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A Methodological Framework for the Economic Evaluation of CO_2 Emissions from Transport

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ABSTRACT

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 €331 million for the community, whereas a simple liberalisation ("Trend") increases the costs derived from global warming by about €228 million.

Keywords: CO_2 Economic Evaluation, Damage Cost, Avoidance Cost, Transport, Brenner Base Tunnel

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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 (Contaldi and Ilacqua, 2003) and for about 96% of the emissions in the transport sector (Tight et al., 2005). Secondly, traditional mitigation measures have an effective impact on CO_2 levels, but not on other polluting GHGs (Takeshita, 2011). 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 to 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 (EC, 2003; Wang et al., 2007).

CO_2 is detrimental neither to the environment nor to health if it does not exceed a threshold of 350 parts per million by volume (ppmv) (Hansen et al., 2008). However, its concentration has grown by over 25% in the last 150 years, passing from 288 ppmv in 1850 to 390 ppmv in 2010 (NOAA/ESRL, 2012). 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, since in the last twenty years transport emissions have grown about 30% (Figure 1), thus making this the only sector not to provide a reduction in comparison with 1990 (Kahn Ribeiro et al., 2007; EC, 2009).

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 (UN, 1998) 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 (van Essen et al., 2003; Fornasiero and Libardo, 2011) or advanced traffic demand management schemes (Bell et al., 2012).

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 (TRB, 2008). 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 timeframe of global warming impacts, making the evaluation of CO_2 externality particularly complex (Morgan and Keith, 1995; Fisher et al., 2007; Solomon et al., 2007).

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 (ECMT, 2001; Sinha and Labi, 2007). 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 (tC) or in tonnes of carbon dioxide (tCO_2)[3]. 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 \$, £ or € 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, while others derive from scientific analyses. A *Carbon Trading Cost* derived from the EU Emissions Trading System (EU, 2012a) or a *Carbon Tax Cost* (Santos et al., 2010) would belong to the first group, being the result of governmental measures stated at national and international level. Since these measures are largely related to single jurisdictions, the prices will tend to fluctuate (Sumner et al., 2009) and therefore be inherently unsuitable for long-term forecasts (Ellerman et al., 2008). 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

[3] 1 tC = 3.664 tCO_2 (IPCC, 1995).

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 (MSCC), 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 (Watkiss et al., 2005).

Determining CO_2 impacts on future climate and physical changes is the real challenge of this method, because the most important consequences (Table 1; Watkiss et al., 2005) are not easy to predict, due to 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. DICE (Dynamic Integrated Climate-Economy) was one of the first models to be introduced (Nordhaus, 1992): 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 greenhouse gases (Nordhaus, 1992 and 1994). In 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, PAGE and FUND have subsequently become the preferred reference IAMs.

PAGE is based on future climate scenarios as defined by IPCC (2001), modelling both economic and non-economic parameters and determining the damage they cause in the event of temperature increases (Hope, 2006a). 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, since 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, while the period 2100-2300 is based on simple extrapolations (Kuik et al., 2008). The mean and the median values are provided, which are higher than those of PAGE, since 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 (see section 2.3). FUND and PAGE can also be compared, thus obtaining a mean value of the MSCC (Watkiss et al., 2005).

The rapid development of IAMs has encouraged many analyses in 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 $ and £ have been converted to € values by adopting historical rate changes (Bundesbank, 2012; Bank of Italy, 2012).

Some studies summarised in IPCC (1995) were pioneering. Due to their oversimplifications, these studies are not shown here[4]. 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 ExternE Project (EC, 2005) 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 (see section 2.2).

Tol (2005) 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 95 percentile €95.52/tCO_2. Indeed, grey literature has been found to provide higher CO_2 values (Hohmeyer and Gaertner, 1992; Downing et al., 1996; Eyre et al., 1999; Mendelsohn, 2003). Hence Tol concluded that marginal damage costs of CO_2 emissions were unlikely to exceed €12/tCO_2.

HEATCO (Bickel, 2005) 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. (2005) adopted both PAGE and FUND models, applying a discount rate suggested by the Green Book[5] and a time horizon up to 2060. The PAGE model returned a mean value of €18/tCO_2 for the year 2001, while 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.

[4] Interested readers may refer to Clarkson and Deyes (2002).

[5] The Green Book (HM Treasury, 2003) is the UK Treasury guidance for Central Government, setting out a framework for the appraisal and evaluation of all policies, programmes and projects.

Stern (2006) 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 (parts per million by volume); 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 to €71.50/tCO_2 , NRC (2009) 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 2; in order to make them comparable they have been converted to 2010 € values using the European Harmonised indices of consumer prices (EC, 2012).

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" (UN, 1998) or European "20-20-20" targets (EU, 2012b) – 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. Since 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 (MAC) and the marginal social damage curves (MSC). In other words, 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 (Clarkson and Deyes, 2002).

The MARKAL model, adopted by the British DTI (Strachan et al., 2007) 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 (GDP) 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 (Bundesbank, 2012; Bank of Italy, 2012).

Maibach et al. (2000) 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.

The RECORDIT Project (Clas, 2002) was based on the target proposed by the Organisation for Economic Co-operation and Development (OECD) under the Kyoto Protocol for the short term and the IPCC target for the long term. The study provided respectively €37 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 (Nash, 2003) or slightly lower (ECCP, 2001). Maibach et al. (2004) 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 (EC, 2005) was only slightly lower (19 €/tCO_2), since it also took into account the price of the tradable CO_2 permits in 2005, which varied between €18 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, 2007) adopted two different models, namely the POLES and GEM E3. POLES (Criqui, 2001) 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 (Kapros et al., 2012) 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 five-year time step. By using these two models, the scenario adopted aimed at reducing emissions by a good 25% by 2050[6]. 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. (2008) was even more ambitious: restricting CO_2 values to 350 ppmv by 2050. The costs for this challenge were quantified between €74 and €227/tCO_2 by 2025 and between €132 and €381/tCO_2 by 2050.

Results of the most important damage cost studies are summarised in Table 3; in order to make them comparