1.16	100.32	5.02	**105.33**
1.16	69.38	3.47	**72.85**	97.00	0.92	89.24	1.16	103.52	5.18	**108.69**
1.16	72.38	3.62	**76.00**	100.00	0.92	92.00	1.16	106.72	5.34	**112.06**
1.16	75.45	3.77	**79.22**	103.50	0.92	95.22	1.16	110.46	5.52	**115.98**
1.16	78.51	3.93	**82.43**	104.67	0.92	96.29	1.16	111.70	5.59	**117.29**
1.16	81.57	4.08	**85.65**	108.17	0.92	99.51	1.16	115.44	5.77	**121.21**
1.16	84.63	4.23	**88.87**	111.67	0.92	102.73	1.16	119.17	5.96	**125.13**
1.16	87.70	4.38	**92.08**	115.17	0.92	105.95	1.16	122.91	6.15	**129.05**

3.2.2. The Economic Impact of Greenhouse Gas Abatement through a Meta-Analysis: Valuation, Consequences and Implications in terms of Transport Policy



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The economic impact of greenhouse gas abatement through a meta-analysis: Valuation, consequences and implications in terms of transport policy

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ABSTRACT

To quantify the economic impact of greenhouse gas (GHG) emissions is considered one of the most important challenges in transport engineering towards the goal of sustainability. Current values, which are mostly provided by the use of Impact Assessment Models, can vary up to six orders of magnitude (from \$-10.00/tC to \$7,243.73/tC). Within this range, the choice of an adequate monetary value is extremely difficult. In this paper, we create a database with nearly 700 different observations coming from 60 studies on the economic valuation of GHG emissions. Subsequently, we use a meta-analysis to investigate the variation in emissions costs in order to significantly reduce the overall uncertainty. The results of the meta-regression analysis are then tested to assess three possible transport policies that can be implemented at 2050 European levels. A specific unitary economic value of GHG emissions is provided for each policy, thus aiding policy-makers to valuate the real economic impact of transport due to global warming.

1. Estimation of the economic impact of GHG emissions in transport

Transport policy is particularly aware of the problems related to environmental impacts and sustainable mobility. Transports account for about 30% of the European production of greenhouse gases (GHGs) and this number has been steadily increasing in recent years (EC, 2009). CO_{2eq}[1] is fundamental in a comprehensive analysis of infrastructural impacts (Wang et al., 2009): it represents one of the five main parameters to evaluate transport sustainability, together with the adoption of renewable fuels, congestion, criteria pollutants, and prevention of accidents and injuries (Black, 2010). In 2010, the European Commission launched the Europe 2020 strategy that sets three objectives for climate and energy policy to be reached by 2020: reducing GHG emissions by 20% compared to 1990 levels; increasing the share of renewables in final energy consumption to 20%; and moving towards a 20% increase in energy efficiency. All three objectives, somehow, are related to the transport sector and are also important to design the future of transport infrastructure. In addition, the EU continually updates the specific GHG emission values due to different transport modes (EEA, 2013a). Nevertheless, the traditional estimation techniques used in the transport sector are not suitable for the valuation of GHG emission costs.

Cost Benefit Analysis (CBA), among other applications, is normally used to analyse the environmental policies of the transport sector when a fair unitary price is given (De Borger et al., 1997; Turner, 2007). This method generally struggles at providing reliable results, because there is no general agreement about the internalization of costs and the value to assign for GHG emissions. Maibach et al. (2008) made significant attempts in this direction, by comparing the average values calculated in other studies and proposing a range (lower, medium and upper values). Nocera and Cavallaro (2012, in press-a) adopted a similar approach, based on avoidance and damage costs. Both of these articles suggest a deeper investigation of the emissions values, considering more accurate and statistically robust analyses.

Being aware of these critical issues, some authors (Zito and Salvo, 2011; Scarpellini et al., 2013) suggested the use of the *Multi-Criteria Evaluation* (MCE) as the most suitable method to evaluate the consequences of GHG emissions: MCE allows considering criteria in their own unit of measuring, hence disregarding monetization problems. Among its well-known advantages, MCE permits the selection of parameters to be considered by the stakeholders and may add qualitative criteria to the evaluation.

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[1] CO_{2eq} is the unity of measure that describes the Global Warming Potential (GWP) produced by GHGs, i.e. the concentration of CO_2 that would cause the same level of radiative forcing as that caused by the GHGs (Solomon et al., 2007).

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0967-070X/

Table 1
Classification of the IAMs according to their technical characteristics. *Source*: Ortiz and Markandya (2009).

Classification of the integrated impact assessment models according to their technical characteristics

Type	Acronym	Characteristics	IAM
Fully integrated impact assessment models	FIAM	Models that include an economic growth/dynamics (energy sector comprised), damage and climate modules.	DICE; ENTICE; RICE; FEEM-RICE; WITCH; MERGE; ICAM; MIND; DEMETER
Non-computable general equilibrium models	NCGEM	Models that include only the climate and damage modules. Occasionally, they consist of an energy module as well but without an economic optimization procedure and adopting scenarios provided by third parties.	FUND; PAGE; E3MG; DNE21+; GET
Computable general equilibrium models	CGEM	Models that focus the economic optimization procedure on a greater number of sectors but do not include a climate module.	AIM; EPPA; Imaclim-R; GREEN; ICES; GTAP-E

This allows for the measurement of intangible effects as well (Beria et al., 2012). CO_{2eq} can be included in environmental analyses with other impacts, such as visual ones and noise emissions, thus providing a more comprehensive analysis (Janic, 2003; Tudela et al., 2006). In this sense, MCE represents a holistic view for the evaluation of the external economic effects. However, it may be affected by subjective biasing, such as the choice of criteria (subjectivity, arbitrariness), the weights to be assigned and the risk of double counting (Browne and Ryan, 2011). Furthermore, even within the permissive view that the quantification of emissions leads to a plausible result (a hypothesis that can be stated with some difficulty, especially in the long-term-Nocera et al., 2012), the economic impact on the community still cannot be provided. For these reasons, this method can be considered a heuristic solution, which has not yet solved the issue with enough precision.

A similar argument can be extended to *Cost Effectiveness Analysis* (CEA). This method compares the costs of alternative approaches in producing the same (or similar) results. The outputs are expressed as the optimum abatement price of emissions, i.e. the intersection between the curves of marginal avoidance cost and marginal social damage. The result is a ranking of different solutions, which allows policy-makers an evidence-based comparative analysis. However, this method is limited only to the GHG emissions and cannot be extended to the parameters typically included in a CBA (accessibility, health impacts, security, etc.,) or in a MCE. This aspect makes the analysis restricted. Additionally, it presents some endemic problems. Kampman et al. (2006) suggested that comparisons are difficult if different assumptions and methodologies are considered, including timelines, locations, discount rates, costs and scales. Kok et al. (2011) confirmed this assumption, highlighting that differences up to $\$400/tCO_{2eq}$ can be found according to the different scopes, costs, abatement costing approaches, type of measures, impacts, key assumptions and calculations.

An agreement about the quantification of GHG economic impacts has yet to be found, even if the CBA technique appears to be the more robust approach when a reliable unitary price is provided. The Integrated Impact Assessment Models (IAMs) could be useful for this purpose, because they try to link the unitary value with the physical changes caused by GHG emissions. However, with these models, current estimations can range up to six orders of magnitude (Tol, 2013; Nocera and Tonin, 2014). This range is too vast and can generate misleading results in transport planning and policy to the detriment of the community. In this context, we have been intrigued by the economical valuation of the effects of GHG emissions.

This paper presents the results of a meta-analysis (MA) to statistically measure the systematic relationships among the different GHG emissions reported in literature and the main attributes of the studies that generated the estimates. Section 2 describes, from a theoretical perspective, the IAMs and their main uncertainties. Section 3 introduces a database with a list of the most important studies and variables considered. A meta-analysis regression is then executed, which allows for a reduction in the uncertainty in GHG unitary price. Based on these results, Section 4 introduces a case study to valuate the economic impact of different transport policies in Europe until 2050. Some final notes, related to transport planning and GHG emissions costs, end the contribution.

2. Uncertainty in forecasting GHG emissions and their cost

As stated in the introduction, the assessment of the economic impacts derived from GHG emissions is ordinarily based on the use of IAMs. These models are used as support for the formulation of global and regional policies. Several IAMs, adopting very different premises and parameters, have been developed in the last twenty years. One of the most rigorous attempts to classify IAMs has been provided by Stanton et al. (2008), which identified five main groups: welfare optimization models, general equilibrium models, partial equilibrium models, simulation models and cost minimization models. However, the adoption of this subdivision caused some overlaps, as quoted by the authors themselves. Therefore, Ortiz and Markandya (2009) proposed a different and less ambiguous subdivision. The classification is based on a distinction between three sub-modules: economic growth/dynamics, energy and damage. Fully integrated IAMs (FIAMs) include all three sub-modules. Non-Computable General Equilibrium models (NCGEMs) usually include the climate and damage modules. Only occasionally do they include a simplified energy module, which lacks an economic optimization procedure and adopts scenarios provided by third parties. Last, Computable General Equilibrium models (CGEMs) focus the economic optimization procedure on a greater number of sectors but do not include a climate module (Table 1).

The range of six orders of magnitude determined by IAMs is too vast and does not provide a reliable economic value of global warming. This leads to doubts about if IAMs are helpful for such an aim (Pyndick, 2013). The main cause of this range derives from the adoption of different parameters and the choice of input values, which concur to determine a high degree of uncertainty[2] So far, the literature has not developed this aspect in detail; the uncertainty has been treated only as a marginal topic or as an additional physical variable (Funtowicz and Ravetz, 1993; Kuik et al., 2008). A deeper analysis of this theme is presented in this section. According to Natke and Ben-Haim (1996), we can distinguish two main groups of uncertainties, called respectively "objective" and "subjective". Before describing them, it must be noted that several scientific and economic aspects affect these groups

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[2] For a comprehensive approach to the uncertainty from an epistemological perspective, see Van Asselt and Rotmans, 2002.

Table 2
Objective uncertainties in determining GHG emission price. *Source*: Clarkson and Deyes (2002), elaborated.

Objective uncertainties in determining GHG emission price

Name	Description	Nature
Current level of emissions	This includes the technological difficulties in determining the current emissions of CO_{2eq} in the atmosphere caused by dynamic sources, due to their non-static and inconstant nature. Mostly valid for non CO_2 gasses.	Scientific
Common unity of measure	The adoption of Global Warming Potential (GWP) is an attempt to convert all GHG emissions into a common measure. However, there is a debate about the conversion factors, because the impact of each gas is not univocally accepted.	Scientific
Forecasting methodology	Future travel demand and modal choice are methodological issues that cannot be easily solved. The use of different scenarios can be adopted. A scenario is not a forecast of the future condition but a "representation of visions/images of the future and courses of development organized in a systematic and consistent way" (EC, 2008). A scenario is based on given hypotheses, which are crossed with the initial situation, thus leading to the future sequences of events that the hypotheses imply. Many parallel scenarios are developable, in which the fulfillment of the different hypotheses are considered. The concept of dynamicity is strictly related, considering scenarios not as a static snapshot of future conditions but as logical consequences of events. This method does not give solutions but only future representations organized in a consistent way.	Scientific
Relation between emissions and concentration	There is no link between GHG emissions and concentrations in the atmosphere, as some emissions are absorbed by the oceans and some are sequestered by vegetation.	Scientific
Life-time in the atmosphere	Difficult to predict, especially in dynamic conditions and in constantly increasing values. This aspect refers mostly to other GHGs, rather than CO_2 (Jensen and Hvidt Thelle, 2001).	Scientific
Technical development of the software	This includes the choice of the most suitable algorithms and the accumulation of errors in the different computational phases (Beck, 1987).	Scientific

(Clarkson and Deyes, 2002). The former make the quantification of the future emissions complex, the latter avoid the attribution of a fair unitary price to the unitary emissions.

The aspects of "objective uncertainties" are not directly controlled by modelers, because they are endemically presented in each model and cannot be removed. These uncertainties have a relationship with the limited knowledge of human beings (epistemological approach). They include current level of emissions, forecasting methodology, relation between emissions and concentration, lifetime in the atmosphere and technical development of software (Table 2). These kinds of uncertainty cannot be eliminated because they are innate in human knowledge. Thus, they will not be considered in our analysis.

The parameters of "subjective" uncertainties can be controlled by the modelers and may contribute to understanding the difference in unitary prices. Among them, we include future level of emissions, concentrations and temperatures, climate impacts resulting from an increased $CO2_{eq}$ concentration, physical impacts associated with climate change, economic damage, equity weight, discount rate, adaptation and mitigation (Table 3). These uncertainties are due to different aspects: the impossibility to determine the consequences of nature and its effects, the different attitude of humans towards environmental problems, the development of new technologies, etc. The modelers chose the parameters and the most suitable scenarios according to their perspective. Using this framework, not only are the scientific and technological assumptions fundamental but also the ethical and political ones as well. Indeed, the national and political choices can largely influence the decision through the choice of the equity weight and discount rate. For example, developing countries consider themselves as relatively new GHG emitting nations. Hence, they would expect to pay a lower price in comparison with developed countries.

The final choice of the unitary carbon value is affected by a vast degree of uncertainty, caused by the co-presence and overlapping of the single uncertainties previously mentioned. In determining the final value, the literature (Klein et al., 2007; Stanton et al., 2008; Tol, 2009, 2013) highlights the importance of these parameters: the model type, the pure rate of time preference (prtp), the projection of future damages, the sectors included in the damage function, the geographic scale of different impacts, the increase in temperature and the equity across time and space and an approach based on adaptation or mitigation. However, also other aspects have to be taken into account. In the next section, we analyse the most relevant causes through a statistical approach, trying to reduce the vast range currently available in literature and provide more reliable values for unitary $CO2_{eq}$ emissions.

3. A statistical approach to understand the cause of uncertainty

According to the importance given by IPCC to GHG emissions, a significant number of studies have tried to calculate the economic damage of climate change in the last 25 years. This attempt has been made at global level, as the European, American and Australian analyses provided by Maibach et al. (2008), NRC (2010) and Litman (2011) illustrate. Furthermore, some authors provide useful meta-analyses about marginal abatement costs (Fischer and Morgenstern, 2003; Kuik et al., 2008), emphasizing the need to better explain the cost differences according to the choice of the parameters. To this aim, Tol (2008, 2013) made available several values derived from studies pertaining to the cost of carbon emissions. The single studies usually include the authors' names, publication year, currency used, years of emission and a set of other variables. These were created by the author in order to take other physical and economic effects into account. However, Tol's work has an essential point that makes the statistical analysis non-exhaustive. The database includes only studies carried out with the PAGE, FUND and DICE models, without considering others. The statistical analysis is limited to specific IAMs and the values provided are only partially representative. Ackerman (2009) criticizes this aspect of the first version of Tol's database (2008); in the latest version (Tol, 2013), the same critical issue has not been solved.

For these reasons, we have created a new and more comprehensive database. It is based on a wider number of studies (60 authors and 699 values, Appendix A), IAMs (mostly including PAGE, FUND and DICE, but also Intera, Open Framework, RICE, UDEB, MAGICC, SCCRAM, SGM, WIAGEM, MiniCAM, MARKAL, MERGE, CETA, MARIA, IAM, AMIGA, COMBAT, EPPA, EDGE, GEMINI-E3, GRAPE, GTEM, and GIM[3]) and a greater number of variables.

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[3] For further details about these models, interest readers may refer to Ortiz and Markandya (2009) and to Füssel (2010).

Table 3
Subjective uncertainties in determining GHG emission price.

Subjective uncertainties in determining GHG emission price

Name	Description	Uncertainty
Future levels of emissions	This value is strictly connected to the future socio-economic conditions, as well as the technological developments. The increase in population and economic growth determines the increase of emissions; on the other hand, technological progress allows for a reduction in specific emissions.	Scientific
Future concentrations and temperatures	Respectively expressed in parts per million by volume (ppmv) and in degrees (°C), these values are the results of different forecasts and different hypotheses, as described in point 2 of objective uncertainties. The adoption of different scenarios (generally defined by IPCC and EMF and developed by the modelers) also determines different concentrations and temperatures.	Scientific
Climate impacts resulting from an increased concentration of greenhouse gases	The increase of GHG concentration in the atmosphere causes climate impacts that are not univocally shared. Potentially, they include eight main groups (Watkiss et al., 2005): sea level rise, energy use, agricultural impacts, water supply, health impacts, ecosystems and biodiversity, extreme weather events and major events. Each IAM can consider only a portion of these impacts.	Scientific
Identifying the physical impacts associated with climate change	The consequences that climate change produces on a given region in terms of variations in the landscape. The risk here lies mainly in making allowances for, or over – or underestimating certain aspects, thus not including them in the final value.	Scientific
Economic damage	IAMs are based on the assumption that climate change will produce economic damage, which is a function of the temperature variation raised by a coefficient. The choice of this coefficient (usually quadratic) noticeably affects the value of the damage: in PAGE, for example, passing from a quadratic function to a cubic one determine a change of about 23% (Dietz and Hope, 2007).	Economic
Equity weight	The emissions of GHGs do not have the same economic impact on every country. The consequences are strictly related to the national GDP and national willingness to pay to avoid the environmental, economic and social consequences. The adoption of the equity weight (Fankhauser et al., 1997) is an attempt to include this issue within the final value of GHG emissions.	Economic
Discount rate	For environmental studies, this value coincides with the Social Rate of Time Preference. It can be defined as "the rate at which individuals discount future consumption over present consumption, on the assumption of an unchanging level of consumption per capita over time" summed with "an additional element, if per capita consumption is expected to grow over time, reflecting the fact that these circumstances imply future consumption will be plentiful relative to the current position and thus have lower marginal utility" (HM Treasury, 2003).	Economic
Adaptation	Adaptation is a variable of the estimate function, which describes the efforts required to handle the consequences of climate change. It concerns complex behavioral, technological, and institutional adjustments at all levels of society. Some models (e.g., DICE) do not contain structural components that represent adaptation explicitly, whereas other models (e.g., FUND) adopt it as an estimate parameter. To this aim, various approaches are used (e.g., spatial analog, microeconomic modeling; Tol, 2005).	Economic

Each study listed in the database has been divided into five main parts, which include:

1) General information about the study and economic value of GHG emissions[4]: the name and year of the study, its nature and the GHG economic value in 2010.
2) Description of the scenario considered in the analysis: type of model adopted, reference scenario, characteristics in terms of temperature increase, concentration, temporal horizon and geographic scale.
3) Valuation of the economic impacts: analysis in terms of GDP variation, discount rate, equity weight, damage function and other economic parameters that influence the final price.
4) Analysis of the physical impacts considered: according to Watkiss et al. (2005), the unitary value of GHG emissions is determined by the number and type of categories taken into account by the author. These categories include: sea level rise, energy use, agricultural impact, water supply, health impact, ecosystem and biodiversity, extreme weather events and major events/large scale discontinuity.
5) Specifications: other relevant aspects not included in the previous points.

Table 4 denotes the list of variables included in our meta-analysis of the economic impacts of climate change, showing the mean and standard deviation for each. Most of the related studies have been published between 2004 and 2012. The average economic value is \$276.49/tC (std. dev. 668.78). The range, expressed in 2010 US dollars, goes from \$-10.00/tC to \$7,243.73/tC. The high standard deviation means that there is high variability in the economic values of climate change, and that these values are spread out over a large range (Table 5). The rare negative values mean that climate change can initially have positive impacts. Tol (2008) asserts that this is partially explained by the fact that "*the global economy is concentrated in the temperate zone, where a bit of warming may well be welcomed because of reductions in heating costs and cold-related health problems*".

The meta-analytic regression model is given in Formula 1:

$$\ln(\cos t2010) = a + bX_i + u_i \quad (1)$$

The dependent variable, ln(cost2010) in the meta-regression equation, is the vector of the cost emission values in 2010 US dollars. The subscript i assumes values from 1 to 699 (number of observations), a is the constant term, b are the coefficients of the vector of explanatory variables X and u is a vector of residuals. We express the equation in the form of a natural log to account for the right skewedness of the different economic impacts of climate change. This implies that undesirable attributes are more likely than desirable ones (Nocera and Tonin, 2014). Also, the log transformation allows us to interpret the coefficients of the regression model easily, as a one percent change in the independent variable's value leads to a $b \times 100\%$ change in the dependent one.

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[4] The unitary price can be expressed either as $\$/tCO_{2eq}$ or as \$/tC. In the statistical analysis provided in Section 3, we refer to the latter unity of measure, because it is more frequently used in studies. The conversion can be made by adopting the relation: 1 tC = 3.664 x 1 tCO_{2eq} (Metz, 2001).

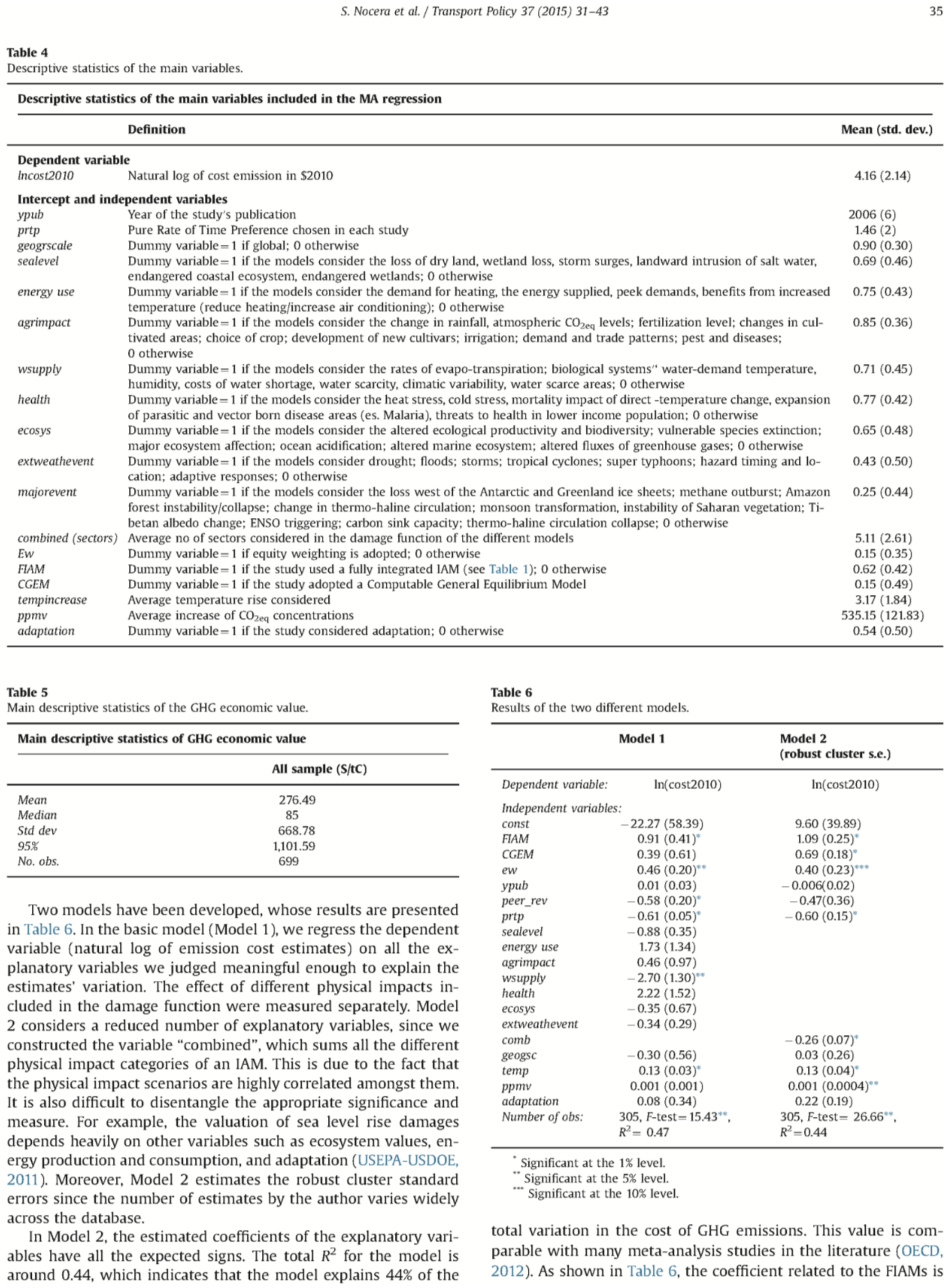

Table 4
Descriptive statistics of the main variables.

Descriptive statistics of the main variables included in the MA regression		
	Definition	**Mean (std. dev.)**
Dependent variable		
lncost2010	Natural log of cost emission in \$2010	4.16 (2.14)
Intercept and independent variables		
ypub	Year of the study's publication	2006 (6)
prtp	Pure Rate of Time Preference chosen in each study	1.46 (2)
geogrscale	Dummy variable = 1 if global; 0 otherwise	0.90 (0.30)
sealevel	Dummy variable = 1 if the models consider the loss of dry land, wetland loss, storm surges, landward intrusion of salt water, endangered coastal ecosystem, endangered wetlands; 0 otherwise	0.69 (0.46)
energy use	Dummy variable = 1 if the models consider the demand for heating, the energy supplied, peek demands, benefits from increased temperature (reduce heating/increase air conditioning); 0 otherwise	0.75 (0.43)
agrimpact	Dummy variable = 1 if the models consider the change in rainfall, atmospheric CO$_{2eq}$ levels; fertilization level; changes in cultivated areas; choice of crop; development of new cultivars; irrigation; demand and trade patterns; pest and diseases; 0 otherwise	0.85 (0.36)
wsupply	Dummy variable = 1 if the models consider the rates of evapo-transpiration; biological systems" water-demand temperature, humidity, costs of water shortage, water scarcity, climatic variability, water scarce areas; 0 otherwise	0.71 (0.45)
health	Dummy variable = 1 if the models consider the heat stress, cold stress, mortality impact of direct -temperature change, expansion of parasitic and vector born disease areas (es. Malaria), threats to health in lower income population; 0 otherwise	0.77 (0.42)
ecosys	Dummy variable = 1 if the models consider the altered ecological productivity and biodiversity; vulnerable species extinction; major ecosystem affection; ocean acidification; altered marine ecosystem; altered fluxes of greenhouse gases; 0 otherwise	0.65 (0.48)
extweathevent	Dummy variable = 1 if the models consider drought; floods; storms; tropical cyclones; super typhoons; hazard timing and location; adaptive responses; 0 otherwise	0.43 (0.50)
majorevent	Dummy variable = 1 if the models consider the loss west of the Antarctic and Greenland ice sheets; methane outburst; Amazon forest instability/collapse; change in thermo-haline circulation; monsoon transformation, instability of Saharan vegetation; Tibetan albedo change; ENSO triggering; carbon sink capacity; thermo-haline circulation collapse; 0 otherwise	0.25 (0.44)
combined (sectors)	Average no of sectors considered in the damage function of the different models	5.11 (2.61)
Ew	Dummy variable = 1 if equity weighting is adopted; 0 otherwise	0.15 (0.35)
FIAM	Dummy variable = 1 if the study used a fully integrated IAM (see Table 1); 0 otherwise	0.62 (0.42)
CGEM	Dummy variable = 1 if the study adopted a Computable General Equilibrium Model	0.15 (0.49)
tempincrease	Average temperature rise considered	3.17 (1.84)
ppmv	Average increase of CO$_{2eq}$ concentrations	535.15 (121.83)
adaptation	Dummy variable = 1 if the study considered adaptation; 0 otherwise	0.54 (0.50)

Table 5
Main descriptive statistics of the GHG economic value.

Main descriptive statistics of GHG economic value	
	All sample (\$/tC)
Mean	276.49
Median	85
Std dev	668.78
95%	1,101.59
No. obs.	699

Table 6
Results of the two different models.

	Model 1	**Model 2 (robust cluster s.e.)**
Dependent variable:	ln(cost2010)	ln(cost2010)
Independent variables:		
const	−22.27 (58.39)	9.60 (39.89)
FIAM	0.91 (0.41)*	1.09 (0.25)*
CGEM	0.39 (0.61)	0.69 (0.18)*
ew	0.46 (0.20)**	0.40 (0.23)***
ypub	0.01 (0.03)	−0.006(0.02)
peer_rev	−0.58 (0.20)*	−0.47(0.36)
prtp	−0.61 (0.05)*	−0.60 (0.15)*
sealevel	−0.88 (0.35)	
energy use	1.73 (1.34)	
agrimpact	0.46 (0.97)	
wsupply	−2.70 (1.30)**	
health	2.22 (1.52)	
ecosys	−0.35 (0.67)	
extweathevent	−0.34 (0.29)	
comb		−0.26 (0.07)*
geogsc	−0.30 (0.56)	0.03 (0.26)
temp	0.13 (0.03)*	0.13 (0.04)*
ppmv	0.001 (0.001)	0.001 (0.0004)**
adaptation	0.08 (0.34)	0.22 (0.19)
Number of obs:	305, *F*-test = 15.43**, R^2 = 0.47	305, *F*-test = 26.66**, R^2 = 0.44

* Significant at the 1% level.
** Significant at the 5% level.
*** Significant at the 10% level.

Two models have been developed, whose results are presented in Table 6. In the basic model (Model 1), we regress the dependent variable (natural log of emission cost estimates) on all the explanatory variables we judged meaningful enough to explain the estimates' variation. The effect of different physical impacts included in the damage function were measured separately. Model 2 considers a reduced number of explanatory variables, since we constructed the variable "combined", which sums all the different physical impact categories of an IAM. This is due to the fact that the physical impact scenarios are highly correlated amongst them. It is also difficult to disentangle the appropriate significance and measure. For example, the valuation of sea level rise damages depends heavily on other variables such as ecosystem values, energy production and consumption, and adaptation (USEPA-USDOE, 2011). Moreover, Model 2 estimates the robust cluster standard errors since the number of estimates by the author varies widely across the database.

In Model 2, the estimated coefficients of the explanatory variables have all the expected signs. The total R^2 for the model is around 0.44, which indicates that the model explains 44% of the total variation in the cost of GHG emissions. This value is comparable with many meta-analysis studies in the literature (OECD, 2012). As shown in Table 6, the coefficient related to the FIAMs is positive and statistically significant at the 1% level. This indicates that this type of model has a positive relationship with the economic effect of climate change. The same holds true for the CGE model type when adopting robust cluster standard errors.

According to the results of Model 2, more recent publications reduce the value of emission costs, albeit this is not statistically significant at the standard level. Similarly, peer-reviewed studies have a negative and statistically significant effect, indicating the economic impact of climate change tends to be lower. On the contrary, the value for climate change is predicted to increase when the practice of weighting impacts in different regions is applied. Increasing the number of sectors included in the IAMs results in lower values for climate change impacts. This result is not unexpected given the different strategies and policies implied by using one or more physical impacts modules. They produce costs and benefits of climate change protection that can have differing values in the sector considered.

The average global temperature increase and the concentration of CO_{2eq} denoted by year of analysis are significant and have the expected sign. Increasing temperature and concentration of CO_{2eq} will increase the economic impacts of climate change. For example, in Model 2, the increase in temperature by one degree, all else held constant, increases the average cost of GHG emissions by 13%. Correspondingly, an increase of 100 points in ppmv will raise the average cost of GHG emissions by 10%.

As expected, the meta-analysis finds that the cost of GHG emissions decreases with the pure rate of time preference. Holding all else constant, a one percentage-point increase in the pure rate of time preference implies a 60% decrease in the cost of GHG emissions. This result is a confirmation that the choice of the discount rates is central to any assessment of climate change policy. Also, this will have a major effect on policies that pertain to the distant future and the transport sector. Given a certain fixed amount of costs, this implies that higher discount rates tend to reduce the present value of benefits, hence weakening the implementation of current, sound actions. The variable related to the adaptation costs is positive but not statistically significant. We include it in our model because most IAMs consider only the costs of mitigation strategies, leaving aside the adaptation to climate change.

By adopting model 2 of Table 6, we obtain the estimated equation expressed in formula 2:

$$
\begin{aligned}
&\ln(\mathrm{cost2010}) = 9.60 + 1.09{\cdot}\mathit{FIAM} + 0.69{\cdot}\mathit{CGEM} + 0.40{\cdot}\mathit{ew} \\
&-0.006{\cdot}\mathit{ypub} - 0.47{\cdot}\mathit{peer\ rev} - 0.60{\cdot}\mathit{prtp} + \\
&-\ 0.26{\cdot}\mathit{comb} + 0.03{\cdot}\mathit{geogsc} + 0.13{\cdot}\mathit{temp} \\
&+0.001{\cdot}\mathit{ppmv}{+}0.22{\cdot}\mathit{adaptation} \qquad (2)
\end{aligned}
$$

In Section 4, we use these findings and the model developed in this paper to show how it is possible to estimate the economic impact of GHG emissions according to the adoption of specific policy measures.

4. Case study: European policies for a sustainable transport

4.1. Definition of the scenarios and GHG emissions

The case study presented here is based on the assumptions and data provided by SULTAN (EC, 2013a). SULTAN is a European project funded by the European Commission's Directorate and based on the development of different policy scenarios in the transport field until 2050. As stated in the introduction, transport is the only sector to have not provided a reduction in GHG emissions in comparison with 1990 levels. This trend can be changed by adopting political measures (Nocera and Cavallaro, 2011). SULTAN tries to forecast what the future might be like, if certain transport conditions or measures are introduced.

If compared to other models, SULTAN has been voluntarily kept simple. The results are directly calculated from inputs, without optimization and feedback loops to adjust some results in response to others. Its simplicity helps for transparency, but it is necessary to be aware of the model's limitations. Recalling Section 2, the adoption of a limited number of parameters can be considered adequate because it avoids the overlapping of singular uncertainties. Heavily structured models do not necessarily contribute a better result, burdening the mathematical formulation without a tangible gain.

Thirteen single scenarios[5] (i.e. scenarios that adopt a single specific measure) and five combined scenarios[6] (i.e. scenarios that introduce two or more specific measures) have been developed. They assess the GHG 'Life cycle' emissions, also called 'well-to-wheel', which denote the combination of direct and indirect emissions. The former (also known as 'tailpipe' or 'tank-to-wheel') are released from the point of use of the fuel or energy carrier (i.e. from the vehicle). The latter (also known as 'fuel cycle' or 'well-to-tank') are released during extraction, refining, transport and supply of a fuel or energy carrier.

These scenarios are based on self-consistent European databases, which provide reliable historical data for the entire EU. Furthermore, data are divided into several classes, which include the complete range of transport modes: cars, vans, trucks, bus, motorcycle, passenger and freight train, aviation, inland and maritime shipping.

SULTAN defines the scenarios starting from two kinds of inputs: "fixed" and "policy". The former group refers to those parameters that are defined before launching the simulation. These remain constant in every scenario because they are not affected by policy decisions. Examples of fixed inputs include: the amount of vehicles and travel demand for the reference scenario, the discount rate applied by society and travellers and the survival rate of vehicles. The latter group ("policy" inputs) determines the specific characteristics of each scenario. Several parameters belong to policy inputs, including "modes", "powertrains", "fuels" and "powertrains/fuels"[7].

In our analysis, we consider only three of the eighteen scenarios developed by SULTAN: "Business as usual" (BAU), "Mandatory new Vehicle Emission Limits" (VEL) and "Technical and non-technical measures" (TNTM). This analysis can also be extended to the other 15 scenarios not considered here.

"BAU", "VEL" and "TNTM" are representative of three different policies concerning environmental issues. Speaking broadly, "BAU" implies a conservative approach, "VEL" assures the introduction of moderate measures, whereas "TNTM" can be considered as the real fulfilment of a sustainable transport attitude.

"**BAU**" scenario illustrates the expected continuation of the *status quo*. It is mainly based on the population growth estimated

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[5] Scenario 0: Business as usual. Scenario 1: Reduce GHG intensity of fuel. Scenario 2: Mandatory new vehicle emission limits. Scenario 3: Package of cycling and walking improvement measures. Scenario 4: Improved spatial planning. Scenario 5: Package of mobility management measures, including improved public transport. Scenario 6: Improved freight intermodality. Scenario 7: Improved speed enforcement. Scenario 8: Harmonized EU motorway speed limit. Scenario 9: Fuel-efficient driver (FED) training. Scenario 10: Company car tax reform. Scenario 11: CO_2 price tax. Non-CO_2 price tax. Scenario 12: Equivalent duty and VAT rates for fuels.

[6] Scenario C1: Technical Measures: Reduce energy GHG intensity. Scenario C2: Technical Measures: Mandatory new vehicle limits + biofuels. Scenario C3: Scenario C2+Spatial planning and modal shift measures. Scenario C4: Scenario C3+Speed and driver training measures. Scenario C5: Scenario C4+Taxes.

[7] For further information, readers may refer to Hill et al. (2010).

Table 7
"BAU" scenario, travel demand and GHG emissions for years 2010–2050.

"BAU" scenario, travel demand and GHG emissions for years 2010-2050	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Passenger demand (billion pkm)	7,006.93	7,692.71	8,193.50	8,710.40	9,190.56	9,588.01	9,942.40	10,258.96	10,514.72
Freight demand (billion tkm)	13,534.65	15,248.35	17,037.22	18,319.56	19,692.65	21,012.26	22,280.16	23,483.39	24,598.57
GHG emissions (Mt/CO_{2eq})	1,529.38	1,532.40	1,479.10	1,434.98	1,407.23	1,391.94	1,376.92	1,366.63	1,351.41

by the United Nations and the transport data provided by TREMOVE (EC, 2013b), ExTREMIS (EC, 2013c) and COPERT 4 (EEA, 2013b). Values, originally forecasted until 2030, are then extrapolated until 2050. A constant growth in the travel demand can be seen for both passengers and freights from 2010 (7,006.93 billion pkm and 13,534.65 billion tkm) to 2050 (10,514.72 billion pkm and 24,598.57 billion tkm), 50% and 81%, respectively. Total transport GHG emissions decrease slightly and constantly, leading to a yearly emission of 1,351.41 Mt in 2050, down from a starting value of 1,529.38 Mt in 2010 (Table 7).

"**VEL**" scenario analyses the impact of new emission limits for the rail, road, air and water transport modes. Compared with BAU, the same travel demand and modal split are considered. The differences lie mainly in a general improvement of vehicular efficiency (Table 8). Each travel mode is required to reach specific targets in powertrain technologies. Until 2020, car and van specific emissions will be limited to 95 and 135 gCO_2/pkm respectively. All of the terrestrial means of transport (car, bus, van, passenger train, and truck) will lower their emissions 20–30% by 2020 and 90% by 2050. The exception to this is freight rail, who is expected to decrease by 80%. Last, air and maritime efficiency is expected to increase by 1.5% yearly.

Yearly GHG emissions released from transport in this scenario decrease constantly and more rapidly than in "BAU", dropping from 1,529.38 Mt in 2010 to 826.93 Mt in 2050 (Table 9).

"**TNTM**" can be considered the most virtuous amongst all the scenarios developed in SULTAN. It is composed of both technical and non-technical measures. The first group contains all the measures referred to as emission standards (as previously described in "VEL"), plus an increase in the use of biofuels.

The second group is broader and includes:

- Spatial planning measures, which determine change in demand and occupancy factors.
- Co/modality and modal shift.
- Speed measures and fuel efficient driver training assumptions.
- Tax/economic measures, including the reform of company car taxes, CO_2 price taxes for all modes of transport and equivalent fuel taxes.

Table 8
: "VEL" scenario: general additional improvement to fleet efficiency in comparison with "BAU". *Source:* EC (2013a).

"VEL" scenario: general additional improvement to fleet efficiency **Transport mode/Year**	**2010**	**2015 (%)**	**2020 (%)**	**2030 (%)**	**2040 (%)**	**2050 (%)**
Car		1.0	2.0	3.0	4.0	5.0
Bus		1.0	2.0	3.0	4.0	5.0
Motorcycle		0.0	0.0	0.5	1.0	2.0
EU aviation		2.5	4.9	9.5	14.0	18.2
Intl aviation		2.5	4.9	9.5	14.0	18.2
Passenger rail		0.0	0.0	0.0	0.0	0.0
Van		1.0	2.0	3.0	4.0	5.0
Medium truck		2.0	4.0	7.0	10.0	10.0
Heavy truck		2.0	6.0	7.0	10.0	10.0
Inland shipping (a)		4.9	9.6	18.2	26.0	33.1
Inland shipping (b)		4.9	9.6	14.0	18.2	18.2
Maritime shipping		4.9	9.6	18.2	26.0	33.1
Freight rail		0.0	0.0	0.0	0.0	0.0

Each of these measures determines a variation in the travel demand and modal shift, whose analytical reconstruction can be found in Hill et al. (2010). The aggregate values for this scenario are presented in Table 10. The travel demand, both for freight and passenger transport, is lower in comparison with other scenarios (8,076.33 pkm and 19,839.04 tkm in 2050). The yearly emissions are also noticeably lower. In 2050, the emissions are expected to be 131.73 Mt, about 90% less than in the "BAU" scenario.

To summarize, the three scenarios previously discussed forecast different levels of GHG emissions. SULTAN provides values every five years until 2050 and for the total amount of the period considered (2010–2050). This last value is equal to about 58,601 Mt/CO_{2eq} in "BAU", slightly diminishing in "VEL" (51,954 Mt/CO_{2eq}, −11.5%). Finally, it is equal to about 30,759 Mt/CO_{2eq} in "TNTM" (−47.5% in comparison with "BAU") (Table 11, Fig. 1).

4.2. The economic value of GHG emissions

To determine the economic unitary values of GHG emissions, we refer to the stabilization targets expressed by IPCC (2013); Table 12. According to this table, it is possible to quantify the expected increase in $CO2_{eq}$ concentration and temperature by analysing the variation in GHG emissions for the period 2000–2050. To reach this global target, a similar development of the global policies for other non-European countries has to be considered. This is obviously a complex issue that can be dealt with in a politically shared approach. Despite this, the European scale can be considered large enough to obtain such results at a continental level.

For the period 2000–2050, the "BAU" scenario should grant a reduction of GHG transport emissions equal to about 3%, decreasing from 1,392.2 Mt/CO_{2eq} to 1,351.4 Mt/CO_{2eq} (Fig. 2). It allows for an expected increase in concentration up to 585.6t13[8] ppmv and temperature by 3.17 °C. The reduction of $CO2_{eq}$ emissions in the "VEL" scenario is expected to be about 41%, passing from 1,392.2 Mt/CO_{2eq} (year 2000) to 826.9 Mt/CO_{2eq} (year 2050). This is likely to produce a GHG concentration equal to 517 ppmv and an increase in temperature by 2.64 °C. Concluding, the reduction of GHG emissions in "TNTM" is assumed to be about 91%, passing from 1,392.2 Mt/CO_{2eq} in 2000 to 131.7 Mt/CO_{2eq} in 2050.

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[8] A linear correspondence has been assumed between the change in emissions and the ranges of temperature and concentrations, within the range provided by IPCC. For example, recalling Table 13, a decrease of GHG emissions by 30% leads to a concentration of 535 ppmv and a temperature variation of 2.8 °C, whereas an increase of GHG emissions by 5% determines a concentration of 590 ppmv and a temperature variation of 3.2 °C.

Table 9
: “VEL” scenario, travel demand and GHG emissions for years 2010–2050.

“VEL” scenario, travel demand and GHG emissions for years 2010-2050

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Passenger demand (billion pkm)	7,006.93	7,692.71	8,193.50	8,710.40	9,190.56	9,588.01	9,942.40	10,258.96	10,514.72
Freight demand (billion tkm)	13,534.65	15,248.35	17,037.22	18,319.56	19,692.65	21,012.26	22,280.16	23,483.39	24,598.57
GHG emissions (Mt/CO_{2eq})	1,529.38	1,517.42	1,475.56	1,400.56	1,312.81	1,204.20	1,088.33	966.96	826.93

Table 10
: “TNTM” scenario, travel demand and GHG emissions for years 2010–2050.

“TNTM” scenario, travel demand and GHG emissions for years 2010-2050

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Passenger demand (billion pkm)	7,006.93	6,728.76	6,638.92	6,754.81	6,807.52	7,130.76	7,424.23	7,770.25	8,076.33
Freight demand (billion tkm)	13,534.65	12,158.51	13,657.23	14,220.8	14,787.5	16,014.46	17,231.08	18,550.64	19,839.04
GHG emissions (Mt/CO_{2eq})	1,529.38	1,190.53	1,056.05	887.11	737.98	576.47	436.11	276.52	131.73

Table 11
Yearly and overall GHG emissions in “BAU”, “VEL” and “TNTM” scenarios. *Source*: EC (2013a).

Yearly and overall GHG emissions in “BAU”, “VEL” and “TNTM” scenarios

Year	BAU Mt	VEL Mt	TNTM Mt
2010	1,529.38	1,529.38	1,529.38
2015	1,532.40	1,517.42	1,190.53
2020	1,479.10	1,475.56	1,056.05
2025	1,434.98	1,400.56	887.11
2030	1,407.23	1,312.81	737.98
2035	1,391.94	1,204.20	576.47
2040	1,376.92	1,088.33	436.11
2045	1,366.63	966.96	276.52
2050	1,351.41	826.93	131.73
TOTAL (2010-2050)	**58,601.21**	**51,954.96**	**30,759.28**

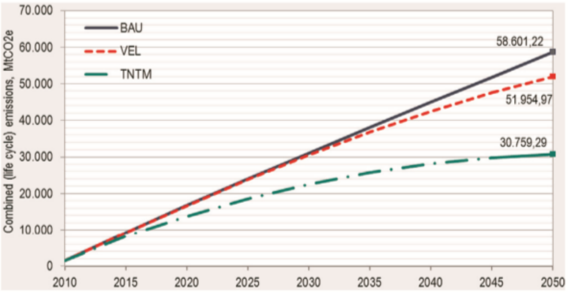

Fig. 1. Total cumulative GHG emissions in “BAU”, “VEL” and “TNTM” scenarios (years 2010–2050).

This is expected to lead to a stabilization of the concentration at about 445 ppmv and an increase of temperature by 2.0 °CTable 13.

The estimation of the GHG emissions enables us to predict their unitary economic values by utilizing formula 2. We modify only the temperature increase (temp) and the concentration (ppmv) according to the value previously defined and maintain all other parameters the same for the three scenarios (Table 13). Hence, we obtain a 2010 unitary price equal to \$191.77/tC (confidence interval is \$189.16 and \$194.37) in “BAU”, \$165.29/tC in “VEL” (confidence interval is \$162.69 and \$167.89) and \$139.96/tC in “TNTM” (confidence interval is \$137.36/tC and \$142.56/tC).

The \$/tC value can be transformed into \$/tCO_{2eq} by considering the conversion factor of 3.664 (Metz, 2001; CDIAC, 2014): the

Table 12
Correlation between change in GHG emissions, temperature and $CO2_{eq}$ concentration. *Source*: IPCC (2013).

Correlation between Change in GHG emissions, temperature and CO2eq concentration

Category	$CO2_{eq}$ concentration (ppmv)	Global mean temperature increase (°C)	Change in global CO2eq emissions in 2050 (% of 2000 emissions)
I	445–490	2.0–2.4	−85 to −50
II	490–535	2.4–2.8	−60 to −30
III	535–590	2.8–3.2	−30 to +5
IV	590–710	3.2–4.0	+10 to +60
V	710–855	4.0–4.9	+25 to +85
VI	855–1130	4.9–6.1	+90 to +140

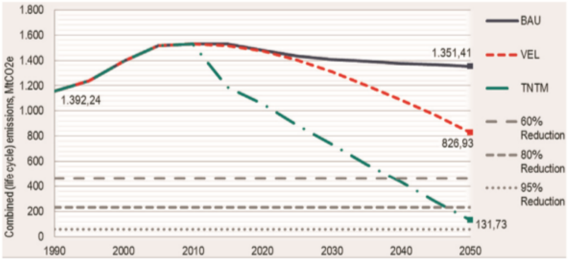

Fig. 2. Yearly GHGs emissions in BAU, VEL and TNTM scenario (years 2010–2050).

economic emission of a single ton of CO_{2eq} is \$52.34 in “BAU”, \$45.11 in “VEL” and \$38.20 in “TNTM”.

Finally, these unitary values are multiplied by the 2010 GHG emissions, thus obtaining the yearly economic impact of GHG emissions. These are equal to \$80,048 M in “BAU”, \$68,990 M in “VEL” and \$58,422 M in “TNTM” (Table 14).

They can be considered a reliable economic value for GHG emissions in transport, if the policies forecasted in the three scenarios previously described are taken into account. In order to estimate the overall economic impact of these choices, the values developed in this study have to be extended for the whole period (until 2050) and should adopt the most opportune discount rate. However, this is not a technical aspect but a political one and it is left to the decisions of policy-makers and their ethical perspective.

Table 13
Cost prediction of GHG emissions according to the changes in temperature and GHG concentrations.

Cost prediction of GHG emissions according to the changes in temperature and GHG concentrations

	Estimated coeff.	**BAU**	**VEL**	**TNTM**
Const	17.1483			
FIAM	1.0917	1	1	1
CGEM	0.6867	0	0	0
ew	0.3977	1	1	1
ypub	−0.0058	2006	2006	2006
peer_rev	−0.4740	0	0	0
prtp	−0.5932	3.00	3.00	3.00
combined	−0.2636	3	3	3
geogrscale	−0.0288	0	0	0
temp	0.1298	3.17	2.64	2.00
ppmv	0.0012	586	517	445
adaptation	0.2211	1	1	1
Unitary economic cost of GHG emissions (\$/tC)		**\$191.77** (\$189.16–\$194.37)	**\$165.29** (\$162.69–\$167.89)	**\$139.96** (\$137.36–\$142.56)

Table 14
Yearly price of CO2eq emissions according to the changes in temperature and GHG concentrations (2010).

Yearly price of $CO2_{eq}$ emissions according to the changes in temperature and GHG concentrations (2010)

Scenario	**CO2eq concentration (ppmv)**	**Global mean temperature increase (°C)**	**Change in global CO_2emissions in 2050 (% of 2000 emissions) (%)**	**Economic value of a single ton of carbon referred to year 2010 (\$/tC)**	**Economic value of a single ton of $CO2_{eq}$ referred to year 2010 (\$/tCO_{2eq})**	**2010 CO_{2eq}emissions (Mt)**	**Cost of CO_{2eq}emissions in 2010** (M\$)
BAU	585.6	3.17	−3	191.77	52.34	1,529.38	80,047.75
VEL	517	2.64	−41	165.29	45.11	1,529.38	68,990.33
TNTM	445	2.0	−91	139.96	38.20	1,529.38	58,422.31

If compared to the values considered at the continental level, our valuations are rather high. Adopting the European Union Emissions Trading Scheme[9] (EU ETS; EC, 2013d), set up in 2005, values have fluctuated between €30.00/tCO_2 and €4.00/tCO_2 (about \$144.85/tC and \$19.88/tC respectively; Strahan, 2013). However, cap-and-trade programs have shown substantial vacillations in the price of oil, which discourages large-scale investment in alternative forms of energy (NT, 2013) and consequently in the reduction of GHG concentration.

For this reason, a carbon tax is normally preferred (Avi-Yonah and Uhlmann, 2008; Santos et al., 2010). Widely varying values are provided, according to the decision of each country. Scandinavian nations generally assign higher values. In Sweden and Finland, the price is equal to \$121.62/tC (Andersen and Skou, 2010). In 2007, Norway taxed gasoline at a price equal to \$226.29/tC. However, these countries are an exception in the continental panorama. In other cases, the tax is either not applied or considerably lower (Sumner et al., 2009), thus highlighting all the difficulties at international level to assign a fair and shared price to GHG emissions. In 2012, Australia has recently tested a mixed approach: from 1st July 2012, a tax of 23 AUD/tC (about 16€/tC) has been introduced, which rises annually by 2.5%. After 1st July 2015, the tax will be substituted by an ETS. An important aspect regards the use of the tax revenues: they could be part of a broader mitigation strategy, adopted to fund general government budgets, returned to (low-income) customers or to cut the taxes on the general population. The choice of the better destination is left to the policy-makers, but the risk that revenues from carbon taxes be seen as a way to increase government revenues rather than provide environmental benefits should be avoided.

5. Conclusions

This paper tackles the important issue of determining a unitary price for the greenhouse gas emissions in transport policy. Only political choices based on robust economic values can guarantee a reliable valuation of their impacts and a coherency with the proposal of specific measures. In this sense, the values currently provided by the scientific literature, ranging up to six orders of magnitude, are not helpful.

This criticality has brought significant consequences at different territorial scales, including both the (inter)national level and the local one. In the former case, the definition of global CO_2 policies has been vague and more focussed on generic reduction targets, rather than on concrete measures, with all the related problems recalled in the introduction. At local level, where concrete solutions have to be implemented, urban mobility plans cannot evaluate the effects of GHG urban emissions properly. This produces a discrepancy between the assumptions of the plan and the effectiveness of the measures: theoretically, GHG reduction is considered as one of the overall goals to be reached; but in practice, CO_2 economic impact of specific measures is not quantified. As a result, the adoption of mobility measures (aiming at traffic

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[9] EU ETS is based on the 'Cap-and-Trade' law. The maximum amount of CO_2 that factories, power plants and installations can emit without paying a fee is limited to a given value (i.e., "cap"). Within this cap, companies receive emission allowances that they can sell to or buy from one another (i.e., "trade"). The cap-and-trade system works well with stable sectors, such as industry and electrical power plants, where quantifying emissions is relatively easy with measuring devices in the smoke stacks. With existing technology, cap-and-trade is not easily extendible to other sectors, such as transportation, buildings and agriculture.

decongestion, improvement of public or alternative transport and not specifically designed for CO_2 reduction) is also expected to have generic indirect impacts on GHG reduction. In this framework, the possibility for policy makers and stakeholders to misinterpret the results of transport actions, passing on potential decision failures to the mere detriment of the community. This may result in grossly inefficient policy not only in terms of transport, because money invested for such aims may be used elsewhere providing greater benefits to the community.

The outcome provided in this paper, based on a statistical approach for reducing the fluctuating range of carbon estimation through the analysis of a new database specifically elaborated, allows for the possibility of interpreting political choices in terms of capital allocation through the overall benefits achieved. By adopting the model presented in formula 1, the policy-makers can understand the variance in the carbon cost according to the variation in objectives posed at political level (including an explicit reference to parameters such as reduction of GHG concentration, increase of temperature and pure time rate of preference) and acting consequently. The case study presented in Section 4 has revealed the possible economic consequences in terms of GHG reduction deriving from the adoption of different transport policies at European level. Specific elaborations of the database according to the different scales and geographic areas should be a useful further step to provide a fair range of values that can be consistently used within transport planning. In Nocera and Cavallaro (2014b), we have illustrated the potential benefits at local level, explaining how the method could be methodologically integrated in a sustainable urban mobility plan ("SUMP"). Particularly, it can be helpful for determining a fair price for a carbon tax (or a fuel tax, which is easier to be monitored), correcting emission externalities and inducing a better driving behavior, vehicle's purchase and usage choice.

However, determining a fair price for transport GHG emissions can be ineffective, if not supported by an adequate analysis that specifies the fields of application, the expected results, the temporal horizons, the connections with other sectors and the investments deriving from the adoption of the measures. In this sense, a rigorous and long-lasting approach not influenced by a single legislature or a specific political party is necessary. At the same time, the continuous monitoring of the intermediate phases should be guaranteed, in order to adapt the strategies according to the final objectives previously set. Some past experiences of some northern European countries (such as Sweden, Finland and Norway) seem to confirm the validity of this option. In Denmark, for instance, a carbon tax has already been introduced in 1993 and its price has been kept almost constant through the years (from an initial value of $16.91, it has only slightly decreased to $16.41 in 2005; Sumner et al., 2009). A part of the revenues (about 40%) is specifically allocated for the environmental subsidies. As a result, global CO_2 emissions have decreased by a good 15% in the period 1990–2005.

Further research in this field could focus on the possible refinement and updating of the evidence included in the database, although our analysis tends to be in the direction that neither should have large effects on the results in terms of the mean values and standard deviation. The use of new and alternative appraisal techniques (such as the Multiple Agent Multi-Criteria Decision Making) could be integrated into the evaluation process usefully (Nocera et al., in press).

However, considering the highlighted limitations, disparate beliefs about economic growth, future technical changes and the damage caused by climate change currently occurring, the results presented in this paper seem promising. They suggest that it should be possible to attribute a fair economic value to GHG emissions in project appraisals, indicating the actual extent of the obstacles on the road to reaching effective progress on climate change valuation, thus improving conditions for a robust evaluation and achieving an operative policy step in the meaningful consideration of carbon emissions.

Appendix A. List of the studies analysed in the databank

Aaheim, A., Fuglestvedt, J. S., Godal, O. (2006) 'Costs savings of a flexible multi-gas climate policy'. *The Energy Journal*, (Special Issue# 3), 485–502.

Ackerman, F., Stanton E.A. (2012) 'Climate Risks and Carbon Prices: Revising the Social Cost of Carbon'. *Economics—the Open-Access, Open-Assessment E-Journal*, 6(10), 1–27.

Ackerman, F., Munitz, C. (2012) 'Climate damages in the FUND model: A disaggregated analysis'. *Ecological Economics*, 77(0), 219–224.

Anthoff, D., Tol, R.S.J., Yohe, G.W. (2009c) 'Risk Aversion, Time Preference, and the Social Cost of Carbon'. *Environmental Research Letters*, 4(2–2), 1–7.

Anthoff, D., & Tol, R.S. (2010) 'On international equity weights and national decision making on climate change'. *Journal of Environmental Economics and Management*, 60(1), 14–20.

Anthoff, D., Hepburn, C.J., Tol, R.S.J. (2009) 'Equity weighting and the marginal damage costs of climate change'. *Ecological Economics*, 68(3), 836–849.

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Other studies not quoted here are included in Weyant, J. P., de la Chesnaye, F. C., & Blanford, G. J. (2006).

Appendix B

See Table B.1.

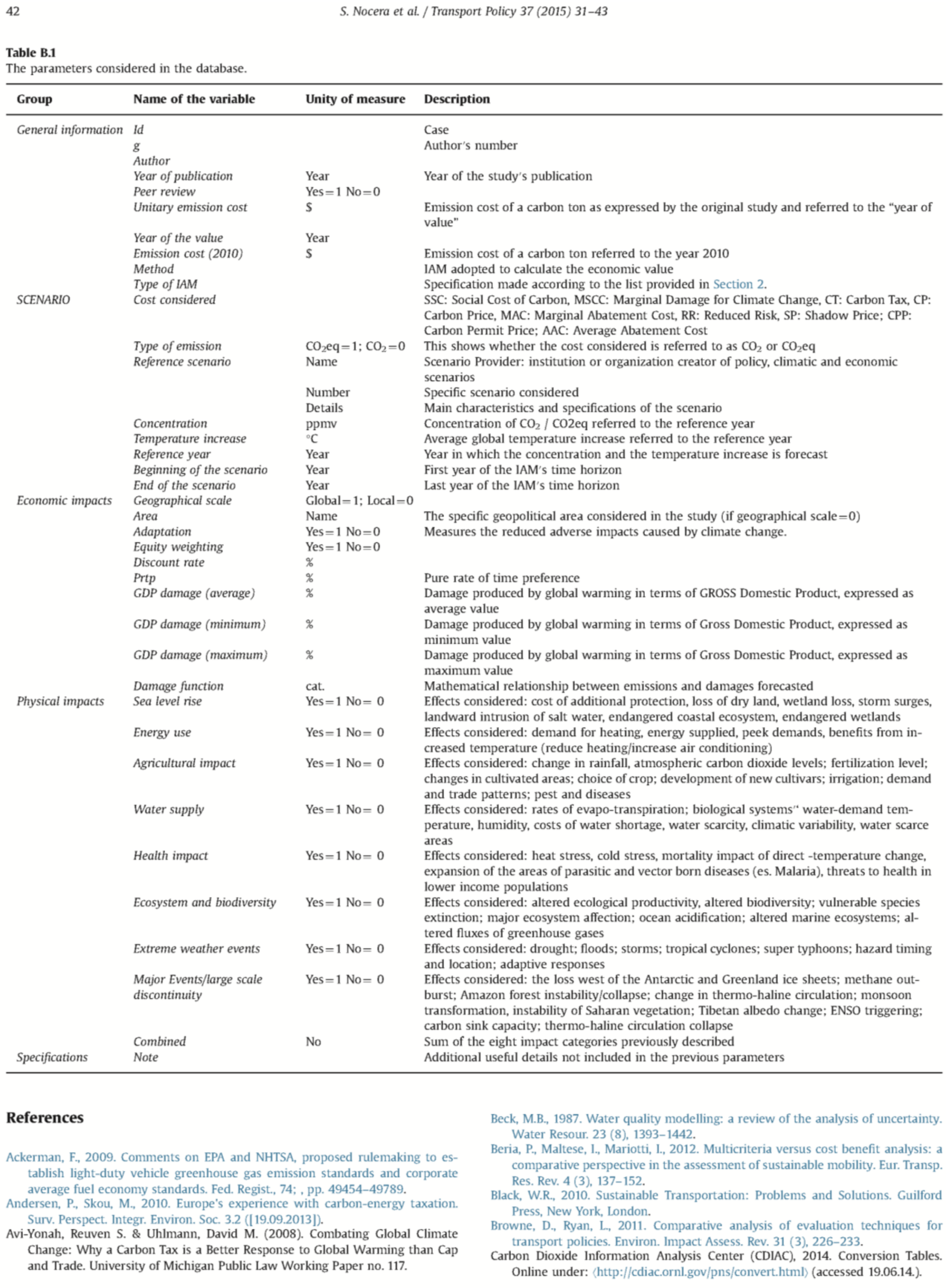

Table B.1
The parameters considered in the database.

Group	Name of the variable	Unity of measure	Description
General information	*Id*		Case
	g		Author's number
	Author		
	Year of publication	Year	Year of the study's publication
	Peer review	Yes = 1 No = 0	
	Unitary emission cost	$	Emission cost of a carbon ton as expressed by the original study and referred to the "year of value"
	Year of the value	Year	
	Emission cost (2010)	$	Emission cost of a carbon ton referred to the year 2010
	Method		IAM adopted to calculate the economic value
	Type of IAM		Specification made according to the list provided in Section 2.
SCENARIO	*Cost considered*		SSC: Social Cost of Carbon, MSCC: Marginal Damage for Climate Change, CT: Carbon Tax, CP: Carbon Price, MAC: Marginal Abatement Cost, RR: Reduced Risk, SP: Shadow Price; CPP: Carbon Permit Price; AAC: Average Abatement Cost
	Type of emission	$CO_2eq = 1$; $CO_2 = 0$	This shows whether the cost considered is referred to as CO_2 or CO_2eq
	Reference scenario	Name	Scenario Provider: institution or organization creator of policy, climatic and economic scenarios
		Number	Specific scenario considered
		Details	Main characteristics and specifications of the scenario
	Concentration	ppmv	Concentration of CO_2 / CO2eq referred to the reference year
	Temperature increase	°C	Average global temperature increase referred to the reference year
	Reference year	Year	Year in which the concentration and the temperature increase is forecast
	Beginning of the scenario	Year	First year of the IAM's time horizon
	End of the scenario	Year	Last year of the IAM's time horizon
Economic impacts	*Geographical scale*	Global = 1; Local = 0	
	Area	Name	The specific geopolitical area considered in the study (if geographical scale = 0)
	Adaptation	Yes = 1 No = 0	Measures the reduced adverse impacts caused by climate change.
	Equity weighting	Yes = 1 No = 0	
	Discount rate	%	
	Prtp	%	Pure rate of time preference
	GDP damage (average)	%	Damage produced by global warming in terms of GROSS Domestic Product, expressed as average value
	GDP damage (minimum)	%	Damage produced by global warming in terms of Gross Domestic Product, expressed as minimum value
	GDP damage (maximum)	%	Damage produced by global warming in terms of Gross Domestic Product, expressed as maximum value
	Damage function	cat.	Mathematical relationship between emissions and damages forecasted
Physical impacts	*Sea level rise*	Yes = 1 No = 0	Effects considered: cost of additional protection, loss of dry land, wetland loss, storm surges, landward intrusion of salt water, endangered coastal ecosystem, endangered wetlands
	Energy use	Yes = 1 No = 0	Effects considered: demand for heating, energy supplied, peek demands, benefits from increased temperature (reduce heating/increase air conditioning)
	Agricultural impact	Yes = 1 No = 0	Effects considered: change in rainfall, atmospheric carbon dioxide levels; fertilization level; changes in cultivated areas; choice of crop; development of new cultivars; irrigation; demand and trade patterns; pest and diseases
	Water supply	Yes = 1 No = 0	Effects considered: rates of evapo-transpiration; biological systems'' water-demand temperature, humidity, costs of water shortage, water scarcity, climatic variability, water scarce areas
	Health impact	Yes = 1 No = 0	Effects considered: heat stress, cold stress, mortality impact of direct -temperature change, expansion of the areas of parasitic and vector born diseases (es. Malaria), threats to health in lower income populations
	Ecosystem and biodiversity	Yes = 1 No = 0	Effects considered: altered ecological productivity, altered biodiversity; vulnerable species extinction; major ecosystem affection; ocean acidification; altered marine ecosystems; altered fluxes of greenhouse gases
	Extreme weather events	Yes = 1 No = 0	Effects considered: drought; floods; storms; tropical cyclones; super typhoons; hazard timing and location; adaptive responses
	Major Events/large scale discontinuity	Yes = 1 No = 0	Effects considered: the loss west of the Antarctic and Greenland ice sheets; methane outburst; Amazon forest instability/collapse; change in thermo-haline circulation; monsoon transformation, instability of Saharan vegetation; Tibetan albedo change; ENSO triggering; carbon sink capacity; thermo-haline circulation collapse
	Combined	No	Sum of the eight impact categories previously described
Specifications	*Note*		Additional useful details not included in the previous parameters

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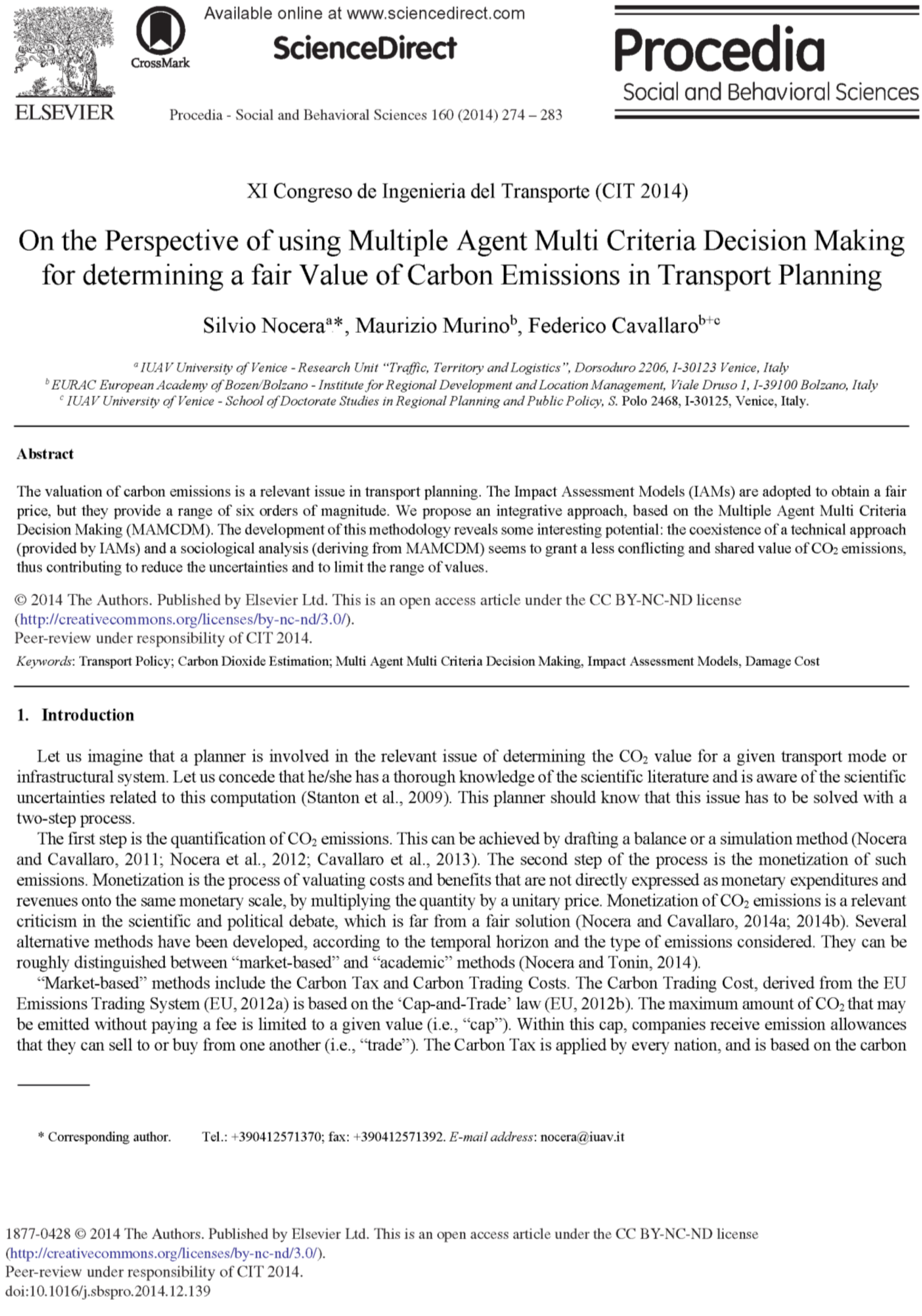

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On the Perspective of using Multiple Agent Multi Criteria Decision Making for determining a fair Value of Carbon Emissions in Transport Planning

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Abstract

The valuation of carbon emissions is a relevant issue in transport planning. The Impact Assessment Models (IAMs) are adopted to obtain a fair price, but they provide a range of six orders of magnitude. We propose an integrative approach, based on the Multiple Agent Multi Criteria Decision Making (MAMCDM). The development of this methodology reveals some interesting potential: the coexistence of a technical approach (provided by IAMs) and a sociological analysis (deriving from MAMCDM) seems to grant a less conflicting and shared value of CO_2 emissions, thus contributing to reduce the uncertainties and to limit the range of values.

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1. Introduction

Let us imagine that a planner is involved in the relevant issue of determining the CO_2 value for a given transport mode or infrastructural system. Let us concede that he/she has a thorough knowledge of the scientific literature and is aware of the scientific uncertainties related to this computation (Stanton et al., 2009). This planner should know that this issue has to be solved with a two-step process.

The first step is the quantification of CO_2 emissions. This can be achieved by drafting a balance or a simulation method (Nocera and Cavallaro, 2011; Nocera et al., 2012; Cavallaro et al., 2013). The second step of the process is the monetization of such emissions. Monetization is the process of valuating costs and benefits that are not directly expressed as monetary expenditures and revenues onto the same monetary scale, by multiplying the quantity by a unitary price. Monetization of CO_2 emissions is a relevant criticism in the scientific and political debate, which is far from a fair solution (Nocera and Cavallaro, 2014a; 2014b). Several alternative methods have been developed, according to the temporal horizon and the type of emissions considered. They can be roughly distinguished between "market-based" and "academic" methods (Nocera and Tonin, 2014).

"Market-based" methods include the Carbon Tax and Carbon Trading Costs. The Carbon Trading Cost, derived from the EU Emissions Trading System (EU, 2012a) is based on the 'Cap-and-Trade' law (EU, 2012b). The maximum amount of CO_2 that may be emitted without paying a fee is limited to a given value (i.e., "cap"). Within this cap, companies receive emission allowances that they can sell to or buy from one another (i.e., "trade"). The Carbon Tax is applied by every nation, and is based on the carbon

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content of fuels or on the estimated CO_2 emitted in the fuel combustion process (Santos et al., 2010). The Carbon Tax is normally the preferred method for the transport sector (Avi-Yonah et al., 2008) because it is easier to enforce and less influenced by market fluctuations; the Cap-and-Trade system, on the other hand, works well with stable sectors, such as industry and electrical power plants, where quantifying emissions is relatively easy.

"Academic" methods consist mainly of "Avoidance" and "Damage" Costs. They are based on the quantification of the economic impacts deriving from the environmental consequences of CO_2 emissions. The Avoidance Costs (also known as "Mitigation" or "Control" Costs) quantify the funds required to reduce CO_2 emissions and to lower their atmospheric value. Avoidance Costs are based on a cost-effectiveness analysis that expresses the optimum price to achieve a given target. From an economic perspective, it is a method that determines the least cost option to achieve a required reduction level of CO_2 emissions. Emissions are at their optimum level when the incremental social costs of additional abatement (i.e., reducing emissions by one tonne) are equal to the additional social benefits of avoided damage.

The Damage Cost method assesses the future physical impacts of climate change and links them to consequences on a society and its economy. This method is based on a Cost Benefit Analysis (CBA), which determines the optimal policies to adopt on the basis of the environmental, social and economic consequences expected, and then evaluates whether the benefits are expected to exceed the costs.

There is no absolute method for calculating a reliable unitary economic value of CO_2. However, for long-term analyses, the use of the Damage Cost is preferred, because it is neither related to political decisions or scenarios (like the Carbon Tax or Avoidance Cost) or to market fluctuation (like carbon trade). Furthermore, this method is adopted in other environmental analyses of external costs, thus making the results comparable with other fields. Nevertheless, by adopting the Damage Cost method, the range provided by the literature is enormous, which spans six orders of magnitude (Tol, 2008; Nocera and Cavallaro, 2012).

The question that a planner must address is how to obtain a fair value of such emissions, if the range of the unitary values is so vast. This paper tries to solve the problem by proposing the MAMCDM as a possible solution. The paper is structured as follows: in section two, a different theoretical approach is presented, based on a sociological method. Sections three and four investigate this method in greater detail, describing respectively the MAMCDM and its possible adoption in the valuation of CO_2 emissions. Some conclusions and future proposals end the contribution, showing how MAMCDM could be used to support transport decision-making and the development of correct policies in the valuation of carbon dioxide.

2. From a "hard science" approach to a sociological perspective

As stated in the introduction, the Damage Cost is the preferable method for long-term analysis of CO_2 values. The Damage Cost can be obtained in different ways: it is possible to multiply estimates of the ''physical effects'' of climate change with estimates of their price (Fankhauser, 1994, 1995; Nordhaus 2008; Nocera and Cavallaro, 2014; Tol, 2002a, 2002b). Alternatively, Bosello et al. (2012) use similar estimates of the physical impacts but compute the general equilibrium effects on welfare. Finally, other methods may consist of using observed variations (across space) in prices and expenditures to discern the effect of climate (Nordhaus, 2006), or in drafting self-reported well-being (Maddison and Rehdanz, 2011).

The Impact Assessment Models (IAMs) are the technique most adopted to valuate the Damage Costs deriving from CO_2 emissions (Stanton et al., 2009). IAMs link the unitary value with their physical changes caused by CO_2 emissions, thus establishing a direct connection between the physical changes caused by the emissions and their economic consequences.

Nonetheless, the range of values included is between -\$10.00 /tC and \$7,243.73/tC (Nocera and Tonin, 2014). To limit this vast range, a meta-analysis of the values proposed by literature can be made (Nocera et al., 2014). The main descriptive statistics of this meta-analysis, based on 699 observations, reveal that the mean value is 276.49 \$/tC, the median 85\$/tC, and the standard deviation 668.78\$/tC. This kind of technical analyses can be relevant to determine the main statistics deriving from the IAMs. They also contribute in reducing the uncertainties of the carbon price. However, these approaches do not consider the dynamic interactions between the different positions of the actors involved in the process of determining the final price.

To understand this point, a different perspective is introduced. This vision is mostly selected in the social sciences and is based on the social construction of acceptance. If we reformulate the process previously described as adopting a sociological perspective (Pinch and Bijker, 1984), what happens by adopting the IAMs is that differing explanations are sought for what is taken to be a scientific truth or falsehood (approach "A" in figure 1). In the case of CO_2 emissions, this would mean to reach a univocal relationship between global warming, climate changes, discount rates and all the parameters previously listed. There is a huge debate about these aspects (Tol, 2013), and a final agreement is very difficult to be found due to the presence of several uncertainties (Clarkson and Deyes, 2002). Unavoidably, this has led to the vast range of values previously recalled. A polarization of positions and the adoption of a DEAD approach (acronym of Decision, Education, Announcement and Defense: Hartz-Karp, 2007) are the most common consequences. In such cases, the risk is the adoption of a proposal, which coincides with the point of view of the authorities or stakeholders that have greater interests but does not consider other relevant instances. This position includes the problems related to the lack of participation; its consequences are visible in many transport fields, but mostly when the realization of new infrastructures and the introduction of new transport policies are considered (Caruso, 2010; Cavallaro and Maino, 2014).

On the other hand, an alternative approach ("B" in figure 1) suggests that all knowledge and knowledge-claims be treated as being socially constructed. This implies the switch from a pure technical analysis to a more comprehensive vision. This method is mostly used in the management of social conflicts, where the final effect is unknown, stances are different, and more viewpoints are considered. CO_2 emission price can be included in this group: here, the environmental and economic effects of emissions are not univocally determined (Watkiss et al., 2005) and several conflicting positions can be found (Stern, 2007). Nevertheless, to our knowledge, this sociological approach has yet to have been used in the valuation of CO_2 emissions. It could be based on the *frame theory,* as proposed by Schön and Rein (1994). A frame represents the actors' values and mental conception of the world. It allows for the understanding of the different actors' background and the reasons behind their specific positions. As far as CO_2 is concerned, this can be produced by analyzing the vast number of variables that must be chosen by the modelers in IAMs to determine a price, as better clarified in the next section. This first phase allows determining the different positions as well as the controversies of the actors involved in the process. The following phase is the construction of a shared methodology through a process of reframing: this implies a redefinition of the problems starting from a new approach, combined in a dynamic way with the aspects that were previously only partially considered or omitted. Reframing is a complex conceptual operation, which, operatively, can be produced by using a MAMCDM. At the end of this phase, a more shared vision about the problems may be obtained, based not only on the scientific approach, but also on the social acceptance of the method and its results: an Announce, Discuss, Decide (ADD) approach. The two different approaches previously described are schematized in figure 1.

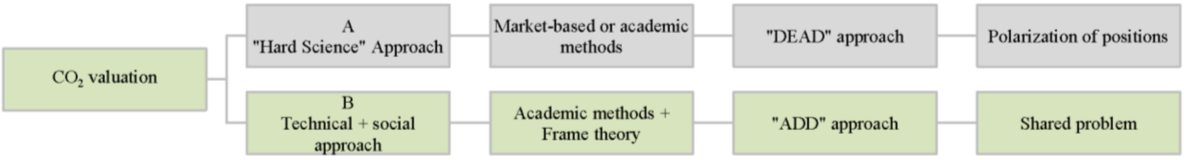

Figure 1. Two alternative approaches to evaluate CO_2 emissions

Since a relationship between MAMCDM and CO_2 is still lacking, the technical and social approach has not yet been adopted. The aim of the next two sections is to fill this gap, first by describing the MAMCDM (section 3) and then by linking it to the valuation of the transport emissions (section 4).

3. Multiple Agent Multi Criteria Decision Making (MAMCDM)

MAMCDM is a methodology that aims to support the process of decision, election, evaluation and negotiation of a suitable alternative when a number of agents (or groups of agents) are involved. This method is the combination of an evaluation method, the Multi Criteria Analysis (MCA, presented in section 3.1), with the Multi Agent System (MAS, described in section 3.2). Together, these two parts constitute an evaluation system that can take into account different criteria and different perspectives (section 3.3).

3.1 Multi Criteria Analysis

Multi Criteria methods are a type of decision analysis specifically designed for use in situations where it is important to transparently incorporate multiple considerations into a decision making process. MCA allows for the consideration of different performance criteria, especially those who cannot be reported in monetary terms. The main goal is to provide a clear, rational, documentable, comprehensive and defensible evaluation process. For this reason, MCA is a well-known method, widely adopted in different branches of transport, such as sustainable transport systems (Tzeng et al., 2005), decision support systems (Brand et al., 2002), time network equilibrium and system optimum problems (Yang and Huang, 2004), and urban network analyses (Cantarella and Vitetta, 2006).

In short, the method is based on seven steps (Sinha and Labi, 2007). First, the identification of the alternatives to be compared to has to be provided. This is achieved through the technical development of several alternative options, such as scenarios or projects.

Second, the performance criteria have to be chosen: this is a crucial point, because this decision determines the parameters on which the evaluation is based.

Third, the relative importance of such criteria has to be established. This process is called "weighting" and can be made through different methods, such as equal weighting, direct-weighting, regression-based observer-derived weighting, Delphi approach, gamble method, pairwise comparison and value swinging.

Fourth, a common unit of measurement has to be established, so that the comparison between criteria can be provided. This process is called "scaling" and can be obtained through a value function approach (if there is certainty in the evaluation) or through a utility function approach (if the evaluation is made under uncertainty). In cases of certainty, the scalar index of preferences is defined, which are the values of each level of a performance criterion (Keeney and Raiffa, 1976); in cases of uncertainty, a more general approach is adopted, which takes into account the risk preferences of the decision-maker as well.

Fifth, using the scale established during the last step, the levels (impacts) of each criterion for each alternative action are quantified.

Next, the performance criteria have to be amalgamated. This means that a unique value has been finally obtained for each scenario or project, which is the sum of all the scaled and weighted performance criteria.

This leads to the seventh and last phase, which is the choice of the most preferable solution. This choice can be expressed in mathematical terms, as seen in formula 1):

$$\mathrm{F}(\mathrm{x}) = \{\mathrm{c}_1(x), \dots, c_i(x), \dots, c_k(x)\} \qquad 1)$$
$$x \in A \ = [\mathrm{a}_1, \dots, \mathrm{a}_j, \dots, \mathrm{a}_n]$$

where:
F(x) is the function of maximization or minimization, according to the objective of the evaluation;
c is a criterion taken into account in the analysis;
a is an alternative taken into account in the analysis;
A is the set of all the alternative solutions;
k is the number of criteria;
n is the number of alternatives.

When the decision about the best option is acted on, a sensitivity analysis can be carried out to verify which variations can effectively influence alternative performances (Cossu, 2005). Sensitivity analysis can be methodological, on criteria or on weights.

3.2 Multi Agent System

A Multi Agent System (MAS) models the interactions of agents (or groups of agents) in a given environment. MASs are strictly connected to the game theory, a mathematical approach that studies interactions between self-interested agents (Binmore, 1992). This kind of research has been developed in the framework of the computer sciences, decisions theory and operative research. The concept has been rapidly extended (Kubera et al., 2010), and agents are currently divided between ***very simple agents*** (passive agents or agent without goals, such as an apple), ***active agents with simple goals*** (such as wolves and sheep in a prey-predator model) and ***very complex agents*** (cognitive agents, indifferently human or virtual, which require many complex calculations).

A MAS is not an evaluation technique, such as MCA. If used alone, it does not help us to choose the best solution for a specific goal. Indeed, it is conceived to determine the relationships between actors and the environment, thus allowing to address several problems in combination with specific evaluation techniques (Ferber, 1999). Therefore, MAS can contribute to bring problem solving activity to a distributed dimension, rather than to a centralised approach, being that the former is well known as an effective approach (Davis and Smith, 1983). Furthermore, MAS gives the possibility to make artificial universes, which are small laboratories for the tests of theories about behaviours and the description of specific interaction mechanisms.

Considering its very wide conception, a MAS is constituted by an environment where agents interact. Five main characteristics can describe the environment (Norvig and Intelligence, 2002):

1) *Observability*. If the perception of an agent gives access to the complete state of the environment at each point in time, the environment is fully observable. This means that the agent can detect all relevant aspects to choose a specific action. Vice versa, an environment might be partially observable, if inaccurate information or unknown elements are given.
2) *Determinism*. If the future state of an environment is completely determined by the current state and the actions executed by an agent, an environment is deterministic; otherwise, it is stochastic.
3) *Episodicity or sequentiality*. In an episodic environment, the choice of actions in each event depends only on the latter and the next one does not depend on the actions taken previously in other events.
4) *Dynamism*. If the environment can change while an agent is deliberating, it is dynamic; otherwise, it is static. Static environments are easier to be dealt with, because the agent does not have to look at the world while deciding on an action. Dynamic environments, on the other hand, are continuously demanding a choice from the agent. If the environment does not change with the flow of time, but the agent's performance score does, the environment is called semidynamic.
5) ***Discreteness.*** A partition does not allow for a continuity of space, time or perception. Discreteness can be applied to the state of the environment, to the way time is handled, and to the perceptions and actions of the agent.

Referring to the aim of the research presented in this paper, a group of decision makers can be seen as a MAS, interacting in a partially observable, stochastic, sequential, dynamic and continuous environment. The group decision activity could benefit from a decision support system (DSS), hence called Group Decision Support System (GDSS), a technology to support project collaboration through the enhancement of digital communication. These types of programs are used to support customized projects requiring group work, input to a group and various types of meeting protocols (Power, 2007). The wide use of software and technology suggested the research in GDSS progressively points out the importance of moderating the outcomes (Lim and Benbasat, 1992). A Negotiation Support System (NSS) needs a Decision Support System (DSS) for each negotiating party electronically linked to the other DSSs, allowing the negotiating groups to communicate electronically, creating the so-called Group Decision Negotiation Support System (GDNSS).

3.3 Multiple Agent Multi Criteria Decision Making

MAMCDM is a holistic approach that combines MCA and MAS. It aims to provide actors with a computer-based support system able to aid the decision process with a semi-structured decision task. In other terms, a choice-model that allows direct interaction with data and scenarios (Lim and Benbasat, 1997). The negotiation activity calls for a direct IT linkage between the actors and their support systems, thus forming a GDNSS. In a MAMCDM, the following elements have to be considered: a set D of d actors (s); a set A of n alternatives (a); a set C of k criteria (c); a mediator agent M. Operatively, MAMCDM runs on three main steps.

First, every actor s produces an individual $k \times n$ matrix with its evaluations and weights, w, on the alternatives a. Weighting is an important phase of MCA. It reflects the decision makers' preferences by the score they confer to each criterion k (Dodgson et al., 2009). The sum of the scores is unitary, and their repartition can determine an individual "pre-order rank", which is a list where the alternatives are sorted according to the preferences of every single decider. The specification "pre-order" suggests that this rank is still susceptible to changes from the following phases. Second, from those individual evaluations derives the group matrix **G** and a single ranked list of preferences (called "collective pre-order" rank). Third, the negotiation/group-decision process is carried out, where the mediator M participates actively. These three phases are described here in detail.

The first step consists of a MCA carried out by each actor, who assigns weights to the alternatives. Soon after, the pairwise comparison of the alternatives related to the specific criteria determines the preliminary preference order. Pairwise comparison (PC) is a consolidated technique. In decision making; a common problem are the missing judgments, especially when the number of alternative, k, is high. Indeed, PC strength lays in the several methods scholars developed to derive the priorities of the k alternatives even if a $k{\times}n$ matrix is incomplete (Fedrizzi and Giove, 2007). Preference levels can be measured on a scale going from 0 (no preference) to 1 (full preference). If the comparison between two alternatives results in a small deviation, there is either a weak preference or none at all, while clearer preferences are expected for broader deviations. Rather than pointing out a unique decision, this method helps actor to find the alternative that best suits their goals. The method provides a comprehensive and rational framework for structuring a decision problem, identifying and quantifying conflicts and synergies, clusters of actions, and highlighting the main alternatives and the structured reasoning behind this (Figueira et al., 2005). From the analysis of the flows, it is possible to understand many of these data.

A preference flow φ measures how an alternative, or group of alternatives, is preferred. Each alternative will result in two flows. The flow is called *positive* when it expresses how much an alternative a is preferred to the remaining $n – 1$ ones. It measures the strength of the alternative a and it is expressed by $\varphi_+(a) = (1/n-1)\sum_{a1 \neq aj} \pi\left(a_1, a_j\right)$, where $\pi\left(a_1, a_j\right)$ is one arc of preference between two alternatives. The positive flow $\varphi_+(a)$ plus the negative one $\varphi_-(a) = (1/n-1)\sum_{aj \neq a1} \pi\left(a_j, a_1\right)$, which measures how much the other $n – 1$ alternatives are preferred to the alternatives a (hence, its weakness), gives the net flow $\varphi(a) = \varphi_+(a) - \varphi_-(a)$ (VPsolutions, 2013). Flows can mainly be analysed with partial or complete ranking. Complete ranking presents an ordered list mathematically ordered by summing net and positive flows. Instead, partial ranking permits a comparison that enlightens conflicts and incomparabilities by keeping the flows separated. That is, an alternative could be preferable because of a particular feature, while could not score so well on another criteria. What we have here is an incomparability, or conflict.

The matrix in table 1 summarizes how an agent judges the alternatives according to the evaluation criteria. It provides their individual pre-order of the alternatives.

$$
\begin{array}{cccccc}
 & c_1 & \cdots & c_i & \cdots & c_k \\
a_1 & \varphi_{11} & & \varphi_{1i} & & \varphi_{1k} \\
\vdots & & & & & \\
a_j & \varphi_{j1} & & \varphi_{ji} & & \varphi_{jk} \\
\vdots & & & & & \\
a_n & \varphi_{n1} & & \varphi_{ni} & & \varphi_{nk}
\end{array}
$$

Table 1. The matrix with the criteria and the weights of each agent

where:

φ is the net flow that represents the evaluation of an agent concerning a specific criterion on an alternative;

j is the index attributed to alternative a: $A = \{a_j\}$, $j = 1 \ldots n$;

i is the index attributed to criteria c: $C = \{c_i\}$, $i = 1 \ldots k$.

Subsequently, every individual matrix can be converted into a net flow $\varphi_{si}(a)$, which represents the score that every actor s, according to the criterion i, attributes to the alternatives in the set A (Espinasse et al., 1997; formula 2):

$$\varphi_{si}(a) = \frac{1}{(n-1)\sum_{j=1}^{n}\left(P_{si}(a,x_j) - P_{si}(x_j,a)\right)} \qquad 2)$$

where:

φ, a, j, i are defined above;

s is the index attributed to actors: $D = \{d_s\}$, $s = 1 \dots d$;
P is the preference function.

Every agent involved in the process has to produce their net flow $\varphi_{si}(a)$. Then, by summing all the $\varphi_{si}(a)$ for all the k criteria, the net flows $\varphi_s(a)$ for each agent s on an alternative a is calculated (formula 3).

$$\varphi_s(a) = \sum_{i=1}^{k} \varphi_{si}(a) \qquad 3)$$

The second step coincides with the creation of a matrix where the evaluation of the agents regarding the different alternatives are collected (table 2, columns D_1, D_s, D_d). Hence, given the net flows for each single actor on an alternative $\varphi_s(a)$, as described in formula 3), the group net flow φ_g for an action a can be calculated. It is the sum of individual net flows $\varphi_s(a)$ for every actor, with w_{si} representing the weight associated to every criterion i by the actor s, where the sum of the weights distributed through the k criteria by a decider s is 1:

$$\varphi_g(a) = \sum_{s=1}^{d} w_s \sum_{i=1}^{k} w_{si} \frac{1}{(n-1)\sum_{j=1}^{n} P_{si}(a,x_j) - P_{si}(x_j,a)} \qquad 4)$$

where:
φ, a, d, j, k, i, P are defined above;
g represents the group as a sum of the single actors;
w_{si} is the weight associated to each criterion i by the actor s.

The second phase ends by inserting into the matrix the values of the net group flows $\varphi_g(a)$ as calculated with formula 4). Now, the mediator is able to outline the collective pre-order of the listed alternatives. The net flow $\varphi_g(a)$ is represented in the last column *Group net flow(a)* of the matrix **G** (table 2).

Action	D_1	… D_s	… D_d	*Group net flow* (a)
a_1…	$\varphi_1(a_1)$	$\varphi_s(a_1)$	$\varphi_d(a_1)$	$\varphi_g(a_1)$
a_j…	$\varphi_1(a_i)$	$\varphi_s(a_i)$	$\varphi_d(a_i)$	$\varphi_g(a_i)$
a_n	$\varphi_1(a_n)$	$\varphi_s(a_n)$	$\varphi_d(a_n)$	$\varphi_g(a_n)$

Table 2. The mediator matrix **G**

This process provides an ordered list of preferences, which is only partially satisfactory. The ordered list of group net flows $\varphi_g(a_1)$ rank final scores, overlooking contingent incomparabilities and conflicts emerging from the pairwise comparison of alternatives and criteria. If we recall the theoretical framework as expressed in section 2, $\varphi_g(a)$ allows for the enlightenment of the actors and their frames. The following phase consists of reframing the problem and in finding an agreement between the different instances. This can be made through the negotiation process and the introduction of a mediation's agent (third phase of the MAMCDM process).

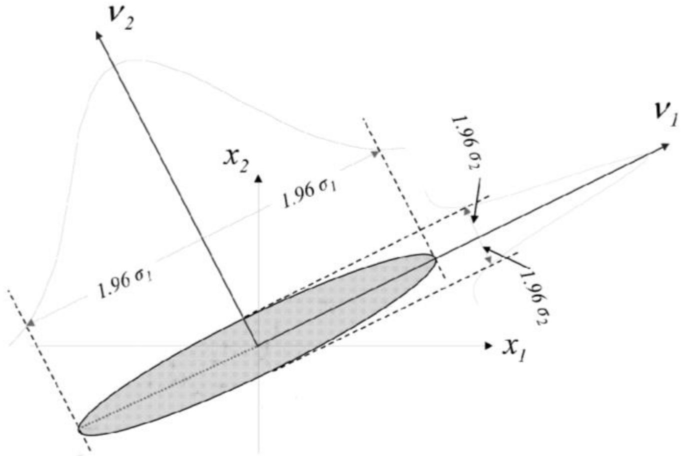

Figure 2. A geometrical representation as an orthogonal transformation of matrices flows. Source: Marsili-Libelli, 2014, modified

The most interesting feature of the process is its capability to enlighten potential conflicts, as outlined by the pairwise comparison. In order to perform this, a shift from the mathematical to a graphical representation of data can be useful. In this sense, MAMCDM allows for directly observing and evaluating any possible perspective: weights, actions, actors and criteria in any useful combination, to highlight the most substantial reasons for conflict. Data matrices can be expressed as coordinates in a multidimensional space, where each variable exists in one axis. To report the matrices to a bi- (or tri-) dimensional representation, a dimension-reduction technique called Principal Components Analysis (PCA) is required. PCA allows for defining orthogonal dimensions (as represented by the principal components v_1, v_2 in figure 2) in order to show data from the point of view which provides the maximum information from data distribution.

Furthermore, the process is helpful when data present a consistent autocorrelation, that is, the same information shared by two different variables. Even if the two/three dimensional representation of the problem implies a loss of information, arguably, the less important part of the data matrix, it is the maximum possible quantity of information from the k-dimensional representation. The first principal component is the one with the largest variance, and each following component has the highest variance under the constraint that it be orthogonal to the preceding components (Jolliffe, 2005). The PCA process works as follows: two dimensional representation of data is scattered on a reference plan (x_1, x_2). The axis v_1 and v_2 represent the widest data distribution for the given principal components, maximizing their variance. The change of the reference plan deriving from the rotation of the x_1 and x_2 to the v_1 and v_2 axis is a change of perspective. Its aim is to choose the observation point of view that shows the maximum amount of data, recalling the "reframing" theory here. Indeed, looking directly alongside the v_1 axis, the plan provides the maximum amount of information on the component v_1, considered within two standard deviations σ_2 from its mean (the v_1 axis). The same can be said for the component v_2.

Let us consider the net flows $\varphi_g(a)$ in formula 4): from this graphical data reduction it is already possible to identify the conflicting actors, which are represented by ajar vectors. Similarly, from formula 2), it is possible to evaluate the relative performance of an action on any criterion, according to the preference function defined by the decision-maker.

The spatial representation provides more intuitive information about actions, criteria and weights to be managed. Points in the Cartesian space represent actions: the closer the points are to each other, the more similar the actions are. A vector that joins a specific point with the center of the Cartesian plane represents a specific parameter (criterion, agent or alternative, at discretion), whose length indicates its relative discriminating power: the longer the axis, the more discriminating the parameter is. If the parameters under observation express similar preferences, then axes oriented in similar directions represent them; vice versa, two divergent vectors mean that there are opposing preferences.

The negotiation process consists of discussing with the agents the willingness to keep distance from their main preference. Spatially, a line that links the center of the axes and the coordinates (x,y) in the space that represent the preferred choice. By setting up a deterministic elasticity, expressed in percentage, every actor expresses the willingness to consider as acceptable another position included in this range. The point of agreement has to be fairly collocated according to the position of every agent and the equilibrium condition that better fits the actors. It could coincide either with a Nash Equilibrium condition, a solution that maximizes the payoff of each agent based on fairness, or with a Pareto Optimum, that is, the point of achievable joint evaluation from which no further joint gain is possible.

4. Use of MAMCDM in CO_2 valuation

So far, MAMCDM has been adopted in specific fields, mostly related to computer sciences, biology and robotics (Belz and Mertens, 1996; Bonetti et al., 2012). Other studies refer to the application towards environmental problems (Morais and de Almeida, 2007; Haralambopoulos and Polatidis, 2003). In the transport field, MAMCDM has been used for specific tasks mostly related with management operations. For example, Tzeng et al. (2005) pursued a MCA of alternative-fuel buses for public transportation where experts from different decision making groups were involved. Another important transport field is related with fuzzy analysis (Teng and Tzeng, 1996; Wang and Lee, 2007; Yeh et al., 2009).

In this section, we propose the use of MAMCDM to determine a fair price for CO_2 emissions. The process should proceed as follows: first, a set of fictitious actors s has to be defined. Each represents a different point of view and is included in a context of variable power balance (i.e., the different influence of actors on the final choice of the value is included in the analysis).

Every agent has their own understanding about the criteria that affects the final unitary value of CO_2 emissions and different weights to attribute them (figure 3, point 1). These criteria c mostly coincide with the inputs or the specifications required to run an IAM. They can be roughly included in the following main groups: a general definition of the IAMs and their technical characteristics, the future scenario forecasted by each actor, the physical changes and the economic impacts (table 3).

Each of these parameters is a relevant issue in the academic debate. Let us consider, for example, the discount rate to be adopted. Higher discount rates lead to lower values and vice versa. The variation of the unitary CO_2 cost is very high: according to Watkiss et al. (2005), the value decreases from €249/tC to €102/tC when the 1% and 3% discount rates are considered, all other parameters remaining the same. The damage function is another critical parameter. It represents the mathematical transformation of climate change in economic values. Peck and Teisberg (1994) demonstrated the differences in adopting a linear rather than a cubic function (the interval grows from approximately \$34-118/tC to \$34-710/tC).

Group	Criteria			
1) Description of the IAM	*Year of publication*	*Unitary emission cost*	*IAM adopted*	
2) Economic impacts	*Reference year*	*Geographical scale*	*Adaptation measures*	*Equity weighting*
	Discount rate	*Pure Rate of Time Preference*	*GDP damage*	*Damage function*
3) Scenario	*Description of the scenario*	*CO_2 concentration*	*Temperature increase*	
4) Physical changes	*Sea level rise*	*Energy use*	*Agricultural impact*	*Water supply*
	Health impact	*Ecosystem and biodiversity*	*Extreme weather events*	*Major events/large scale discontinuity*

Table 3. List of criteria to be included in a MAMCDM for CO_2 emissions

Similar conditions can be found for the other parameters as well. By adopting the traditional IAM methods, every modeller decides the reference values arbitrarily and the final output is determined by this personal choices. Indeed, MAMCDM proposes a mediation in order to make opinion convergent towards a shared value. Each actor produces their "preferences table" (table 4, part A), in which their points of view relative to the evaluation criteria are expressed. The best value is the actor's optimal solution and range represents their willingness to move from the optimal solution. For example, in table 4 two polarized actors are fictitiously sketched (figure 3, point 2). Actor 1 could represent the point of view of an environmentalist, whereas actor 2 could be the paradigm of an industrialist. The preference function indicates their rough opinion about the criteria. Considering discount rate, it is possible to argue about a potential conflict. The environmentalist prefers an alternative with a high discount rate because of a thoughtfulness about future generations: therefore, he decides to assign to the criteria a high weight (25 points of 100, figure 3, point 3). The industrialist's position is very different (3.5/100), thus establishing a topic of discussion between the two actors. The ranking process begins (figure 3, point 4). According to the preferences of the single actors, the alternatives (table 4, part B) will be ranked in lists of preferences (one for each actor), as expressed in part C of table 4. These lists' preferences are produced by adopting pairwise comparison and will consist of ranked alternatives, which better fit with the actors' perspectives, interests and objectives.

The next step of this process is constituted by the analysis of the ordered lists of preferences (figure 3, point 5). These lists are outranked according to the preference net flows, which can be conceived as the inclination to a preference based on the parameters that fit best to the requirements of each actor.

A - PREFERENCES OF THE ACTORS

		Discount rate	*Equity weighting*	*N° of impacts*	*Carbon Tax*	*CO_{2eq} concentration*	*Temperature increase*
Actor 1	**Preference function**	*max*	*max*	*max*	*min*	*max*	*min*
	Weights assigned	25/100	25/100	19/100	5/100	15/100	11/100
	Best value	2.5	yes	5	n/a	550	2.5
	Range	2	---	1	n/a	n/a	n/a
Actor 2	**Preference function**	*min*	*min*	*min*	*min*	*max*	*min*
	Weights assigned	3.5/100	3.5/100	18/100	30/100	25/100	20/100
	Best value	0	n/a	2	no	650	5
	Range	4	n/a	n/a	----	305	10

B – CRITERIA

	Discount rate	*Equity weighting*	*N° of impacts*	*Carbon Tax*	*CO_{2eq} concentration*	*Temperature increase*
Alternative 1	5	no	5	yes	550	2.5
Alternative 2	10	no	4	yes	450	2.5
Alternative 3	n/a	no	0	no	450	n/a
Alternative 4	n/a	no	4	yes	1150	5.4

Table 4. Example of a preferences table, choice of the criteria and ranked preferences

Finally, the preferences can be graphically ranked. The spatial distance between two alternatives represents the degree of preference. Ranks will be recalculated under different grades of the actors' disposition to negotiate, which is the willingness to distance themselves from their first preference. In this phase, the negotiation plays a main role and the adoption of a GDNSS is required. The degree of flexibility is imposed for each actor deterministically: the point of maximum agreement represents the expected parameters most widely accepted to produce a shared estimation (figure 3, point 6).

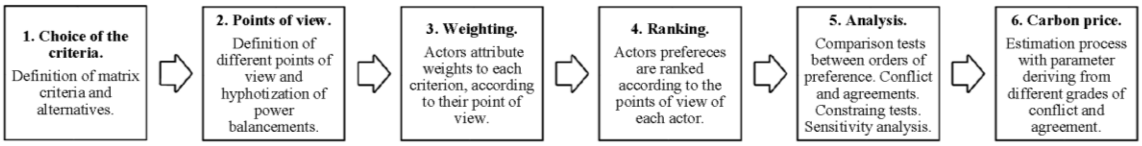

Figure 3. Schematization of the process to obtain a shared price of CO_2 emissions by using the MAMCDM

This estimation process will not rely only on an ex-post mediation of different technical approaches. Indeed, the process results from a deeper analysis, which aims to understand frames and to redefine them through a shared approach. The method is conceptually very different in comparison with the technical valuations, including the ex-post statistical meta-analyses, because it is based on human interactions and decisions taken before the production of a final value.

5. Conclusions and next steps

Most of the strategies currently adopted in transport planning and policy-making recommend that decisions be evidence-based and community-centered. Evidence-based decisions require a thorough understanding of current information regarding the territory considered, as well as the development and analysis of a good number of possible outcomes of different management options. Community-centered decisions should incorporate preferences, values, beliefs, thoughts, and other possible circumstances related to the elaboration of strategies that rank the welfare of the community as a distant first: this implies that an issue should be considered critical, only if conceived as such by relevant social groups. At the political level, (e.g. the Aarhus Convention), there is an attempt to make the decisional process on environmental and transport planning more accessible to the public. Nevertheless, complex aspects have not been based on these premises and are mostly addressed by adopting a mere technical approach. The perspective of the society has not been taken into account adequately, thus leading to misunderstandings and conflicts between different perspectives because a real debate has been prevented and the positions tend to be polarized. This DEAD approach favors decision-makers and postpones, or even omits, a real discussion with citizens.

This is also the case for CO_2 emissions. If we recall the dilemma of the transport planner as expressed in the introduction, it is clear that an evidence-based and community-centered solution has not been found yet. The adoption of the traditional CO_2 valuation methods cannot provide satisfactory results due to the vast ranges of values. From a technical perspective, IAMs seem to be the most effective approach, as they link CO_2 unitary price with environmental changes and economic damages. However, they cannot determine a shared approach, because they only consider the perspective and beliefs of the modeler, which is very subjective.

The statistical meta-analyses are only partially effective to solve this issue, because they do not take into account the dynamics and the mediation processes between the different points of view of the stakeholders (community-centered approach). This paper has introduced the Multiple Agent Multi Criteria Decision Making as an integrative solution to introduce a plural vision in the analysis. It allows the inclusion and weighting of the different points of views of the actors involved in the decision-making process. MAMCDM is designed to support decision making in complex circumstances identical to those posed by many common management decisions (i.e., operations research, computer science, environmental science, engineering, economics, energy, and water sources). A theoretical reconstruction of the process has been developed, revealing its adaptability to this kind of study and its innovative approach to the topic. A first explicative example has illustrated the potentials of this model practically. Further studies have to be carried out, in order to better specify this approach, including the development of a sharable methodology and the calibration on a real case study.

Nevertheless, this is a first step to integrate a plural methodology into a technical one, thus helping the transport planner to provide an evidence-based and community-centered CO_2 valuation.

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3.3. Inclusion in mobility plans: the carbon efficiency

Aware of the difficulties to find the most suitable form of plan to deal with CO_2 emissions (and not only), the EU has proposed the introduction of the Sustainable Urban Mobility Plan (SUMP). SUMP builds on existing practices and includes integration, participation, and evaluation principles to satisfy the mobility needs of citizens (Wefering et al., 2014). It considers several objectives. Some of them are those expressed in a traditional traffic plan: to improve safety and security, the efficiency of the goods and passenger transport, to reduce air and noise pollution. Others are more difficult to quantify, such as the objective to enhance the attractiveness and quality of the urban environment and urban design for the benefits of citizens, the economy and society as a whole (Bührmann et al., 2013). In this sense, SUMP is not a technical development of a sectorial knowledge; rather, it is the result of a multidisciplinary and integrated process, which comprises status analysis, vision building, objective and target setting, policy and measure selection, active communication, monitoring and evaluation.

Figure 4: The designing process of a SUMP. Source: Wefering et al., 2014

According to figure 4, activity 5.1 can consider the reduction of CO_2 emissions as one of the priorities for urban mobility. Consequently, the identification of the most effective measures to reach this target have to be provided within action 6.1. However, when trying to create a SUMP only general guidelines are given, while there is a lack of technical solutions to address specific topics such as carbon reduction. These aspects are demanded to the phase of transport programming, which should determine the work to be performed in a specified period to accomplish the objectives set, with due regard given to the relative urgency of work (TRB, 1978). This method has to select cost-effective projects reflecting community needs and develop a multiyear investment strategy within budgetary constraints over the planning horizon previously defined.

The two scientific articles that constitute this section are strictly connected. The article "*The ancillary role of CO_2 Reduction in Urban Transport Plans*" (Nocera and Cavallaro, 2014b) highlights the difficulties of some relevant European local transport and mobility plans to address the theme of CO_2 emissions actively. At the same time, the article discusses the ambiguous role of SEAPs: on the one hand, they present an (over)simplified approach to consider the measures in relation with carbon issues; on the other hand, they cannot cover the complexity of an integrated transport approach.

The article "*Carbon Estimation and Urban Mobility Plans: Opportunities in a Context of Austerity*" (Nocera et al., 2015b) tries to solve the carbon issue and urban mobility plans, by proposing a methodology to internalize the CO_2 impacts of measures. This methodology bases on a three-step approach, which partially takes into account the methodologies described in 3.1 and 3.2. First, a description of the measures to be included in the plan and their expected CO_2 results is carried out. Second, the economic valuation of the benefits is assessed. Third, CO_2 evaluations are included in a more comprehensive CBA that takes into account also other relevant transport issues and the choice of the most suitable measures is performed. The analysis refers to the periods of austerity, when considering carbon emissions as having a minor role can have critical consequences that could lead to wrong evaluations about the definition of priorities and the efficient allocation of money. The case study of the Italian city of Bologna, where a Municipal Structural Plan has been recently adopted, is presented. The methodology applied within this plan allows to calculate the costs of the measures, the carbon benefits and their efficiency, thus granting a comprehensive overview regarding the CO_2 aspects related to the transport measures.

3.3.1. The Ancillary Role of CO_2 Reduction in Urban Transport Plans

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The Ancillary Role of CO_2 Reduction in Urban Transport Plans

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Abstract

Saving CO_2 emissions constitutes one of the most delicate challenges of transport engineering. Coherently with EU and national directives, urban mobility and traffic plans should consider CO_2 savings as one of the goals to be reached. In an apparent contradiction, however, the measures generally proposed within urban transport plans seem to operate primarily for different aims, such as decongestion, improvement of public or alternative transport modes, determining an ancillary role of CO_2 emissions. Recently, other multidisciplinary forms of planning (e.g., SEAP) have been proposed; which also do not fully consider the complexity of the integrated transport approach. To solve this criticality, this paper presents a two-step method (balance and valuation) for considering CO_2 explicitly within mobility plans.

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Keywords: Transport Planning, Urban Transport Plan, CO_2 Emissions

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1. Introduction: the importance of CO_2 emissions in transport

The reduction of CO_2 emissions deriving from the circulation of private vehicles is considered as one of the most relevant problems in transport planning (Black, 2010). At European level, transport is responsible for about 26% of the total emissions (EC, 2005) and its increase, in comparison with 1990 levels, has been about 30% (EC, 2009),

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being the only civil sector not providing a reduction in last 20 years. At urban level, such figures are even higher: transport accounts for about 40% of the overall urban emissions (Glaeser & Kahn, 2010).

This means that transport is a real issue when concerning the reduction of carbon emissions, and it is not actively contributing to their reduction, as required from international agreements such as the Kyoto Protocol (UN, 1998) or the European "20-20-20" targets (EC, 2012). According to several technical reports, this could bring to severe damage to the community in the form of severe temperature increases and other environmental, social and economic consequences (IPCC, 2007) .

Two different strategies are normally referred to as the main ways of reducing carbon emissions. The first focusses on the supply side and intends to improve the energy efficiency of vehicles, to reduce the carbon content of the energy used and to improve the efficiency of ITS systems (Bell et al., 2012). The second one is centred on the demand side and aims at diverting demand segments to less impacting transport modes. So far, the emphasis of transport policies has been mostly focused on the supply side at the expense of measures designed to influence travel behaviours (Anable & Bristow, 2007), whereas the studies regarding demand are limited (Libardo & Nocera, 2008). Several technological solutions, particularly within car passenger and freight technology, have been developed and transport plans highlight their relevance in addressing the CO_2 issue. King (2007) states that market ready technology could reduce CO_2 emissions of new cars by 30% within 5 to 10 years. This is valid for the private car, but a comprehensive analysis about the effectiveness of the measure should also take into account the availability and cost of oil. In addition, the "rebound" effect seems to influence the price of certain transport solutions (Sorrell & Dimitropoulos, 2007): for example, the owners of a new vehicle tend to use it more than needed to abate the overall cost per kilometre, making the improvements in vehicle efficiency not lead to a corresponding decrease in overall vehicle emissions. Moreover, the evidence on the cost-effectiveness of behavioural instruments has been downplayed: total CO_2 from transport is a product of both the efficiency of the vehicles used and of the way they are used. If the users are asked to cooperate in order to achieve a carbon abatement, awareness campaigns or a series of measures must be promoted.

The distinction between supply and demand can be reinterpreted from a broader perspective, by adopting the distinction between push- and pull-measures (as discussed thoroughly in Nocera & Cavallaro, 2011). The former have been defined as those measures imposed on travellers and freight operators in order to influence individual decisions. They can be divided into financial instruments (e.g., taxes, charges and tolls) and technical and regulatory constraints (e.g., orders and bans). They are closely related to a more efficient and equitable transport pricing, seeking to require transport users to bear a greater proportion of the real costs of their journeys (including costs of pollution, accidents and infrastructure). On the other hand, pull-measures have been defined as those measures implemented in order to discourage the use of cars and trucks by improving the attractiveness of existing public transport alternatives. The results of our previous analyses (Nocera et al., 2012; Nocera & Cavallaro, 2012, 2014) identified the combined adoption of push- and pull-measures as mostly effective in promoting CO_2 savings when the realization of new infrastructures is at-stake.

2. The limited approach of urban transport plans

The European Green Book on the Urban Environment clearly states that CO_2 emissions must be taken into account to develop a sustainable mobility concept in urban areas (CEC, 2007). This document lists some measures, to be further investigated within the national context, with the overall goal of creating a new mobility culture and a reduction of urban congestion. Alternatives to the use of the private car, such as walking, cycling, public transport or the use of the motorbike and scooter have to be attractive and safe, so that citizens will prefer them over the car. Authorities should promote co-modality and reallocate space that becomes available after congestion mitigation measures. Intelligent and adaptive traffic management systems also have to be incentivized.

The issue of urban mobility is addressed at national and local level in a coordinated way, through the development of national and local plans. The single States provide general guidelines through the development of the national transport plans; because of the vast territorial scale and the differences of specific cities, the practical solution is demanded at local level, with the adoption of the regional, provincial and local transport plans. Particularly, this last form of plan seems to offer the most appropriate answers: a local transport plan aims at providing a sustainable form of urban mobility that considers the social, economic and environmental aspects. Such plans include the improvement of road safety and circulation, the reduction of air and noise pollutants, environmental protection, energetic saving and the concordance with other plans. Not surprisingly, the reduction of CO_2 emissions is set as one of the main objectives. The plan should provide a strategy to obtain such a reduction, through the adoption of specific measures. In practice, this occurs only rarely: as already mentioned in the introduction, a good number of plans focus on the supply side of the problem, highlighting the role of technological advances in the matter. Although increased efficiency confers economic benefits in its own right, its effectiveness in reducing fuel consumption and emissions depends on how consumers alter behaviour in response to cheaper energy services due to improved efficiency. To obtain the total savings potential from increased vehicle efficiency would require complementary measures (demand-side) to restrain demand increases, in which case the costs of achieving the reduction would fall. These demand-side measures are normally proposed in the plans but without providing a correspondence with the expected results in terms of CO_2 reduction, as well as the methodologies to evaluate the results economically. Therefore, the link between the measures and the expected reduction of CO_2 emissions is missing. The plan suggests that the reduction of CO_2 traffic emissions is one of the most urgent interventions to be carried out, and it can quantify them difficultly.

Several cases at European level confirm this condition. In France, the urban transport authorities elaborate the Plans de Déplacements Urbains (PDUs), obligatory for cities with more than 100,000 inhabitants and voluntary for smaller ones. PDU aims to assure coordination among all transport modes and to promote less polluting and more energy efficient modes. This can be achieved by reaching specific targets: to improve road safety; to reduce car traffic; to develop public transport and the less polluting sustainable transport systems (Cappelli et al., 2013); to exploit metropolitan routes and to implement traffic information; to organise and regularise on-street parking and public parking; to manage and regulate freight transport and multimodal transport (Cappelli & Nocera, 2006); to promote commuter plans for companies and public administrations; and finally, to develop integrated ticketing for the scope of mobility, parking and co-modality (Bührmann et al., 2013). CO_2 abatement is indirectly considered in the second point (“development of less polluting transport”), but no specific mention about how to reach this goal are given. To integrate this lack, the Paris PDU (CRI, 2012) provides an environmental annex, mostly focused on the externalities related to pollutant substances, including also CO_2. However, the analysis is limited to the past years and no forecasts about future emissions and their economic costs are provided (the only mention about future conditions concerns the technological improvements and reduction in terms of specific emissions expected for the new vehicles).

Vienna is another relevant example that confirms the discrepancies between the goals of the plan and the methods to reach them. The Municipal transport agency has developed the Verkehrsplan (Winkel, 2006), based on the directives of the 1999 Climate Protection Programme (Klimaschutzprogramm, KLIP). According to the Kyoto protocol, the KLIP prescripts a reduction of CO_2 emissions deriving from transport by 5% per capita between 1987 and 2010. To accomplish this goal, the traffic plan designs a set of specific interventions, mostly focussed on the modal split: the increase of public transport to 40%, cycle lanes to 8% and the contextual reduction of private vehicles (25%) by 2020. However, the plan specifies neither the contribution of the single measures to the reduction of CO_2 emissions, nor the expected costs.

The case of London is similar. The London Plan (London Plan Team, 2011) is the programmatic representation of the Mayor’s vision in terms of development, growth and wellness, including not only transport but also other spatial and energetic issues. One of the goals of the plan is the reduction of CO_2 emissions by 60% by 2025, thus reaching a level lower than in 1990: a particularly ambitious result that goes beyond the European “20-20-20” targets. The plan lists the areas of intervention, including energy network decentralization, sustainable design and construction, improving the use of renewable energies, encouraging renewable technologies, rationalizing heating and cooling, urban greening, green roofs and waste self-sufficiency. The measures to achieve this goal are presented without their specific effectiveness on CO_2 reduction, especially when the transport field is considered. The reason rests on the primary goal of the transport policies proposed in the document, which is to create “a city where it is easy, safe and convenient for everyone to access jobs, opportunities and facilities with an efficient and effective transport system which actively encourages more walking and cycling”. The environmental dimension is not ignored, but it is considered a consequence of other primary objectives. CO_2 reduction is left primarily to other urban fields, such as energy efficient buildings and energy efficient production from alternative sources and fuels.

In Italy, the legislation includes two main plans at local level: namely, the urban traffic plan (Piano Urbano del Traffico, PUT) and the urban mobility plan (Piano Urbano della Mobilità, PUM). PUT is a compulsory plan composed of a set of interventions aiming at improving urban road circulation of pedestrians, public and private vehicles. It is conceived for a short period (the validity is 2 years), hypothesizing an infrastructural urban layout basically unvaried. It is compulsory for all municipalities exceeding 30,000 inhabitants and for those municipalities characterized by a relevant seasonal flow of tourists. According to the Italian rules of the road (Italian ministry of infrastructures and transports, 1992), four main objectives have to be obtained: improvement of circulation (here including both movement and stops); improvement of road safety and security; reduction of atmospheric and acoustic pollutants; energy saving. The indicators adopted to evaluate the effectiveness of this plan are: improvement of circulation conditions (movement and stop); enhancement of road safety; reduction of acoustic and atmospheric contamination (criteria pollutants); energy saving activities; equity (Cascetta & Montella, 1998). The improvement of these technical performances is expected to have positive results on other social and environmental aspects, including the reduction of GHG emissions. However, this is an indirect consequence, not quantified. The old traffic plan of Rome (Comune di Roma, 1999) is representative in this sense, as it does not even mention the issue of CO_2 emissions.

PUM is a more comprehensive form of plan. It aims to improve the mobility system of a city, not limited on the circulation of its vehicles. Introduced by the Italian National Law 340/2000, PUM can be adopted by Municipalities on a voluntary basis. It covers a temporal horizon of at least 10 years, which makes this plan theoretically appropriate to deal with long-term transport aspects. PUM aims at integrating the urban interventions with European and national policies regarding the development of infrastructures, thus granting an intermediate level between, on the one hand, the National, regional and provincial transport plans and, on the other, the urban traffic plan. The overall objectives of a PUM are clearly expressed in the national law: ensuring the accessibility of jobs and services to all; improving safety and security; reducing pollution, GHG emissions and energy consumption; increasing the efficiency and cost-effectiveness of the transportation of persons and goods; enhancing the attractiveness and quality of the urban environment. It is expected to obtain these ambitious objectives through the adoption of concrete measures, including the formulation of future scenarios, the identification of actions to be financed, the monitoring of the effects produced (Regione Veneto, 2004), as well as the introduction of specific measures aimed at improving the infrastructural and transport systems. The theoretical framework is comprehensive and detailed. However, in practice, the Italian approach has revealed significant criticisms. From an economic perspective, the national fund necessary to implement the measures proposed in the PUM has never been operative and only the drafting of the documents has been financed by the Italian Ministry of Transport and Infrastructure, thus creating a discrepancy between the planning and the operative phases. Other criticalities concern the contents: the national guidelines focus on the realization of infrastructures at metropolitan area, but ignore the connection to the national and regional infrastructural level (ISFORT, 2011). Furthermore, the procedures to integrate the PUM with the master plan are missing, as well as the integration with local traffic plans. At operative level, an individual Municipality has to elaborate and implement its own strategies. With its limited financial possibilities, this means a prioritization of interventions. Aspects related to environment and health (including CO_2 emissions) have been considered secondarily, being indirectly obtained by solving the problems of congestion and modal shift. An emblematic example of this approach is the PUM of Rome. It does not ignore the environmental aspects; however, it refers primarily to the criteria pollutants. CO_2 emissions are mentioned briefly, by providing a hypothetical scenario (not described in its assumptions) and based on the forecast of the cars circulating in the future. The methodology is simplistic: the impacts of the measures are calculated by multiplying the expected distance saved by the unitary emissions. No relationship between measures and results is given. The Italian panorama includes examples of plans that try to focus more on the issue, such as the PUMs of Genua (Comune di Genova, 2010) and Venice (Comune di Venezia, 2008). Here, the reduction of CO_2 emissions is expressly one of the priorities and the methods to obtain this goal are outlined. The analysis of the historical data and the forecasts up to 2020 reveals that a reduction of GHG emissions by 20% cannot be obtained through only a renovation of the vehicle fleet, but a contextual reduction of traffic is necessary as well. The percentage of such reductions is a function of the target fixed at political level (for example, a 20% reduction of transport CO_2 emissions can be obtained with a diminution by 5% of traffic in comparison with current levels, whereas a reduction of emissions by 30% implies a decrease in traffic by 15%). The different options are developed by proposing five scenarios. For each of them, the infrastructural measures and policies are suggested. However, even in this case, no information about the costs and benefits produced by the adoption of these measures is given.

Recently, an evolution of the traditional urban mobility plan has been proposed, which focusses not only on the technical aspects but includes the human, social and environmental dimensions as well. The Sustainable Urban Mobility Plan (SUMP; Wefering et al., 2014) builds on existing practices and takes due consideration of integration, participation, and evaluation principles to satisfy the mobility needs of people today and tomorrow for a better quality of life in cities and their surroundings. The ultimate scope of a SUMP is to design a city for its inhabitants, by taking into account several objectives. Some of them are typical for a traffic plan: to improve safety and security, the efficiency of the goods and passenger transport, to reduce air and noise pollution. Other aspects are less technical and most difficult to be quantified, such as to ensure that all citizens are offered transport options that enable access to key destinations and services or to enhance the attractiveness and quality of the urban environment and urban design for the benefits of citizens, the economy and society as a whole (Bührmann et al., 2014). In this sense, SUMP is not conceived as a technical development of a sectorial knowledge; it is rather the result of a multidisciplinary and integrated process that comprises status analysis, vision building, objective and target setting, policy and measure selection, active communication, monitoring and evaluation. However, to create a SUMP only guidelines are given and many criticalities seem not yet solved, particularly referring to the possible effects on key environmental impacts of transport - namely noise, air quality and CO_2 emission. SUMP is a concept that lacks a practical implementation and a broadly accepted definition and terminology.

To summarize, what emerges from a typical urban mobility or transport plan is a general discrepancy between the overall goals (CO_2 reduction is considered among them) and the effective policies adopted (there are no measures directly related to the reduction of carbon emissions). This does not necessarily mean that CO_2 is ignored. It means that measures conceived for other purposes (e.g., reduction of traffic, increase in the use of public transport, fostering alternative means of transport, reduction of criteria pollutants) seem to give a certain carbon gain as a secondary effect, also producing an indirect positive effect on CO_2 emissions. This is not only due to technical difficulties in quantifying and evaluating the emissions (Nocera & Cavallaro, 2014), but is also caused by political choices. CO_2 is often seen as a global problem: consequently, it can occur that politicians prefer to address other issues mostly related to local scale to increase their consensus with their potential voters. It derives that the real effects of CO_2 may be underestimated or not adequately evaluated in terms of transport planning.

3. A possible solution to assess GHG emissions in mobility plans

To solve the problem of CO_2 emissions in transport planning, an integration to the current approach is necessary: being CO_2 reduction fixed as one of the specific objectives of the plan, direct measures should be proposed, whose effectiveness and applicability at urban level could be tested. Practically, this means to decline the generic guidelines of SUMPs in concrete measures. In Nocera et al. (2012) and Cavallaro et al. (2013), we developed two possible approaches to quantify CO_2 emissions related to the introduction of a specific new infrastructure along a transnational corridor. Referred to urban areas, the approach is partially different and many alternatives can be adopted. The Multi Criteria Analysis (MCA) and the Multiple Agent Multi Criteria Decision Making (MAMCDM) are a first possibility (Scarpellini et al., 2013; Nocera et al., 2014): MCA allows considering criteria in their own unit of measuring, hence disregarding monetization problems. GHG emissions can be part of a deeper analysis that includes other values to decide the most effective measures. However, this method can be affected by important subjective biasing: Browne & Ryan (2011) consider the choice of the criteria, the weights to be assigned and the risk of double counting as the most significant. Alternatively, a Cost Effectiveness Analysis (CEA) can be adopted. This method basically compares the costs of alternative approaches in producing the same result. The outputs of a CEA regarding CO_2 emissions are expressed as the optimum abatement price of emissions, i.e. the intersection between the curves of marginal avoidance cost and marginal social damage. The limit of this method is that it has to be applied to each objective separately, thus preventing a comparative analysis (like in MCA) and making the analysis restricted. Moreover, to grant the comparability of results, the assumptions of the different alternatives have to be similar.

The Cost Benefit Analysis (CBA) is a possible alternative solution. Indeed, this approach is normally preferred to analyse the environmental policies of the transport sector when a fair unitary price is given (Turner, 2007). In the analysis of CO_2 emissions, CBA can be conceived as the result of an energetic and economic balance. Such combined approach, currently missing in urban mobility plans, can be partially derived from the Sustainable Energy Action Plan (SEAP - EU, 2010[†]) and partially from our previous research in valuation of GHG emissions (Nocera and Cavallaro, 2014). The schematization of such process is illustrated in figure 1.

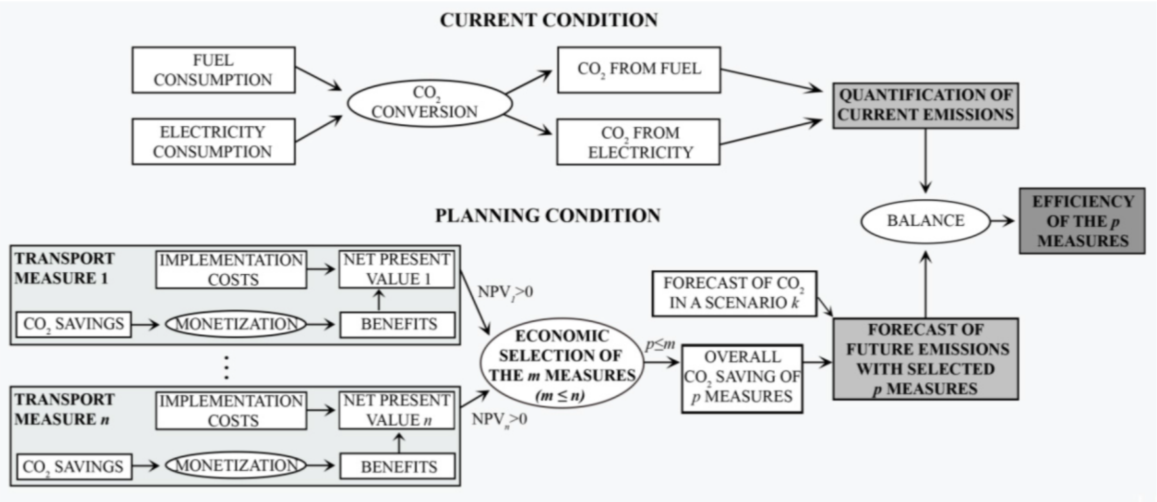


Figure 1. Schematization of the process to include CO_2 evaluation in mobility plans.

The method starts by preliminarily analysing the current condition to be obtained through the quantification of CO_2 emissions deriving from transport in a given year. To this aim, the guidelines of SEAPs suggest to calculate the adoption of the fuel sold at municipal/provincial level by the petrol stations, as well as the electricity adopted for the circulation of trains and electric-powered means of transport. Through appropriate coefficients of transformation (IPCC; 2006; Terna, 2009), it is possible to derive the CO_2 emissions from the electricity and petrol used in a given locality, thus obtaining the baseline emission inventory (BEI).

Subsequently, a set of transport measures has to be chosen and evaluated, according to the reduction target fixed by the mobility plans. To this aim, each measure has to be accompanied by a description of the activities required for their complete adoption, the cost estimation, timing, energy savings and CO_2 reductions, in order to make the choice as transparent as possible. In Table 1, a couple of transport measures are presented, which have been proposed for the city of Granada. At the end of this part of the process, it is possible to define the reduction of CO_2 emissions that the plan has to achieve, as well as the expected costs of each action (table 1, columns 4 and 5).

[†] Even if not legally mandatory, SEAP is a significant environmental instrument at local level to achieve the EU 20-20-20 target (Radulovic et al., 2011), having reached about 5,750 subscriptions from Mayors and covering about 187,500 inhabitants through the whole of Europe (Covenant of Mayors, 2014). SEAP outlines the activities and measures foreseen by signatories in order to fulfil their commitments, with corresponding periods and assigned responsibilities. The goal is to propose a radical change of the current energy model. This plan includes different fields, such as buildings, equipment/facilities, local electricity production, transport and local heating/cooling generation.

Table 1. Transport measures as proposed by the SEAP of Granada to reduce CO_2 emissions. Source: City of Granada, 2012.

MEASURE	DATE	DESCRIPTION OF THE MEASURE	CO_2 REDUCTION (t/year)	COST (€)
Public Transport improvement	2009-2020	Improving the public transport with biofuels, GLP and electricity in public transport. Restructuring of public transport, new minibus line and improving intercity transport.	93.699,97	3.819.251,15
Private and commercial transport ventures	2009-2020	Improving the management rationalization of urban freight distribution, promoting walking and cycling with safe routes and informative materials. Creation of a platform for car sharing. Promotion of cycling and mobility management. Installation of bicycle parking at schools.	22.296,20	2.165.000,00

The following step is the definition of the future emissions, as well as the economic evaluation of the benefits generated by the measures in terms of CO_2 reduction, so that benefits can be related to the costs of implementation through a CBA. With the current methodologies, many difficulties in providing a fair evaluation of CO_2 emission costs seem unavoidable, due the numerous sources of economic and scientific uncertainty, such as the current level of emissions, the forecasting methodologies, the correlation emissions-concentration, temperatures and levels of emissions, the economic damage, the equity weight and the discount rate (Clarkson & Deyes, 2002). Since the range of the estimates covers up to six orders of magnitude (Nocera & Tonin, 2014), it does not allow for the adoption of a fair unitary value. To address this problem, in Nocera & Cavallaro (2014), we proposed yearly values based on a thorough analysis of several European studies carried out in the last 20 years and a statistical approach to define a wider range up to 2035. Three final classes have been defined (the lower, medium and upper ones), according to the different reduction targets fixed by the policy-makers (table 2).

Table 2. CO_2 prices (€/tCO_2) adopted here for the years 2010–2020. Lower, central and upper values. Source: Nocera & Cavallaro, 2014

Year	Lower value (€/tCO_2)	Central value (€/tCO_2)	Upper value (€/tCO_2)	Year	Lower value (€/tCO_2)	Central value (€/tCO_2)	Upper value (€/tCO_2)
2010	19.45	23.14	50.43	2023	26.49	53.90	88.52
2011	19.93	25.46	53.23	2024	27.22	57.06	91.89
2012	20.42	27.77	56.03	2025	27.95	60.22	95.25
2013	20.90	30.08	58.83	2026	28.68	63.37	98.61
2014	21.39	32.40	61.63	2027	29.41	66.53	101.97
2015	21.88	34.71	64.43	2028	30.14	69.69	105.33
2016	22.36	37.03	67.23	2029	30.87	72.85	108.69
2017	22.85	39.34	70.04	2030	31.60	76.00	112.06
2018	23.33	41.66	72.84	2031	32.81	79.22	115.98
2019	23.82	43.97	75.64	2032	34.03	82.43	117.29
2020	24.31	46.28	78.44	2033	35.25	85.65	121.21
2021	25.04	47.59	81.80	2034	36.46	88.87	125.13
2022	25.77	50.75	85.16	2035	37.68	92.08	129.05

By multiplying the expected savings by the unitary price (table 2), it is possible to assign an economic value to the benefits of the single transport measures in terms of CO_2 reduction. This integration allows the adoption of an explicit evaluation of the effectiveness in terms of CO_2 reduction of the measures proposed.

The method previously described may grant four main aspects of a fair evaluation. First, it is possible to measure the performance in an objective manner and within an acceptable degree of accuracy and reliability, thus not making CO_2 a generic externality but an active parameter that affects transport decisions. Second, it is possible to collect, generate or extract reliable data relating to the performance measure without excessive effort, cost or time. This constitutes a relevant advantage because of the limited resources required to monitor the effectiveness of the measures. Third, the performance measures are clear and concise so that the manner of assessing and interpreting its levels can be communicated effectively. This aspect is particularly relevant in transport field, as far as the management of the relationships with stakeholders and public is concerned: a clear and shared definition of the problems, obtained through evident indicators, helps to prevent the increase in social conflicts (Cavallaro & Maino, 2014). Fourth, the method considered should be generalized and not refer to single cases only: with the adequate modifications deriving from the specific urban conditions and transport systems, the method presented in this paper can be iterated and included in different mobility plans.

4. Conclusions

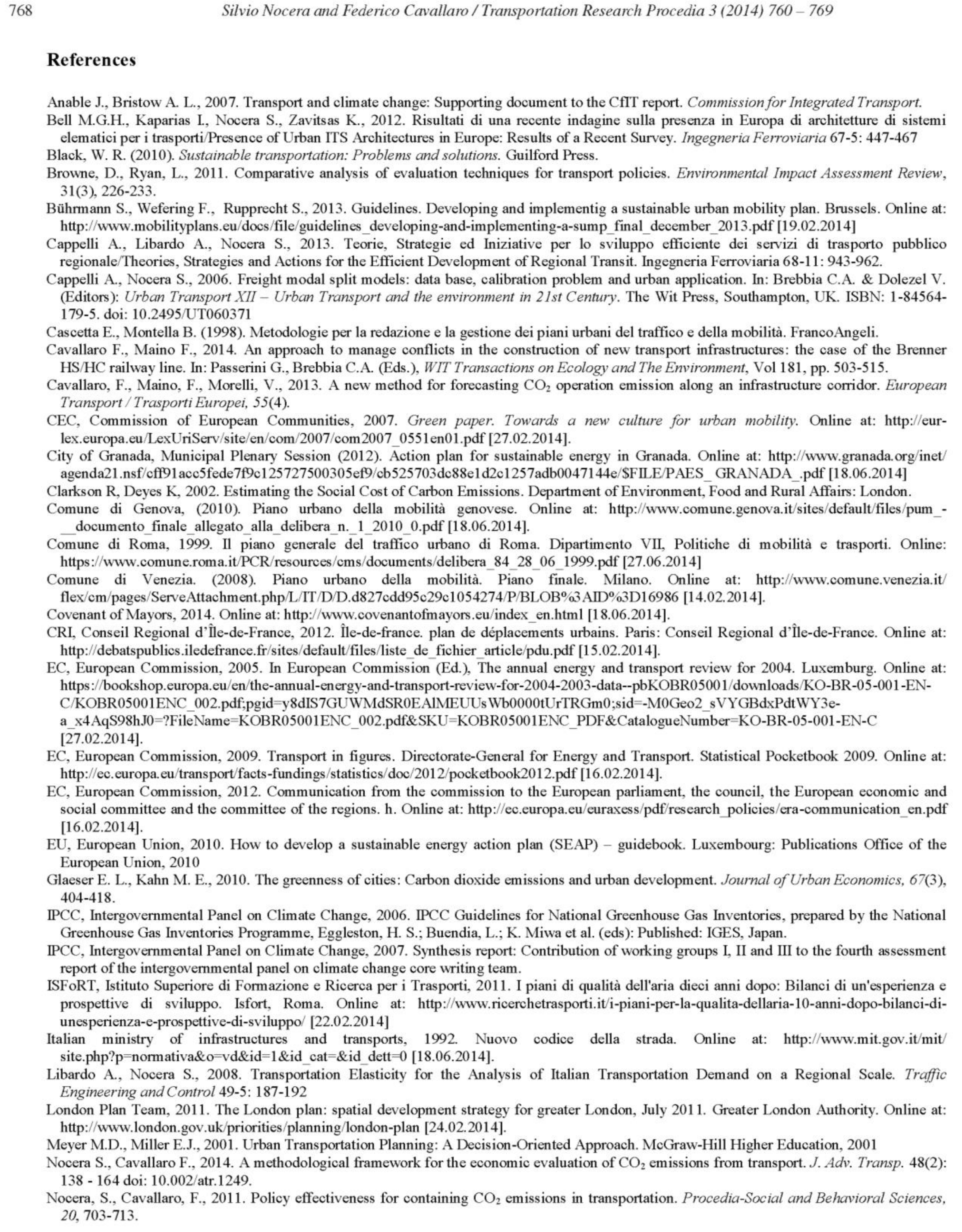
The evaluation of the cost-effectiveness of transport measures for carbon reduction within transport plans addresses at least three preliminary issues: the assumptions about future costs and level of travel demand, the methods applied to compare policies for cost-effectiveness and the evidence of data used in relation to different types and combinations of policy instruments. One of the main difficulties lies in the fact that only a narrow set of measures targets the reduction of carbon levels as a primary aim and that isolation for carbon abating potential has a quite significant degree of uncertainty. Moreover, any estimate of cost-effectiveness is critically dependent on the future that is assumed. High uncertainty, as in any transport plan including the construction of infrastructures, can carry with it precautionary estimates and hence higher costs. Above all, in the long term, uncertainty includes not only travel demand but also targets oil availability and subsequently the cost of conventional fuels. Analyses tend to assume that oil based fuels will continue to exist at affordable prices and quantities, not considering the primary role of hybrid-electric and battery-electric vehicles (Weiss et al., 2012). This may have the effect of overestimating economic growth and/or stability (and thus travel demand) and downplaying the cost of reliance on conventional technologies and the role that could be played by innovation towards alternative fuels and lifestyles.

As illustrated in section 2, the current forms of transport and mobility planning do not seem to evaluate the effects of GHG emissions properly. Local traffic plans generally include their reduction as one of the overall goals but do not quantify the expected impacts of specific measures, nor general values, thus revealing a discrepancy between general aims and indicators. The scheme adopted by this kind of plan focusses more on the adoption of practical measures; it describes the effects in terms of traffic decongestion and improvement of public or alternative transport, without actively assessing the consequences in terms of global warming. This does not necessarily mean that the measures are ineffective, but rather that it is very difficult to appraise their impacts if they are not evaluated specifically, consequently leading to a potentially incorrect appraisal of the overall plan.

To overcome such a critical condition, transport plans have been recently flanked by other alternative forms of plans such as the SEAP, which deal specifically with CO_2 reduction, including different sectors of civil society. However, these plans do not seem to be the most appropriate solution to address the issue of transport emissions, because they focus only on the energetic aspects hereby lacking in the solution of transport issues. Indeed, a mobility plan is very complex thematically and normally requires a holistic approach that includes the relevant values related to traffic circulation, transport modes, etc... CO_2 emissions are one of these points, but cannot be considered as the exclusive one.

In the present paper, we have proposed an integration of the methodology developed by SEAP with a valuation of the benefits deriving from the reduction of CO_2 emissions through a balance. This can be included in urban mobility plans as one of the components that contribute to determine the final proposals. The method has been kept intentionally simple in order to make it available for the use of policy-makers and stakeholders and because of several scientific and economic uncertainties. Several aspects can be improved upon, such as the quantification of current emissions with methods that are more accurate or the definition of a fairer unitary value of emissions by assessing the different uncertainties that affect the process.

Nevertheless, as a transport plan has traditionally reflected the policy concerns of the time in which it was occurring (Meyer & Miller, 2001), carbon emissions have now to be included as a part of it. Because of this, as the success of planners to analyse and evaluate transport systems is influenced by the tools available, it is necessary to conceive efficient and integrative methods to be included within traditional transport analyses. If agreed upon, this approach will likely be trending in transport planning over the next several years, bringing a challenge to transport planners: making sure that this change is made to preserve the substance of the planning process, while at the same time producing the desired results.



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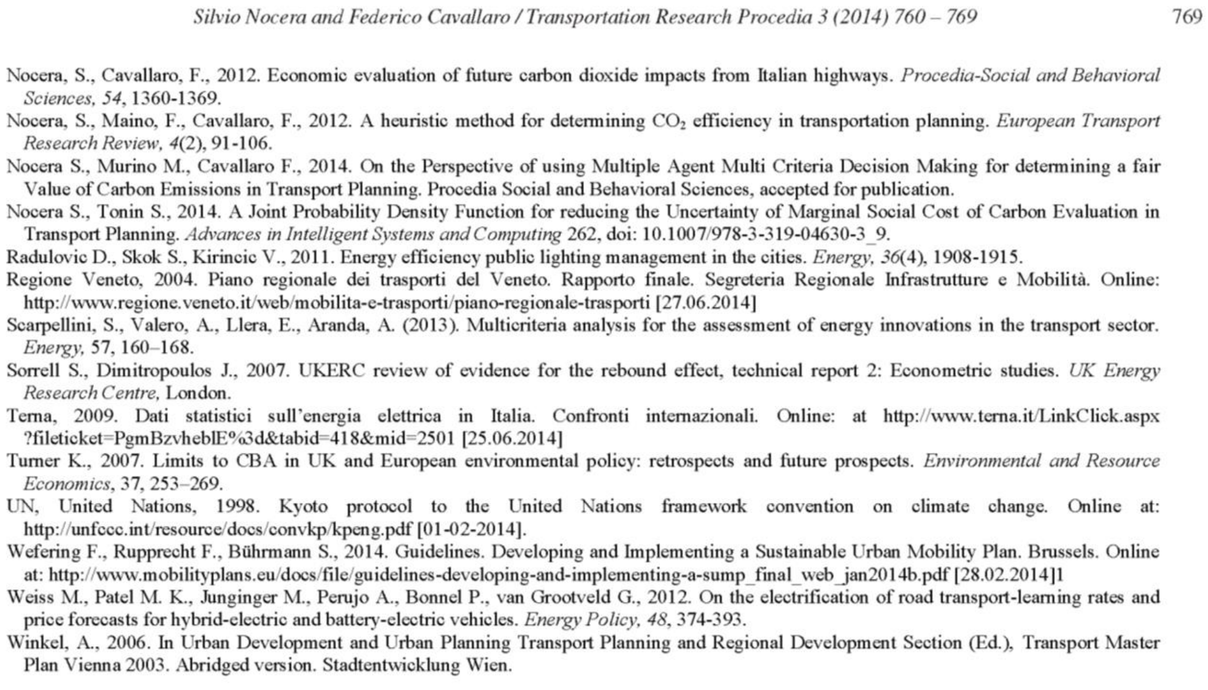

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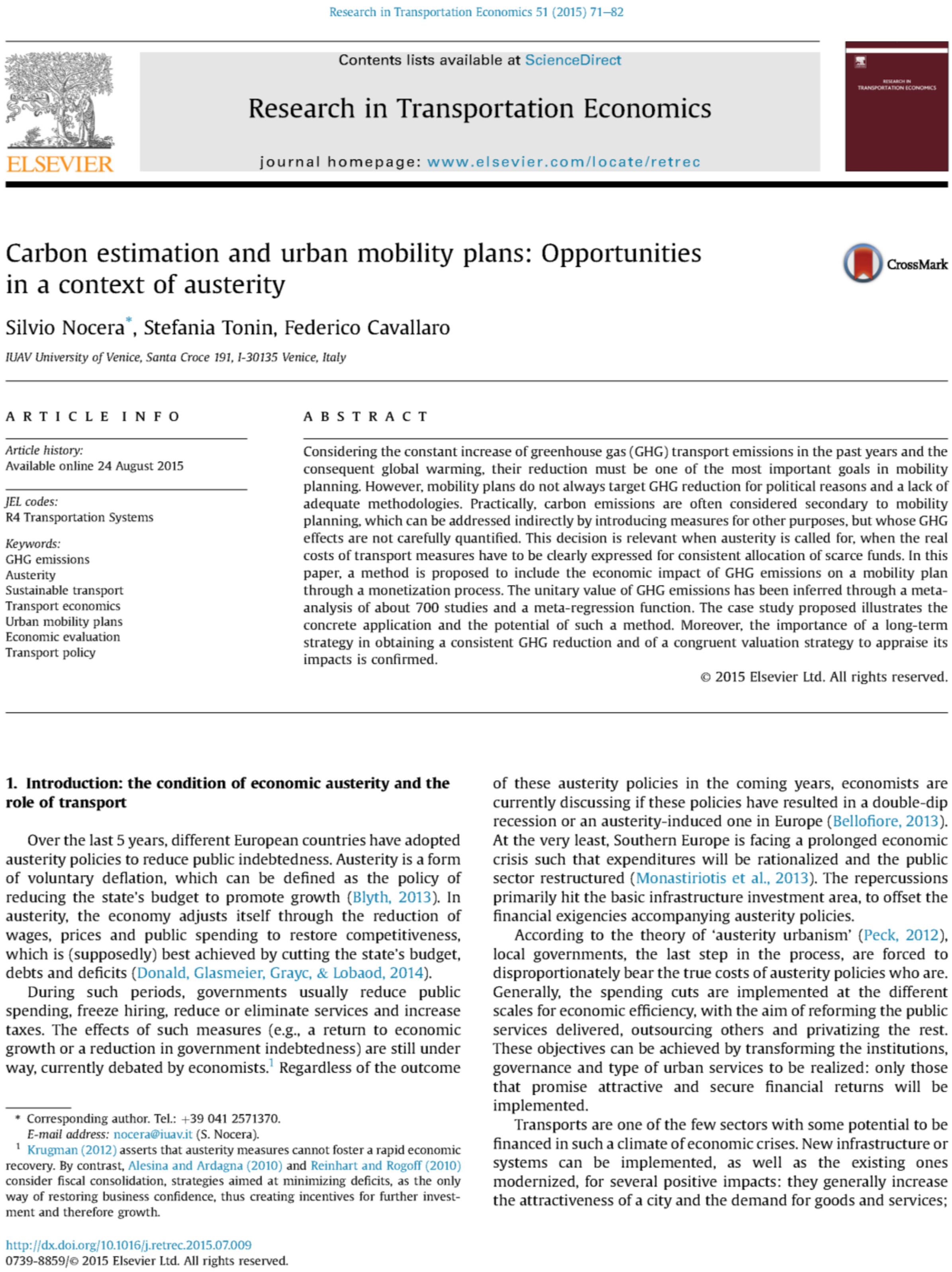
3.3.2. Carbon Estimation and Urban Mobility Plans: Opportunities in a Context of Austerity



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Carbon estimation and urban mobility plans: Opportunities in a context of austerity

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ABSTRACT

Considering the constant increase of greenhouse gas (GHG) transport emissions in the past years and the consequent global warming, their reduction must be one of the most important goals in mobility planning. However, mobility plans do not always target GHG reduction for political reasons and a lack of adequate methodologies. Practically, carbon emissions are often considered secondary to mobility planning, which can be addressed indirectly by introducing measures for other purposes, but whose GHG effects are not carefully quantified. This decision is relevant when austerity is called for, when the real costs of transport measures have to be clearly expressed for consistent allocation of scarce funds. In this paper, a method is proposed to include the economic impact of GHG emissions on a mobility plan through a monetization process. The unitary value of GHG emissions has been inferred through a meta-analysis of about 700 studies and a meta-regression function. The case study proposed illustrates the concrete application and the potential of such a method. Moreover, the importance of a long-term strategy in obtaining a consistent GHG reduction and of a congruent valuation strategy to appraise its impacts is confirmed.

1. Introduction: the condition of economic austerity and the role of transport

Over the last 5 years, different European countries have adopted austerity policies to reduce public indebtedness. Austerity is a form of voluntary deflation, which can be defined as the policy of reducing the state's budget to promote growth (Blyth, 2013). In austerity, the economy adjusts itself through the reduction of wages, prices and public spending to restore competitiveness, which is (supposedly) best achieved by cutting the state's budget, debts and deficits (Donald, Glasmeier, Grayc, & Lobaod, 2014).

During such periods, governments usually reduce public spending, freeze hiring, reduce or eliminate services and increase taxes. The effects of such measures (e.g., a return to economic growth or a reduction in government indebtedness) are still under way, currently debated by economists.[1] Regardless of the outcome of these austerity policies in the coming years, economists are currently discussing if these policies have resulted in a double-dip recession or an austerity-induced one in Europe (Bellofiore, 2013). At the very least, Southern Europe is facing a prolonged economic crisis such that expenditures will be rationalized and the public sector restructured (Monastiriotis et al., 2013). The repercussions primarily hit the basic infrastructure investment area, to offset the financial exigencies accompanying austerity policies.

According to the theory of 'austerity urbanism' (Peck, 2012), local governments, the last step in the process, are forced to disproportionately bear the true costs of austerity policies who are. Generally, the spending cuts are implemented at the different scales for economic efficiency, with the aim of reforming the public services delivered, outsourcing others and privatizing the rest. These objectives can be achieved by transforming the institutions, governance and type of urban services to be realized: only those that promise attractive and secure financial returns will be implemented.

Transports are one of the few sectors with some potential to be financed in such a climate of economic crises. New infrastructure or systems can be implemented, as well as the existing ones modernized, for several positive impacts: they generally increase the attractiveness of a city and the demand for goods and services;

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[1] Krugman (2012) asserts that austerity measures cannot foster a rapid economic recovery. By contrast, Alesina and Ardagna (2010) and Reinhart and Rogoff (2010) consider fiscal consolidation, strategies aimed at minimizing deficits, as the only way of restoring business confidence, thus creating incentives for further investment and therefore growth.

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facilitate easy movement; drive economic growth; and activate a variety of sectorial, spatial and regional effects. Scholars quantify that a dollar spent on infrastructure typically adds \$1.59 to the gross domestic product (GDP) (ESA, 2009). However, huge investments in transport usually increase some negative externalities leading to consequently higher external costs – such as congestion, accidents, air pollution and climate change (Ricardo-AEA, 2014). Presently, the fair calculation of such external costs – above all, the climate change impacts – is considered a serious issue (Musso & Rothengatter, 2013) and the first compelling step in ensuring economic efficiency, more so in the context of austerity and resource scarcity.

The process of decision-making must prioritize settings, rationality and efficient allocation. In the case of carbon estimation, it is difficult to assess the potential cost of climate change. This issue has particular consequences in austerity, when resources are difficult to replace and allocative inefficiency may reduce the social profitability well below the full potential. In these conditions, it is essential to carefully predict the social impacts of modified travel demand and modal choice, thereby lowering the risk of biased parameter estimates and elasticity of demand and substitution. Because a shared methodology and a fair economic value are difficult to find, most of the current mobility plans consider greenhouse gas (GHG) emissions as only one of the externalities to be minimized, which, however, are not actively included in the evaluation (Nocera & Cavallaro, 2014a). This paper attempts to overcome this criticality by proposing – and testing – a methodology that determines the fair value of GHG emissions from transport. The paper is structured as follows: the issue related to transport GHG emissions is presented in the second section, highlighting the current difficulties in including such a value in mobility plan analysis and the implication of this criticality during a period of austerity. In the following sections, a method that addresses the problem actively is described (Section 3) and tested on a case study (Section 4). Some final remarks on the implication in terms of austerity and possibilities offered by our method are presented in the final section.

2. Evaluation of GHG emissions in transport planning during an age of austerity

In general, all studies agree that the most relevant challenge to mobility planning is GHGs. Transport accounts for 24.3% of the total current CO_{2eq} emissions,[2] which increased to about 22%[3] (EU, 2014), compared with the 1990 levels. Urban areas display considerably higher emissions: transport accounts for about 40% of the overall urban emissions (Glaeser & Kahn, 2010).

Although the international community is aware of the problem, it is extremely difficult to find a globally shared approach to address it coherently. This was first attempted in the beginning of the 1990s: the transport Green Paper (EC, 1995) was produced in Europe, with GHG emissions playing a pre-eminent role; at the global level, the Kyoto protocol (1998) and other documents were drafted, and many international conferences organized. Among them, the meeting held in Durban (2011) clearly highlighted the potential contributions at the local scale: because cities manage huge funds, investments and public infrastructure (including transports), they are capable of effectively addressing global warming.

Theoretically, as they are suited to analysing long-term issues covering at least a decade, urban mobility plans can address the issue of GHG emissions. Accordingly, one of the main aims in the national laws is their reduction. However, in practice, the measures related to GHG emissions are often considered ancillary to other primary traffic targets: the Paris Plan de Déplacements Urbains (CRI, 2012), for instance, includes the *'development of less polluting transport'*, but it does not specifically mentioned the method of GHG reduction. The plans of Rome (Comune di Roma, 1999), Vienna (Winkel, 2006) and London (London Plan Team, 2011) are not very different (Nocera & Cavallaro, 2014a).

This approach does not seem appropriate for such an important issue. The reasons for this are severalfold, with some referring to political choices and others being associated with methodological problems. First of all, transport measures conceived for other purposes (e.g., for reducing traffic, increasing the use of public transport, fostering alternative means of transport and reducing criteria pollutants) are normally expected to give a certain carbon gain as a secondary effect, which normally keeps the latter out of the proposition as well as out of the valuation. Some studies offer efficient future technological solutions for carbon gains (Anable & Bristow, 2007), but without providing an overall analysis that includes the supply aspects: fuel consumption and emissions depend on how consumers alter behaviour in response to cheaper energy services due to improved efficiency. If these variations are not assessed, the evaluations cannot be coherent. Second, policymakers tend to consider carbon damage globally but the general scarcity of available resources locally, in order to increase their consensus with potential voters. Third, the numerous economic and scientific uncertainties complicate the valuation of GHG emissions (Clarkson & Deyes, 2002; Nocera, Tonin, & Cavallaro, 2015), as their increase has a number of effects on the climate system and economy over a long period of time. Particularly, one of the main controversial aspects is the choice of the economic, environmental and social effects to be included in the valuation: these may include several fields, such as the agricultural sector, forestry, water resources, ecosystems, biodiversity, coastal zones (sea-level rise), energy use, air quality and human health (Watkiss et al., 2005). The economic value of such damage obviously depends on the effects included in the models as parameters. There is no general consensus on this, thus leading to an uncertain valuation (Nocera & Cavallaro, 2012) that may range up to six orders of magnitude (Nocera, Murino, & Cavallaro, 2014; Nocera & Tonin, 2014).

In a period of austerity in particular, the tendency of downplaying the role of carbon can have critical consequences, concretely leading to wrong definitions of the priorities. The tradeoff process would require the impacts and benefits of the different alternatives to be consistently and completely estimated: although being a methodological error of some consistency contrary to some recent European recommendations (EC, 2011; Wefering, Rupprecht, Bührmann, & Böhler-Baedeker, 2013), this may lead to relevant social and political consequences, with inappropriate allocation of funds or incentives when adopting specific measures.

The appropriate inclusion of GHG valuation in a mobility plan is of concern, requiring a rigorous approach in the phases of transport planning and programming[4] (Sinha & Labi, 2007). To integrate the

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[2] CO_{2eq} is the unity of measure that describes the global warming potential (GWP) produced by GHGs, that is, the concentration of CO_2 that would cause the same level of radiative forcing as that caused by the GHGs (Solomon et al., 2007). Carbon dioxide (CO_2) is the reference unit value of GWP ($1tCO_2 = 1tCO_{2eq}$). CO_2 is the most relevant of the GHGs, with >75% of total anthropogenic GHG emissions (IPCC, 2007); in several environmental assessments (such as the SEAPs described in Section 3), CO_2 is chosen tout court as an indicator of global warming.

[3] In these figures, the terms 'transport', 'international aviation' and 'international maritime transport' are included.

[4] Transport programming is the operative phase that determines the work to be performed in a specified period to accomplish the set of objectives (TRB, 1978). Cost-effective projects reflecting community needs must be selected and a multiyear investment strategy developed within budgetary constraints over the planning horizon previously defined.

two phases and create a synergic approach, the European Union (EU) has recently provided the guidelines of a new form of transport plan, called Sustainable Urban Mobility Plan (SUMP). SUMP presents a long-term strategy for the future development of urban area and their transport and mobility infrastructure and services; it also includes a delivery plan for implementing the strategy in the short term (EC, 2013). In terms of the most relevant mobility aspects, it encourages a shift towards more sustainable modes. In this sense, SUMP is not related to the implementation of mere technical knowledge but rather specifically to traffic and congestion issues. Indeed, it is the result of a multidisciplinary and integrated process that includes status analysis, definition of a vision, objectives and targets, selection of policies and measures, assignment of responsibilities and resources, active communication, monitoring and evaluation (Wefering et al., 2013). One of these objectives includes GHG reduction. However, this flexible plan reveals some limitations when applied practically. For GHG emissions in particular, the technical documents provide only guidelines but not a replicable and scalable method for specific cases. Such a method can only be applied locally or in future shared methodologies.

3. A methodology to include GHG emissions in the transport plan

In this section, a method is proposed to solve the criticality highlighted in SUMPs and to evaluate the GHG efficiency of specific transport measures in transport plans. Nocera, Maino, and Cavallaro (2012) and Cavallaro, Maino, and Morelli (2013) developed two possible approaches to quantify CO_2 emissions when introducing a specific new infrastructure along a transnational corridor. The method can be generalized to every single transport infrastructure or corridor, but not to complex systems such as urban areas. Hence, an alternative approach is required because of the different scale and territorial context. The method presented in this paper is based on three main parts. First, the measures to be included in the plan and their expected results are described (Section 3.1). Second, the benefits are valued (Section 3.2). Third, the most suitable measures were chosen by including CO_2 valuation in a more comprehensive approach that considers other relevant transport issues as well (Section 3.3). The process is schematized in Fig. 1.

3.1. Definition of the transport measures: the methodology (and the limits) of Sustainable Energy Action Plan

First, the method includes defining the transport measures that can be theoretically implemented to reduce GHG emissions. To this end, a parallel form of planning such as the Sustainable Energy Action Plan (SEAP; Covenant of Mayors, 2010) can be used. SEAP is a voluntary plan that attempts to translate the European targets of GHG reduction (at least 20% by 2020) into the local context. To achieve this objective, the plan includes different fields, such as buildings, equipment/facilities, local electricity production and local heating/cooling generation and transport. The methodology works as follows: the current condition must be analysed first using a GHG Baseline Emission Inventory (BEI), which highlights the measured values for each sector. By adopting detailed measures, the long-term strategy and goals are declined at an operative level.

The SEAP guidelines suggest the following six main transport fields of intervention, which can be included among the push and pull measures (Nocera & Cavallaro, 2011): the decline in the need for transport, the increase of the appeal of alternative transport modes, the reduction in the attractiveness of private vehicles, information and marketing, the decrease in municipal and private vehicle fleet emissions and interventions related to smart transports. Each field contains a subset of specific measures that could limit GHG emission (see Appendix 1). Along with each of the chosen measures, the specific context must be described, including those responsible, the implementation cost, the temporal horizon, the estimated energy saving and GHG reductions. After their introduction, emission inventories must be compiled and updated to monitor the progress towards the target. Such an emission inventory is called a Monitoring Emission Inventory (MEI). At the end of the process, the reduction of GHG emissions can be quantified by comparing the BEI and the final version of MEI. The different fields concur in defining an overall urban GHG saving, which is the final output provided by the SEAP.

The outcomes derived from SEAPs have two main criticalities, which make them inherently unsuitable for transport planning. First, according to its nature, SEAP focuses only on the energetic aspects, excluding the other mobility consequences that a specific measure can determine. Second, how the actions would be chosen and what the potential alternatives could be are not explained. In other words, a SEAP is rather deterministic, illustrating only what will be adopted, but without evaluating their effectiveness. The integration of the former criticality in a SUMP appears to be valid, so that the impacts proposed with the specific aim of GHG reduction can be compared with other mobility issues. The latter is widely discussed in the next subsection.

3.2. The effectiveness of transport measures in GHG reduction

Several techniques can be adopted to evaluate the effectiveness of specific transport actions in reducing GHGs. First, multi-criteria analysis (MCA) can be adopted (Scarpellini, Valero, Llera, & Aranda, 2013): it expresses the criteria in their own unit of measure, hence disregarding monetization issues when an appropriate unitary value cannot be assigned. Thus, GHG emissions are part of a

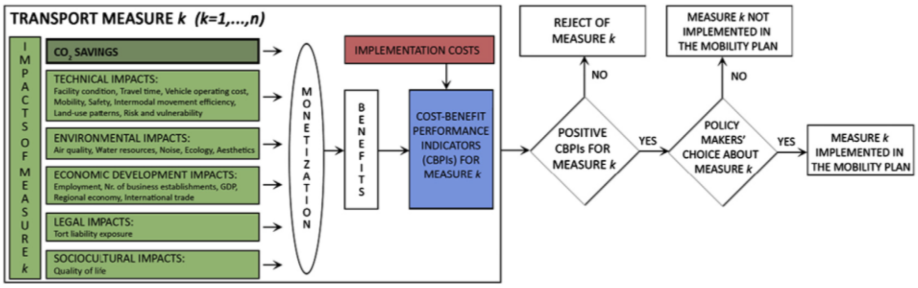

Fig. 1. schematization of a process to include GHG evaluation in a mobility plan.

deeper analysis that includes other values in order to decide the most effective solutions. This method produces generally sound results; in some cases, however, it can be affected by significant subjective biasing, such as the assignment of the weights and the selection of the criteria to be considered in the analysis (Browne & Ryan, 2011). Alternatively, the literature suggests that a cost-effectiveness analysis (CEA) can be adopted. This method compares alternative solutions to obtain the same result. With respect to GHG emissions, the outputs of a CEA are expressed as the optimum abatement price of emissions, that is, the intersection between the curves of marginal abatement cost and marginal social damage. This method is successful only when a single objective is considered, as it is difficult to combine several objectives. Moreover, to grant the comparability of results, the different alternatives must have similar assumptions. The cost–benefit analysis (CBA) is an alternative solution. This approach is adopted to assess the environmental policies of the transport sector when a fair unitary price is given (Cambridge Systematics, 2008). Many scholars have investigated the methods of valuing the social cost of carbon (SCC) for designing regulatory policy. As mentioned in Section 2, the main problem related to GHG valuation is the presence of many scientific and economic uncertainties that affect the final values (Nocera & Cavallaro, 2014b). The former includes the relation between emissions and atmospheric concentration, the forecast of future travel demand, levels of emissions, concentrations and temperatures, the climate impact resulting from an increased concentration of GHG and the physical impact of climate change. The latter includes the evaluation of the economic damage, the determination of a balanced equity weight, the discount rate to be adopted and the choice of adaptation or mitigation strategies. Maibach et al. (2008) suggest that the Damage Costs or the Avoidance Costs are two of the most suitable methods for adequately valuating GHG. However, the carbon values ranging up to six orders of magnitude are obtained with such methods, from −\$10.00/tC to \$7243.73/tC (Nocera et al., 2015): an adequate unitary value cannot be chosen for the transport carbon policy with this large range. Few attempts have been made to limit the range of estimates by, for example, implementing a meta-analysis of the published SCC estimates (Tol, 2008, 2009; Kuik et al., 2008; Nocera & Tonin, 2014; Nocera et al., 2015). A meta-analysis aims to understand the reasons for such estimation variability and to elucidate the available data. Meta-analyses have been used for at least three main purposes: research synthesis, hypothesis testing and prediction (Van Houtven, Powers, & Pattanayak, 2007). In the present study, a meta-analysis was adopted to predict the SCC due to changes in the main parameters, finally using the results for policy analysis and planning activities. This analysis compares the benefits of different plans and policies changing the critical values related to meta-regressors. Some scholars argue that meta-analysis is debatable, because it summarizes a large amount of data from very heterogeneous studies with different hypotheses using a single number. Furthermore, the method has the following three specific limitations: the use of data based on a small group of authors and models (Stanton, Ackerman, & Kartha, 2009), the predominance of older studies in which extreme scenarios of climate change are considered either insufficiently or not at all (van den Bergh & Botzen, 2013) and the choice of an incorrect econometric model (Fischer & Morgenstern, 2003).

However, a meta-analysis overcoming the three main criticalities was carefully designed. A total of 60 studies offering 699 values were collected based on different integrated assessment models (IAMs) (mostly including Policy Analysis of the Greenhouse Effect (PAGE), Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and Dynamic Integrated Climate-Economy (DICE), but also Intera, Open Framework, Regional Integrated Climate-Economy (RICE), Upwelling-Diffusion Energy Balance (UDEB), Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC), SCCRAM, Second Generation Model (SGM), World Integrated Assessment General Equilibrium Model (WIAGEM), Mini-Climate Assessment Model (MiniCAM), Market Allocation (MARKAL), MERGE, Carbon Emissions Trajectory Assessment (CETA), Multiregional Approach for Resource and Industry Allocation (MARIA), Integrated Assessment Modelling (IAM), All Modular Industry Growth Assessment (AMIGA), COMBAT, Emissions Prediction and Policy Analysis (EPPA), EDGE, GEMINI-E3, GRAPE, Global Trade and Environmental Model (GTEM) and geostatistical inverse modelling (GIM)). The present study was based on a similar database made available by Tol (2008, 2013), but values other than those provided by the IAMs PAGE, FUND and DICE were considered. In addition, several variables other than those considered in Tol's database were included, including how the economic value of cost emissions was calculated (i.e., marginal SCC, marginal damage, carbon tax and marginal abatement cost), the type of model used, the geographical scale, the area of adaptation, the damage function used, the reference scenario and the sectors analysed. Most of the studies mentioned here were published between 2004 and 2012, thus overcoming the criticality of the date of realization and the lack of consideration of extreme events.

The list of variables included in our meta-analysis regression is presented in Table 1, showing the mean and the standard deviation. For comparison, all values of these studies have been reported in 2010 US\$, ranging between −\$10.00/tC and \$7243.73/tC. The average economic value is \$276.49/tC, and the 95% confidence interval is 228.29–328.85 (Table 2). The high standard deviation (668.78) highlights the variability in the economic values of climate change and the spread over a large range. Rarely, some negative values are present, which indicates that climate change can initially have a positive impact, especially on temperate zones, where most of the global economy is concentrated.

After the main GHG statistics are described, a meta-regression function of the cost of carbon emission must be estimated. This indicates first running the regression that estimates the coefficients measuring the influence of each variable and then substituting the effective value corresponding to a plan or policy of interest in the estimated coefficients. Equation (1) defines the variation of the cost of carbon with respect to changes in the determinant variables in the present study:

$$Cost_{2010} = f(S, M, I, C) \tag{1}$$

where $Cost_{2010}$ is the emission cost of carbon in 2010 US\$, a function of different regressors. These regressors are divided into the following four categories: the characteristics of the original study (S) (if the original study is peer reviewed, the year of publication); the characteristics of the IAM (M), specifically if the primary study used a fully integrated assessment model (FIAM) or a computable general equilibrium (CGE)[5] model; the impact categories used (I) (such as energy use, sea-level rise, agricultural impact, water supply, health impact, ecosystem and biodiversity, extreme weather events and combined effect); and the context variables (C) (such as the geographical scale, the choice of prtp, if equity weighting is adopted, the average temperature rise considered and the average increase of CO_{2eq} concentrations).

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[5] In its evaluation of GHG impact, an FIAM model includes the economic growth/dynamics, energy and damage modules. A CGE model focuses on the economic optimization procedure on a greater number of sectors, but it does not include a climate module (Ortiz & Markandya, 2009).

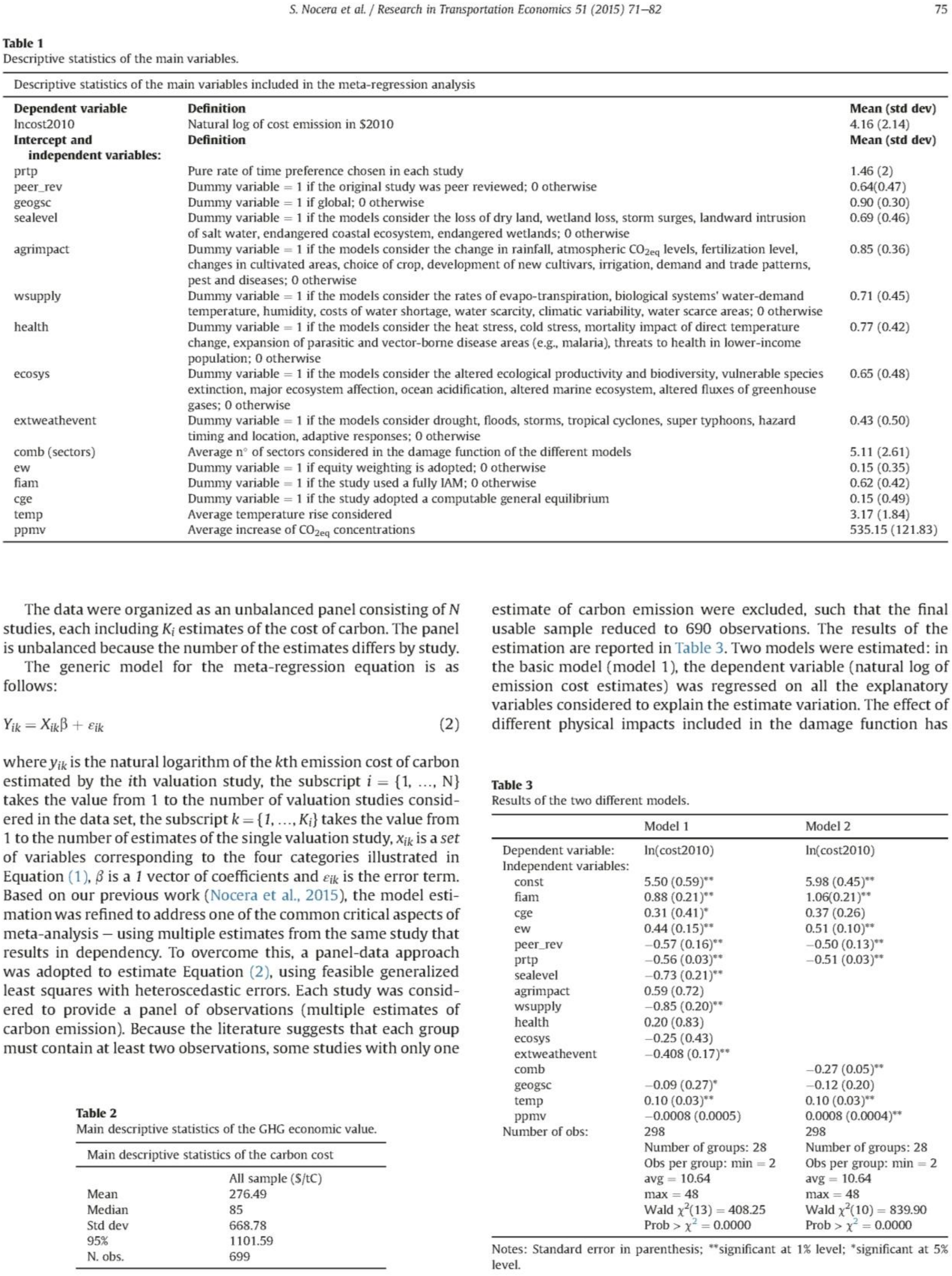

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Table 1
Descriptive statistics of the main variables.

Descriptive statistics of the main variables included in the meta-regression analysis		
Dependent variable	**Definition**	**Mean (std dev)**
lncost2010	Natural log of cost emission in $2010	4.16 (2.14)
Intercept and independent variables:	**Definition**	**Mean (std dev)**
prtp	Pure rate of time preference chosen in each study	1.46 (2)
peer_rev	Dummy variable = 1 if the original study was peer reviewed; 0 otherwise	0.64(0.47)
geogsc	Dummy variable = 1 if global; 0 otherwise	0.90 (0.30)
sealevel	Dummy variable = 1 if the models consider the loss of dry land, wetland loss, storm surges, landward intrusion of salt water, endangered coastal ecosystem, endangered wetlands; 0 otherwise	0.69 (0.46)
agrimpact	Dummy variable = 1 if the models consider the change in rainfall, atmospheric CO_{2eq} levels, fertilization level, changes in cultivated areas, choice of crop, development of new cultivars, irrigation, demand and trade patterns, pest and diseases; 0 otherwise	0.85 (0.36)
wsupply	Dummy variable = 1 if the models consider the rates of evapo-transpiration, biological systems' water-demand temperature, humidity, costs of water shortage, water scarcity, climatic variability, water scarce areas; 0 otherwise	0.71 (0.45)
health	Dummy variable = 1 if the models consider the heat stress, cold stress, mortality impact of direct temperature change, expansion of parasitic and vector-borne disease areas (e.g., malaria), threats to health in lower-income population; 0 otherwise	0.77 (0.42)
ecosys	Dummy variable = 1 if the models consider the altered ecological productivity and biodiversity, vulnerable species extinction, major ecosystem affection, ocean acidification, altered marine ecosystem, altered fluxes of greenhouse gases; 0 otherwise	0.65 (0.48)
extweathevent	Dummy variable = 1 if the models consider drought, floods, storms, tropical cyclones, super typhoons, hazard timing and location, adaptive responses; 0 otherwise	0.43 (0.50)
comb (sectors)	Average n° of sectors considered in the damage function of the different models	5.11 (2.61)
ew	Dummy variable = 1 if equity weighting is adopted; 0 otherwise	0.15 (0.35)
fiam	Dummy variable = 1 if the study used a fully IAM; 0 otherwise	0.62 (0.42)
cge	Dummy variable = 1 if the study adopted a computable general equilibrium	0.15 (0.49)
temp	Average temperature rise considered	3.17 (1.84)
ppmv	Average increase of CO_{2eq} concentrations	535.15 (121.83)

The data were organized as an unbalanced panel consisting of N studies, each including K_i estimates of the cost of carbon. The panel is unbalanced because the number of the estimates differs by study.

The generic model for the meta-regression equation is as follows:

$$Y_{ik} = X_{ik}\beta + \varepsilon_{ik} \quad (2)$$

where y_{ik} is the natural logarithm of the kth emission cost of carbon estimated by the ith valuation study, the subscript $i = \{1, \ldots, N\}$ takes the value from 1 to the number of valuation studies considered in the data set, the subscript $k = \{1, \ldots, K_i\}$ takes the value from 1 to the number of estimates of the single valuation study, x_{ik} is a *set* of variables corresponding to the four categories illustrated in Equation (1), β is a *1* vector of coefficients and ε_{ik} is the error term. Based on our previous work (Nocera et al., 2015), the model estimation was refined to address one of the common critical aspects of meta-analysis – using multiple estimates from the same study that results in dependency. To overcome this, a panel-data approach was adopted to estimate Equation (2), using feasible generalized least squares with heteroscedastic errors. Each study was considered to provide a panel of observations (multiple estimates of carbon emission). Because the literature suggests that each group must contain at least two observations, some studies with only one estimate of carbon emission were excluded, such that the final usable sample reduced to 690 observations. The results of the estimation are reported in Table 3. Two models were estimated: in the basic model (model 1), the dependent variable (natural log of emission cost estimates) was regressed on all the explanatory variables considered to explain the estimate variation. The effect of different physical impacts included in the damage function has

Table 2
Main descriptive statistics of the GHG economic value.

Main descriptive statistics of the carbon cost	
	All sample ($/tC)
Mean	276.49
Median	85
Std dev	668.78
95%	1101.59
N. obs.	699

Table 3
Results of the two different models.

	Model 1	Model 2
Dependent variable:	ln(cost2010)	ln(cost2010)
Independent variables:		
const	5.50 (0.59)**	5.98 (0.45)**
fiam	0.88 (0.21)**	1.06(0.21)**
cge	0.31 (0.41)*	0.37 (0.26)
ew	0.44 (0.15)**	0.51 (0.10)**
peer_rev	−0.57 (0.16)**	−0.50 (0.13)**
prtp	−0.56 (0.03)**	−0.51 (0.03)**
sealevel	−0.73 (0.21)**	
agrimpact	0.59 (0.72)	
wsupply	−0.85 (0.20)**	
health	0.20 (0.83)	
ecosys	−0.25 (0.43)	
extweathevent	−0.408 (0.17)**	
comb		−0.27 (0.05)**
geogsc	−0.09 (0.27)*	−0.12 (0.20)
temp	0.10 (0.03)**	0.10 (0.03)**
ppmv	−0.0008 (0.0005)	0.0008 (0.0004)**
Number of obs:	298	298
	Number of groups: 28	Number of groups: 28
	Obs per group: min = 2	Obs per group: min = 2
	avg = 10.64	avg = 10.64
	max = 48	max = 48
	Wald $\chi^2(13) = 408.25$	Wald $\chi^2(10) = 839.90$
	Prob > $\chi^2 = 0.0000$	Prob > $\chi^2 = 0.0000$

Notes: Standard error in parenthesis; **significant at 1% level; *significant at 5% level.

been measured separately. Model 1 is derived from the following equation:

$$\begin{aligned}\ln(\mathrm{cost2010}_{ik}) = \alpha &+ \mathrm{fiam}_{ik} + \mathrm{cge}_{ik} + \mathrm{ew}_{ik} + \mathrm{peer\_rev}_{ik} + \mathrm{prtp}_{ik}\\ &+ \mathrm{sealevel}_{ik} + \mathrm{agrimpact}_{ik} + \mathrm{wsupply}_{ik}\\ &+ \mathrm{health}_{ik} + \mathrm{ecosys}_{ik} + \mathrm{extweathevent}_{ik}\\ &+ \mathrm{comb}_{ik} + \mathrm{geosc}_{ik} + \mathrm{temp}_{ik} + \mathrm{ppmv}_{ik} + \varepsilon_{ik}\end{aligned} \tag{3}$$

In model 2, the variable 'combined' is used to replace the single physical impact categories of an IAM (which includes sea-level rise, agriculture, water supply, health, ecosystems and extreme weather events here). This new independent variable is created to remove the high correlation among the different scenarios, such that the appropriate significance and measures could not be separated. For example, the valuation of sea-level rise damages depends heavily on other variables such as ecosystem values, consumption and adaptation (USEPA & USDOE, 2011).

In model 2, the estimated coefficients of the explanatory variables have all the expected signs. As shown in Table 3, the coefficient related to FIAM is positive and statistically significant at the 1% level. This indicates that this type of model is positively related to the economic effect of climate change. Similar conclusions are also valid for the CGE model type. The impact of peer-reviewed studies is negative and statistically significant, thus confirming that published scientific articles estimated lower economic costs of climate change than the grey literature. Conversely, the practice of weighting impacts in different regions is predicted to increase the cost of climate change. Increasing the number of sectors analysed by the IAMs results in lower values. This is also expected when the different strategies and policies implied by using one or more physical impacts modules are considered: indeed, such modules produce differing costs and benefits within the same sector. The increases in temperature and CO_{2eq} concentration are statistically significant and expected to increase the economic impact of climate change: in model 2, for example, the increase by one degree, all else held constant, augments the average cost by 10%. Similarly, an increase of 100 points in ppmv raises the average cost of GHG emissions by 8%. Finally, the analysis shows the relationship between the growth of prtp and the reduction of GHG prices: ceteris paribus, a 1% increase in prtp implies about a 50% decrease in the cost of CO_{2eq} emissions. This result further confirms that it is important to choose an appropriate discount rate, because this value can determine significant variations in the final price (Watkiss et al., 2005). Undoubtedly, this has greater consequences mostly on transport policies for the distant future: with a certain fixed amount of costs, higher discount rates tend to decrease the present value of benefits, thus weakening the adoption of current solid actions.

3.3. Choice of the most suitable transport measures

Finally, the method includes evaluating the GHG effectiveness of the various possible measures that can be implemented and selecting the most suitable measure. This can be achieved by multiplying the expected savings (as described in Section 3.1) with the unitary price (using the model provided in Section 3.2). Therefore, an economic value can be assigned to the benefits of a single transport measure in terms of GHG reduction. The value, thus obtained, can actively help in selecting transport measures for a mobility plan. The GHG impact thus becomes an active parameter of a more comprehensive analysis, which also includes aspects related to technical issues (facility condition, travel time, vehicle operating costs, accession, mobility, congestion, safety, intermodal movement efficiency and land-use patterns), economic efficiency (initial costs, life-cycle costs and benefits), environment (air quality, water resources, noise, wetlands and ecology, aesthetics), economic development (employment, number of business establishments, GDP, regional economy and international trade) and legal and sociocultural impacts (tort liability exposure and quality of life) (Sinha & Labi, 2007). Finally, these can be comprehensively evaluated by adopting three cost–benefit performance indicators, such as the net present value (NPV), the benefit–cost ratio (B/C) and the internal rate of return (IRR). These three indicators provide useful information on the performance of the transport measures available, and they can be used to rank the different options. The preferred indicator is NPV, but it is reasonable to present the IRR and B/C criteria as supplementary information, especially within budget constraints (EURP, 2008). The three-step methodology presented in this section aims at integrating an energetic perspective (as derived by SEAP) into a mobility plan, such that GHG effects can be included explicitly in the decision-making process. The inclusion of different approaches can be a valid, rather than a limiting, solution for rethinking mobility problems strategically, which reduces the impacts while also prioritizing projects to maximize benefits (Cambridge Systematics, 2008). In view of this, the mobility plan not only addresses traffic issues but more comprehensively considers social, environmental and economic impacts as well. This implies that the stimuli for transport carbon reduction may be accompanied by changes in the composition of investment and evaluation. In the case of austerity, some kinds of investment (e.g., those concerning new transport infrastructure) are generally restricted, but cheaper, environmentally friendly investment – concerning not only primary pollutants but also GHGs – can expand, thus producing quantifiable effects on the community. Some of this additional spending could, for instance, be aimed at research and development in new technologies (especially those for public transport and ITS investments), thus enabling the reduction in transport costs for the community.

4. The effectiveness of transport measures in GHG reduction: the case study of Bologna

4.1. Bologna: mobility layout and transport plans

Bologna, the countryseat of the Italian Region Emilia-Romagna, is one of the largest and most populated cities in the north of Italy. The metropolitan area of the city houses about one million inhabitants, 38% of whom (380,635) live in the city (CDSCI, 2013). This city is central to Italy with respect to its geographical location and infrastructural network (Appendix 2): railway lines and highways for most long-distance journeys from north to south and vice versa pass through this city. The central station is used by about 58 million passengers per year (about 160,000 passengers/day), thus making it the fifth most frequented station of Italy (FSI, 2014). This city is connected to Milan, Turin, Genoa, Venice, Florence, Rome, Naples, Bari and other main Italian destinations by several daily trains. The new high-speed railway station, inaugurated in 2013, is expected to increase the number of users significantly. The road transport of Bologna is relevant as well: it is the intersection node for the highways that link with Milan (A1, direction north–west), Florence–Rome–Naples (A1, direction south–west), Padua (A13, direction north–east) and Ancona–Bari (A14, direction south–east). Overall, between 80,000 and 100,000 vehicles ply the highways daily, and 120,000–150,000 vehicles use the bypass (22.2 km parallel to the highway) daily. The airport, which is close to the city centre (about 10 km), is used by about 4.5 million passengers yearly, with a constant increase in the last years. At the municipal level, the private car is the preferred transport mode

(35% of the inhabitants, 28% as drivers and 7% as passengers), followed by alternative transport modes (bicycle and walking account for 28%), bus (26%) and moped (11%).

To address the mobility problems adequately, the city administration has decided to adopt two levels of planning. The more comprehensive level is the *Municipal Structural Plan* (Bertocchi et al., 2007). This voluntary and long-term plan attempts to connect the spatial development of the metropolitan area to its mobility. The plan recommends creating a network of 'seven cities' based on urban renewal. Transport can actively contribute to this end, by integrating the different transport modalities and by improving the service of public transport. The plan focuses on this aspect, by proposing some general guidelines and modifications of the current urban layout of the public transport. Other considerations for mobility are not included; the technical issues are addressed in the *Master Plan of the Urban Traffic* (Carlini, Finelli, Cuppini, & Borioni, 2006). This document assesses the mobility problems for the short term (2–4 years), focusing on the following six main issues: reduction of air and noise pollution, energy savings, improvement of road safety, achievement of high levels of accessibility, increase of public transport and contextual reduction of private vehicles to encourage a more eco-compatible stock of vehicles. A set of specific actions is then proposed to address each objective. However, although the reduction of air and noise pollution is included in the main goals of the plan, the issue of GHG emissions is not mentioned, thus confirming its secondary role in transport plans, as widely discussed in Section 2.

4.2. SEAP of Bologna

To address the GHG issues actively, the municipality has recently decided to participate in the Covenant of the Mayors to elaborate an SEAP. The document was formally submitted to European institutions in 2012. According to the 20–20–20 targets, the overall objective of the plan is to reduce CO_2 by 20% by 2020.[6] Transport can actively contribute to this reduction: by implementing a set of measures, SEAP will reduce transport emissions by 96,610 tCO_2/year, 20.1% of the total. This reduction is expected to occur by adopting several measures of three main categories: public transport, municipality transport and private transport. The plan sets 2005 as the reference year: to obtain the final CO_2 reduction, it identifies measures already implemented between 2005 and 2012 (e.g., Table 4, measure 1), measures expected for the whole period (e.g., measure 10), and new measures to be introduced from the year of implementation of the plan (e.g., measure 9).

The effects and costs of the measures already implemented are quantified by adopting historical data, whereas those implemented in the coming years were quantified with models predicting future conditions or economic evaluation (technical projects, budget plan made at the municipal level or by public transport company). However, the impacts in terms of CO_2 reduction are calculated by considering the expected changes in travel behaviour and renewal of the vehicle fleets. For instance, measure 5 hypothesizes that 10% of vehicles currently circulating are replaced by low-emission vehicles (<100 gCO_2/km), whereas the rest of the fleet is constituted by medium-emission vehicles (130 gCO_2/km for petrol and diesel fuel and 120 gCO_2/km for natural gas and gas liquid processing (GLP)). A selection of the measures proposed in the plan, as well as its synthetic description, is presented in Table 4. The economic impact of the different measures varies widely, ranging from an investment of €40,000 for measure 3 to almost €700 M for measure 9.

4.3. Quantification of CO_2 benefits and costs

The evaluation of the measures of the SEAP is limited to the energetic aspect, which is only one of the issues that a transport plan should cover. To determine the real efficiency of the measures, the results of the SEAP should be integrated with a model that can estimate the economic benefits, such as that proposed in Section 3. Here, the significant variables listed in Table 3 are selected based on the scenario forecasted by the decision-makers. The temperature increase and the variation of GHG concentration in the atmosphere are derived from the stabilization targets expressed by IPCC (2013). According to the methodology proposed by the IPCC, it is possible to quantify the expected increase in CO_{2eq} concentration and temperature by analysing the variation in GHG emissions for the period 2000–2050. Six classes are identified, with a range of values; by determining the targeted CO_{2eq} reduction, the variation of temperature and GHG concentration are derived. In this case, the 20–20–20 targets in action up to 2050 are hypothesized, with a 20% reduction in emissions, but this value can be adapted for different strategies. Given such premises, the CO_{2eq} concentration is expected to be 554 ppmv, while the temperature should increase by 2.91 °C. The choice of the prtp lies normally between 1% and 3% (Watkiss et al., 2005), as this is considered a central value. Furthermore, the model used to evaluate the price is hypothesized to be an FIAM that adopts equity weighting, with peer-reviewed methodology. Table 5 illustrates all of the values adopted to calculate the economic unitary value of a ton of carbon, which was estimated to be \$231.15/tC. This value can be transformed into \$/tCO_{2eq} by considering the conversion factor of 3.664 (CDIAC, 2014), thus obtaining \$63.09 as a reference value for the transport measures previously described. Finally, to express it in €, the official exchange rate of January 2010 (€1 = \$1.4389) was adopted (Bank of Italy, 2014): the final reference value is €43.84/tCO_2 (with a confidence interval at the 95% level, from €42.89 to €43.11).

The economic CO_2 benefit of the different measures (Table 6, column e) can be obtained by multiplying the overall CO_2 reduction with the unitary value. These results must be interpreted carefully: the calculation is a static exercise that does not consider the intertemporal welfare implications of the different measures described in Table 6. If the value of the benefits is compared with the costs of implementation for a specific measure, a balance of the CO_2 can be obtained (Table 6, column f). A negative value indicates that the costs of implementation are higher than the benefits produced from carbon reduction; as expected, CO_2 reduction alone cannot justify the investment. This point is illustrated more clearly by the carbon efficiency (Table 6, column g), which is the ratio between the carbon benefits and the implementation costs of the measure.

The results of Table 6 reveal that only mobility management (measure 1) has positive impact (+€337,963) in comparison with the costs of implementation: this indicates that a well-structured mobility management strategy can produce CO_2 benefits (€462,463) that overcome the implementation costs (−€124,500). However, the cost of all other measures is more than their CO_2 benefits (the overall balance is negative, with a value of about −€2,744 M). The efficiency of the measures is very indicative: the overall ratio is about 2%, mostly determined by the realization of new infrastructure (measure 9). This is highly expensive (about €695 M), but relatively lower benefits are produced in terms of CO_2 reduction (€1.6 M).

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[6] The plan specifically addresses the issue of CO_2 emissions, suggesting that the analysis can be extended to other GHGs. Henceforth, to be consistent with the SEAP of Bologna, only CO_2 will be considered in our analysis, but the validity of the method can be extended to all GHGs.

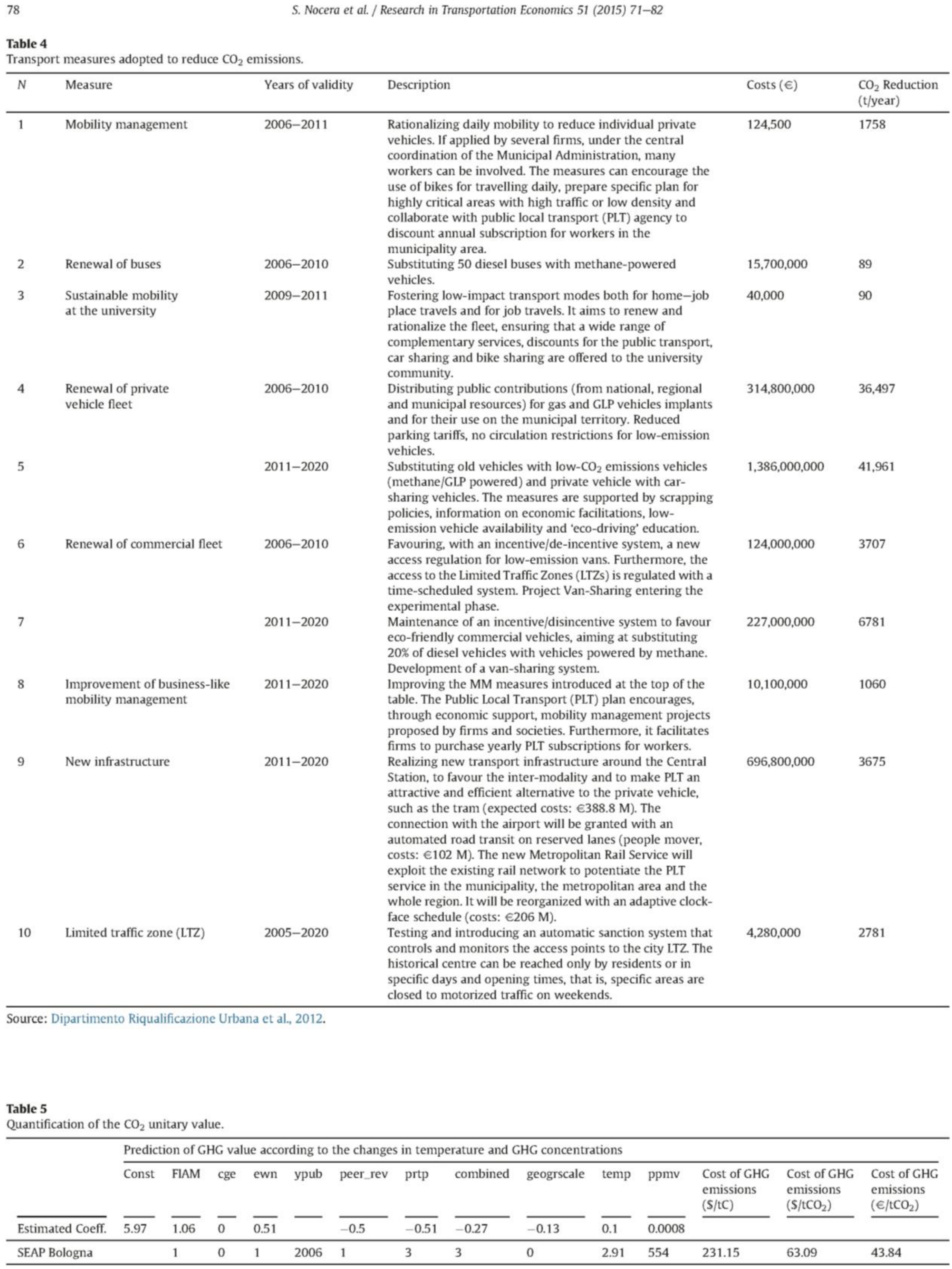

Table 4
Transport measures adopted to reduce CO_2 emissions.

N	Measure	Years of validity	Description	Costs (€)	CO_2 Reduction (t/year)
1	Mobility management	2006–2011	Rationalizing daily mobility to reduce individual private vehicles. If applied by several firms, under the central coordination of the Municipal Administration, many workers can be involved. The measures can encourage the use of bikes for travelling daily, prepare specific plan for highly critical areas with high traffic or low density and collaborate with public local transport (PLT) agency to discount annual subscription for workers in the municipality area.	124,500	1758
2	Renewal of buses	2006–2010	Substituting 50 diesel buses with methane-powered vehicles.	15,700,000	89
3	Sustainable mobility at the university	2009–2011	Fostering low-impact transport modes both for home–job place travels and for job travels. It aims to renew and rationalize the fleet, ensuring that a wide range of complementary services, discounts for the public transport, car sharing and bike sharing are offered to the university community.	40,000	90
4	Renewal of private vehicle fleet	2006–2010	Distributing public contributions (from national, regional and municipal resources) for gas and GLP vehicles implants and for their use on the municipal territory. Reduced parking tariffs, no circulation restrictions for low-emission vehicles.	314,800,000	36,497
5		2011–2020	Substituting old vehicles with low-CO_2 emissions vehicles (methane/GLP powered) and private vehicle with car-sharing vehicles. The measures are supported by scrapping policies, information on economic facilitations, low-emission vehicle availability and 'eco-driving' education.	1,386,000,000	41,961
6	Renewal of commercial fleet	2006–2010	Favouring, with an incentive/de-incentive system, a new access regulation for low-emission vans. Furthermore, the access to the Limited Traffic Zones (LTZs) is regulated with a time-scheduled system. Project Van-Sharing entering the experimental phase.	124,000,000	3707
7		2011–2020	Maintenance of an incentive/disincentive system to favour eco-friendly commercial vehicles, aiming at substituting 20% of diesel vehicles with vehicles powered by methane. Development of a van-sharing system.	227,000,000	6781
8	Improvement of business-like mobility management	2011–2020	Improving the MM measures introduced at the top of the table. The Public Local Transport (PLT) plan encourages, through economic support, mobility management projects proposed by firms and societies. Furthermore, it facilitates firms to purchase yearly PLT subscriptions for workers.	10,100,000	1060
9	New infrastructure	2011–2020	Realizing new transport infrastructure around the Central Station, to favour the inter-modality and to make PLT an attractive and efficient alternative to the private vehicle, such as the tram (expected costs: €388.8 M). The connection with the airport will be granted with an automated road transit on reserved lanes (people mover, costs: €102 M). The new Metropolitan Rail Service will exploit the existing rail network to potentiate the PLT service in the municipality, the metropolitan area and the whole region. It will be reorganized with an adaptive clock-face schedule (costs: €206 M).	696,800,000	3675
10	Limited traffic zone (LTZ)	2005–2020	Testing and introducing an automatic sanction system that controls and monitors the access points to the city LTZ. The historical centre can be reached only by residents or in specific days and opening times, that is, specific areas are closed to motorized traffic on weekends.	4,280,000	2781

Source: Dipartimento Riqualificazione Urbana et al., 2012.

Table 5
Quantification of the CO_2 unitary value.

	Prediction of GHG value according to the changes in temperature and GHG concentrations													
	Const	FIAM	cge	ewn	ypub	peer_rev	prtp	combined	geogrscale	temp	ppmv	Cost of GHG emissions (\$/tC)	Cost of GHG emissions (\$/tCO_2)	Cost of GHG emissions (€/tCO_2)
Estimated Coeff.	5.97	1.06	0	0.51		−0.5	−0.51	−0.27	−0.13	0.1	0.0008			
SEAP Bologna		1	0	1	2006	1	3	3	0	2.91	554	231.15	63.09	43.84

Table 6
Effects of specific transport measures on CO_2 reduction.

	Measure	Costs	Validity	Yearly CO_2 reduction	Overall CO_2 reduction	Overall CO_2 benefits	Balance	CO_2 efficiency
		a)	**b)**	**c)**	**d) = b*c**	**e) = d*43,84**	**f) = e−a**	**g) = e/a**
n		€	**year**	**t/year**	**t**	€	€	
1	Mobility management	124,500	6	1758	10,548	462,463	337,963	3.715%
2	Renewal of buses	15,700,000	5	89	445	19,510	−15,680,490	0.001%
3	Sustainable mobility at the university	40,000	3	90	270	11,838	−28,162	0.296%
4	Renewal of private vehicle fleet	314,800,000	5	36,497	182,485	8,000,806	−306,799,194	0.025%
5	(past + future)	1,386,000,000	10	41,961	419,610	18,397,229	−1,367,602,771	0.013%
6	Renewal of commercial fleet	124,000,000	5	3707	18,535	812,642	−123,187,358	0.007%
7	(past + future)	227,000,000	10	6781	67,810	2,973,037	−224,026,963	0.013%
8	Improvement of business-like mobility management	10,100,000	10	1060	10,600	464,743	−9,635,257	0.046%
9	New infrastructure	696,800,000	10	3675	36,750	1,611,254	−695,188,746	0.002%
10	Limited traffic zone	4,280,000	16	2781	44,496	1,950,867	−2,329,133	0.456%
	Total	**2,778,844,500**		**98,399**	**791,549**	**34,704,388**	**−2,744,140,112**	**0.012%**

Some caveats are necessary to explain the results presented here. First, as the reference scenario is based on a political framework that considers a 20% reduction of emissions by 2050, which is not a very virtuous goal, the benefits derived from the reduction of CO_2 emissions are rather modest as well. If these measures are conceived as part of a more coherent and ambitious policy, then the unitary value of the emissions will increase significantly, thus resulting in a higher efficiency of the measures and a broader social benefit.

Second, these findings are only partial: benefits derived from a comprehensive transport plan include urban and infrastructural aspects (type and organization of roads), environmental issues (traffic, noise and pollutant concentrations), health problems (urban pollution and accidents) and economic and social topics (access to mobility, forms of mobilization, organization of work and flow of goods). Measures have to be evaluated not only for their potential carbon gain but also for their benefits (both positive and negative) to the territory and its inhabitants: in this sense, some land-use transport models used welfare economics effectively and synergically (Anas & Liu, 2007; Kii, Akimoto, & Doi, 2014; Libardo & Nocera, 2008), attempting to find a balance between these two aspects.

Third, this analysis does not consider the dynamic nature of some specific measures, such as the realization of new infrastructure: after being introduced, the expected benefits can have consequences according to the modal shift obtained. In this sense, a static CBA could distort the final values to some extent. Evaluators should, therefore, be aware of this possibility when interpreting the data.

Indeed, the case study presented in this paper clearly demonstrates that several transport measures can be introduced to produce significant CO_2 benefits. Recalling Section 2, this is a relevant finding, because CO_2 benefits are normally considered a secondary aspect, which is not directly included in the evaluation process, thus underestimating the concrete effects of the transport plan.

5. Conclusions

In a period of long-term economic crisis, the general approach towards transport systems, infrastructure or measures is precautionary: investments are normally postponed – or blocked – in order to offset the financial exigencies accompanying austerity policies. Several scholars have proposed a new 'wartime-spirit approach' (Hinton & Redclift, 2009), which implies a voluntary rationing of goods and services. In contrast to this theory, and supported by the economic vision of Stiglitz (2012), our opinion is that strategic investments can deliver positive returns to cities and countries. Transport is considered one of the major factors of a country's competitiveness, but it needs a sustainable and green retrofitting, which in turn calls for a global environmental reform, or a transition to a green economy (UNEP, 2011; OECD, 2011). Green growth is a new strategic narrative ensuring that both environmental and economic problems are addressed. It refers to environmental protection in terms of rewards, rather than additional costs. In this sense, austerity can be viewed as an opportunity to renew approaches to transport, because agents change routines in (or after) a phase of crisis, rather than in a phase of prosperity. Hence, in these periods, the propensity of transport-related stakeholders for innovation is maximal. Highly industrialized countries have discovered that they are technologically advanced in the market segment of low carbon, in comparison with other developing countries (Rothengatter, 2011).

Transport planning and engineering seem ideal fields for the application of these theories, especially in developed countries: policymakers should be able to intercept this attitude towards green infrastructural growth, using the potential of austerity to obtain positive results for the community. This can be resolved by a set of policy measures that internalize negative externalities such as GHG emissions. However, the carbon impacts in urban mobility plans are often neglected or underestimated during analysis. This may be because GHG reduction has been prematurely set as one of the main policy goals, and policymakers validate their decisions with already-obtained consistent results with some complication. Based on this, the results of transport actions can be definitely misinterpreted and potential decisions ruined, negatively affecting the community. This may result in grossly inefficient policy not only in terms of transport, because money invested for such aims may be used elsewhere providing greater benefits to the community.

The methodology discussed in this paper aims at internalizing the GHG effectiveness of specific transport measures included in urban mobility plans, by quantifying their economic benefits and implementation costs. The real challenge, however, is to find a reliable value of carbon emission among the many estimates provided by the economic literature. The model described in Section 3 is based on a meta-analysis of approximately 700 studies; the most significant parameters can be selected to explain the many values of GHG emissions. The results may be used to predict the final GHG economic price at the base of many policy and regulatory contexts, based on the main variables chosen. This method was investigated to calculate the benefits of adopting specific measures, as taken from an energetic plan such as SEAP. This outcome can be compared with other transport impacts – normally included in the evaluation process – to determine a fairer impact of the measures.

By developing this methodology, some progress has been made in reducing the polar values found in the literature and in defining a methodological framework to internalize GHG emissions. SUMPs and all innovative forms of mobility plans can adopt this replicable and scalable method in their evaluations by introducing the appropriate modifications. This must have some potential uses: in the long run, carbon interest will undoubtedly shape future transport patterns and the provision of private, public and freight transport services, despite the key drawbacks of the methodolog used and the large uncertainty of carbon emissions.

Appendix A. List of the main urban transport measures to reduce GHG emissions.

Measure	Description
1) Reducing the need for transport	
Door to door	Provide door-to-door access choices across the urban agglomeration.
Resources optimization	Make an efficient use of space, promoting a 'compact city' and targeting the urban development to public transport (PT), walking and cycling.
Information	Strengthen the use of information and communication technologies.
Short-route protection	Protect existing short routes in the network, to diminish the energy consumption of means of transport.
2) Increasing the attractiveness of alternative transport modes	
a) Public transport	
Solve barriers for PT use	Solve problems related to: uncomfortable stops and inadequate shelters; difficulty in boarding buses; infrequent, indirect and unreliable service; lack of information; high cost of fares; long journey times; lack of inter-modality; comfort; safety.
Valuation indicators	Develop a set of indicators measuring the access to PT of citizens. Perform a comprehensive analysis of the current situation and adopt corrective actions.
Marketing strategy	Develop a marketing strategy and service information availability across PT modes within 'travel-to-work' urban areas. Deal with a communication effort to inform users about the advantages of using PT.
Collective transportation	Promote collective transport programmes for schools and businesses.
Information availability	Provide an integrated information service through call centre, information points and Internet.
Service efficiency	Assure reliable, frequent and cost- and time-competitive PT, which must be safe to use.
Real time information	Provide real-time information, which must be widely available and inclusive of predicted arrival times.
Priority routes	Encourage the creation of 'PT-only' and priority routes.
Institutional collaboration	Work with district councils to ensure high standards of provision and maintenance of PT infrastructure.
Suggestions collecting	Create a suggestion box to consider the ideas of users and non-users in order to improve the service.
Tourist shuttle	Create a free tourist shuttle system with a fixed route and stops at popular tourist destinations.
b) Cycling	
Image	Make cycling appear not only a leisure/sport activity but also a means of transport.
Infrastructure	Plan and make operative an integrated network of cycling paths connecting origins and destinations, separate from motorized traffic.
Route guidance and Info	Make information easy to follow through numbering or colouring of the cycling ways and distances.
Safety	Approve standards for safe driving and avoid the mixture of bicycles and other heavy means of transport.
Links with public transport	Develop parking facilities and rent bicycles at railway stations or PT stops.
Bicycle theft	Impose electronic identification bicycles; realization of a national police registration for stolen bicycles.
Cyclists facilitation	Improve workplace with facilities for cyclists (shower and changing facilities).
c) Walking	
Pedestrian-only zones	Increase the creation of areas where pedestrians have priority and cars cannot circulate.
Low-speed zones	Increase the creation of areas where pedestrians have priority and cars move slow enough.
3) Making travel by car less attractive	
Pricing	Make car drivers pay a fee in the city centre, thus making the private vehicle a less attractive option.
Parking management	Promote the use of an intelligent park management system to control prices, time restrictions and the number of available parking spaces.
4) Information and marketing	
Local marketing campaign	Provision of tailored information about PT, walking and cycling alternatives.
5) Reduce municipal and private vehicle fleet emissions	
Alternative vehicles	Encouraging the purchase of hybrid or entirely electric vehicles.
Public fleet biofuels	Use biofuels in public fleets and ensure that vehicles acquired through public tenders accept their use.
Alternative fuels	Promote hydrogen buses and delivery vans, due to their zero emissions.
Low fuel consumption	Guarantee low taxation regime for hybrid and electric vehicles. Divide vehicles into different categories according to the priorities of the local authority.
Free parking	Guarantee free-park areas for low-emission vehicles.
Special lanes	Guarantee special lanes for alternative fuel vehicles.
Limited traffic zones	Restrict access to specific city zones for high CO_2-emitting cars.
Encourage clean vehicles	Guarantee economic/circulation advantages to low emissions vehicles (e.g., no congestion charges).
Efficient driving information	Provide good practices to drivers, institute driving schools to learn the efficient driving practices.
6) Smart transport	
Urban traffic control systems	Adopt specialized traffic management systems that integrate and coordinate traffic signal control.
Ramp metering	Implement a tool that regulates the flow of vehicles joining the motorway during rush hours.

Source: Covenant of Mayors (2010)

Appendix B. Highway connections of Bologna with the main Italian cities.

Source: Bologna airport (2014), elaborated.

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4. MAIN FINDINGS

4.1. Quantification

The quantification of CO_2 emissions deriving from the introduction of new infrastructures, transport systems or the implementation of specific measures and policies is the sum of several and complex phases that concur in determining the final results. In section 3.1, the CO_2 impact of a new transnational infrastructure (the Brenner HS/HC railway line) was assessed, considering, respectively, the construction and operational phases in all its analytical components.

During the phase of construction, the production of the building materials represents the largest proportion, with about 85% of total CO_2 emissions (68% is due to the cement production); 7% is produced both to ensure lighting, ventilation and cooling of tunnels and for the excavation operations (Maino and Cavallaro, 2015). Finally, the operation on the sites counts for 1%. In absolute terms, the overall amount of CO_2 generated is about 2.28 Mt, a quantity only slightly higher than the emissions generated from road and rail traffic during the time span of one year along the Brenner stretch from Kufstein to Verona[4]. Results of this study allow understanding the most impacting actions during the construction phase, focussing on them to optimize the process and to reduce CO_2 emissions.

The main finding deriving from the analysis of the operational phase of BBT (Cavallaro et al. (2013), is the fundamental role of transport policies in granting a modal shift from road to rail and to obtain concrete results in terms of CO_2 reduction. Only a balanced introduction of push- and pull-measures[5] can guarantee positive results. Indeed, if transport policies continue to postpone their introduction, rail and, mostly, road traffic will further increase. CO_2 emissions are expected to grow accordingly. Counting only on technological development to reduce the carbon pressure has proved not to be effective to solve the issue (Dray et al., 2012). Under these assumptions, the realization of a new infrastructure such as a HS/HC railway line could even be detrimental, because it grants further transport capacity to the corridor. Results deriving from the scenarios created for freight transport and referred to the year 2030 confirm this statement: Trend (prosecution of the current transport policy) presents higher emissions than Do-nothing (about 1.1 Mt/year against 1.0 Mt/year). Hence, transport sustainability,

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[4] These values depend on the scenario and on the reference year considered. Referring to the 2015, total annual emissions are estimated between 1.5 and 2 Mt.

[5] Push-measures are imposed on travellers and freight operators in order to discourage the use of private transport. They can be divided into financial instruments (e.g. taxes, charges and tolls) and technical and regulatory constraints (e.g. orders and bans). Pull-measures are implemented to improve the attractiveness of existing alternatives, such as rail.

which is used at institutional level to justify the investment for this type of infrastructures, could not be supported by these figures. Indeed, this motivation holds, if –and only if- there is a contextual introduction of adequate and integrated policy measures (as developed in Consensus), which aims at shifting the freight from road to rail transport. In this case, CO_2 emissions can lower up to 0.85 Mt/year, thus granting a saving of about 0.2 Mt in comparison with Do-nothing and 0.3 Mt with Trend. Policy makers should consider these aspects, by granting an adequate support to rail transport, even before the opening of the new infrastructure. The trend of recent years at Brenner (UFT, 2013) reveals a constant decrease of tons transported by rail and a parallel increase in road transport, which makes the current condition more similar to Trend than Consensus. If the analysis is also extended to passenger transport (Nocera et al., 2012), the CO_2 difference between the two scenarios is expected to increase, reaching 5.7 Mt for the years 2010-2035: all the conclusions previously drawn are even more valid in this case.

4.2. Economic valuation

Although the local community cannot directly measure the effects, just as occurs for other transport externalities (e.g., noise, congestion), a yearly saving of more than 0.3 Mt CO_2 is a relevant social benefit. In Nocera and Cavallaro (2014a), the potential CO_2 saving granted by the new HS/HC Brenner railway line has been evaluated in economic terms. Results, extended to the years 2010-2035, reveal a difference up to 559 M€ between Consensus and Trend. This amount evaluates the consequences deriving from the missed introduction of adequate transport policies that support the shift from road to rail.

In Nocera et al. (2015a), this approach has been extended to all GHGs and to general transport measures, such as the introduction of more restrictive emission limits for rail, road, air and water transport modes. These measures are implementable at EU level and directly affect the transport policies and carbon reduction targets at continental level. A meta-regression analysis has provided a reliable estimation of the unitary value. This is function of several variables that are decided by the modeller and are based on clear political choices. According to the case study presented, the price is included in a range that varies between \$52.34/tCO_{2eq} and \$38.20/tCO_{2eq}. Such values are rather high if compared with the European Union Emissions Trading Scheme (EU ETS; EU, 2012b) and with most of the carbon taxes applied at global level (except for Scandinavian States, where national governments support alternative energy sources through a high carbon tax).

This discrepancy should pose relevant questions about the most effective methods to mitigate the negative effects of climate change and the solutions adopted. For example, it should be avoided that carbon taxes may become a way to increase government revenues rather than constitute a fund to grant environmental benefits. On the other hand, the possibility that the carbon trade becomes a speculative market is also concrete: since the introduction of the EU ETS, in 2005, the prices have fluctuated between €30.00/tCO_2 and €4.00/tCO_2 (about \$144.85/tC and \$19.88/tC respectively; Strahan, 2013). For such reasons, these methods are not reliable to regulate a long-term strategy.

Indeed, a policy-driven approach is necessary: climate change is a long-term common issue and should be treated as such, despite the typical alternation of political legislatures. This means that the targets about future emissions and about limitation of the temperature increase (i.e., the mitigation approach recalled in the introduction) should be fixed only once and should then be kept constant through the years; doing otherwise would imply a lack of structural commitment. The changes that can be made should regard the way to obtain such reduction, which means the choice of the measures; but the overall objective should not be put into discussion. The unexpected repeal of the carbon tax made by Australia in 2014 has given evidence of how concrete this risk is. Without leading to the same dramatic consequences, the 0.045\$/tCO_2 proposed in California as a reference value for a carbon tax shows the distance between a fair evaluation of the damages produced by CO_2 emissions and their coherent adoption in political decisions. The problem raised in 2.2 about equity weight and its fair adoption at global level still reveals a discrepancy between the theoretical framework and the practical implementation. MAMCDM has revealed good potentialities to make the decision a community-based and international-based process, thus avoiding the dangerous DEAD approach[6], which has often led to the polarization of the positions rather than a convergence on shared results. The experience gathered during the years of the Kyoto Protocol, which was adopted in 1997 and only entered into force in 2005 (without USA and Australia, two of the most CO_2-emitting countries) should be an important lesson to draw from in order to avoid similar partial results in the future. The recent signing of the Paris agreement (UN, 2015) is another chance to propose a joint strategy that could be based on a common evaluation of the CO_2 mitigation strategy.

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[6] Acronym of Decision, Education, Announcement and Defense (Hartz-Karp, 2007).

4.3. Inclusion in mobility plans

Transport planning is based on a multidimensional approach that needs a clear definition of the tasks and the responsibility at each level in order to avoid conflicts. Within the current framework, the long-term and strategic issues are discussed at an international level, while the operative solutions have been demanded to the local mobility plans. Historically, this latter type of plan has reflected the policy concerns of the time in which it was conceived. As highlighted in Nocera and Cavallaro (2014b), traditional transport plans have mostly been traffic-oriented, focussing on solving issues such as traffic flows, congestion and parking places. The recent conceptual shift from transport to mobility planning needs a widening of these objectives, by proposing short- and medium- terms actions inserted in a coherent long-term strategy (Wefering et al., 2014). The current context allows the reduction of CO_2 emissions to become one of the priorities of the plan, and be achieved through measures primarily conceived for this aim.

Following the same purpose, new forms of plan have been recently introduced, which flank and integrate the consolidated methodologies. These plans, whose SEAP is probably the most known, are based on a multidisciplinary approach in order to solve the specific issue of CO_2 emissions. However, if not well coordinated, these plans can create critical overlapping, and even conflicts, with the traditional forms of mobility plan. Rather than a progressive specialization, the real challenge, rather than a progressive specialization, is to establish a correct and gradual integration of these disciplines into a comprehensive plan, which shall be able to address different issues and to manage the conflicts with a broader perspective. Some experiences (e.g. the London Plan; London Plan Team, 2011) confirm the difficulties, but also the potentialities of this approach.

This integration is particularly important for spatial development and transport planning, two disciplines that are conceptually strictly connected, but in most cases separated operatively[7]. The research question is certainly not new (Wegener and Fürst, 1999) and in the past years, it has mostly focussed on the relationship between accessibility and spatial development (Bertolini et al., 2005). The development of land-use transport interaction (LUTI) models has provided concrete solutions in terms of integration between spatial development and infrastructures, mostly in America (Facchinetti, 2002): for instance, transit-oriented development is a direct consequence of the integration of public transport network and town planning. The new challenge is to extend such integration not only to infrastructural

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[7] In Italy, for example, transport and spatial plans are two separate fields, covered from two different types of plans (*Piano Urbano della Mobilità* and *Piano Regolatore Generale*).

issues, but also to the broader concept of mobility defined in the SUMPs, which also includes CO_2 emissions.

Adequate and easy-to-use evaluation tools are necessary, so that policy makers can explain and share their decision in a clear and justifiable way. Nocera et al. (2015b) have defined a methodology to assess the potentialities of specific transport measures to reduce CO_2. Applied to the case study of Bologna, this method has internalized the CO_2 effectiveness of specific transport measures included in urban mobility plans, by quantifying their economic benefits and implementation costs. This tool presupposes a vision towards transport planning, which is in contrast with the austerity and the “wartime spirit approach” (Hinton and Redclift, 2009). Indeed, strategic transport planning can deliver positive returns to cities and countries, but they first need a sustainable retrofitting. Carbon assessment should be part of this evaluation and actively influence the shaping of future transport patterns.

5. CONCLUSIONS

Uncertainty largely affects carbon policies; hence, it is a concept that has occurred very frequently in this thesis. Indeed, the evaluation of transport CO_2 emissions is affected by several scientific and economic components (see section 2), which can determine up to six orders of magnitude in the estimation of the unitary value of carbon. With such a wide range, it is very difficult to provide an accurate evaluation of CO_2 impacts and to intervene with appropriate solutions.

How can these practical difficulties be handled? Provided that planners aim at obtaining right forecasts[8], Flyvbjerg et al. (2003) have suggested that the most effective means for improving forecasting accuracy is not to improve models, but instead to adopt more realistic assumptions and systematically use empirically based assessments of risk. According to this vision, Salling and Banister (2010) developed a model constituted by a deterministic calculation module, which uses CBA to determine a project feasibility, and whose results are then elaborated through a stochastic process based on a Monte Carlo simulation. Similarly, the approach adopted in this thesis has tried to keep the models and formulas as simple as possible. When dealing with long-term forecasts, the concrete risk of producing elegant, but inefficient methodological subtleties should be avoided. Uncertainty remains a critical aspect also in analysing economic and feasibility studies. In such cases, the method of the reference class forecasting (Lovallo and Kahneman, 2003) could be helpful: it compares the outcome of a specific assessment in a statistical distribution from a group of reference projects. This conceptual approach is similar to that adopted in Nocera and Cavallaro (2014a) and Nocera et al. (2015a), which adopts a meta-analysis in order to find a reliable value of GHG emissions based on a big database of similar assessments. Despite these methodological assumptions and simplifications, much work on uncertainty still has to be made, in order to minimize the subjective component (Natke and Ben-Haim, 1996) by assessing it in a dedicated analysis.

The issue of transport CO_2 emissions can find potential interesting synergies with micro-scale models (Hoogendorn and Bovy, 2001): indeed, it has recently been tested in specific road sectors such as the highways (Abou-Senna and Radwan, 2014). This thesis has adopted a macroscopic approach, since the analysis has focused on new transnational infrastructures, policies at the European level and urban measures, where the operation model was not the

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[8] The question is not trivial: due to the enormous economic interests and the political pressures, the tendency to use accurate results to justify the construction of a work, as well as the implementation of a measure, can be concrete. In this case, the question has to be inverted (Flyvbjerg et al., 2006): what others can do to impose on planners the checks and balances that would give planners the incentive to stop producing biased forecasts.

primary issue. However, when dealing with specific measures (e.g. a new pedestrian area or a limited traffic zone), these traffic management aspects become relevant: indeed, the specificities of the intervention play a crucial role, and a comparison among different proposals of the same solution could generate very different results. In such cases, a macro scale modelling can probably be complemented by alternative methods, which simulate detailed temporal and spatial aspects. The impacts of new measures can be verified by adopting simulation programmes, such as the Multi Agent Transport Simulation (MATSim; Balmer et al., 2008), which could be implemented with a specific climate change module specifically developed to this aim. A similar -even if simplified- attempt has been recently provided at mesoscopic scale by Zhou et al. (2015); some other software packages (e.g., PTV VisSim; Visual Solutions Inc, 2010) already include an emission module called EnViVer, but do not consider the phase of evaluation. A similar question was posed by the FP7 project *ICT-emissions* (Samaras et al., 2012), which tried to investigate the micro scale impact of ICT technologies, focussing on single vehicles and drivers' behaviour in response to specific solutions. In this case, the attempt was to obtain generalizable results valid also at the macro scale, but no final solutions were given. Interesting synergies could derive from the inclusion of the perspective developed in this thesis.

The relationship between transport big data and CO_2 emissions is another relevant aspect that may deserve some future investigation. Big data management is becoming a relevant topic in transport (ITF, 2015); however, specific studies regarding the potentialities for the reduction of CO_2 emissions are still either missing or in a very initial phase. In this framework, it would be relevant to assess the implications of specific measures that could be handled through the management and the analysis of big data (e.g., by assessing the behaviour of drivers before and after the introduction of a specific measure such as eco-driving).

Finally, a change of perspective, which assesses the impacts of climate change on transport and mobility, is also possible. Mills and Andrey (2002) identified three main categories: infrastructure, transport operations and transport demand/travel behaviour. Much research has been provided about the first aspect (Jaroszweski et al., 2010), while the two others have been less discussed. Especially the relationship between transport demand and climate change seems an interesting future research theme. In this case, we do not refer to weather changes and their implications on daily behaviour of travellers, but rather on the long run potential effects of global warming and the impact of seasonal patterns, such as the variation in the number of trips or changes in circulation behaviours.

As it can be established from the previous paragraphs, several important research questions are still ongoing, while others present an innovative nature. Further research is necessary to provide the appropriate answer to a complex issue such as CO_2 emissions and transport. This is valid not only at the scientific level, but also at the policy level. The president of the United States of America, Mr. Barack Obama, declared recently, “No challenge poses a greater threat to future generations than climate change”. Transport planners, through the adoption of appropriate long-term strategies, can play an active role towards the resolution of this issue. The current ancillary role of CO_2 emissions in mobility plans cannot be the appropriate solution. However, the rigid application of the principle that “once the carbon shadow price is high enough so that maximum feasible abatement is a welfare improvement, there is no additional meaning to an even higher price”, should be carefully considered. It may result in inefficient policies in terms of transport but not only, since money invested for this aim could be used elsewhere, getting higher benefits for the community. Policy makers have to provide a fair evaluation of social carbon consequences, so that it is possible to interpret the political choices in terms of capital allocation through the overall benefits achieved. The current thesis has contributed to the debate regarding these aspects, by proposing a three-step process based on quantification, evaluation and possible inclusion into mobility plans. This methodology allows considering the impact of transport choices for climate consequences, thus enlarging the set of criteria at disposition to the policy makers, in order for them to select the most effective policies and measures to be adopted.

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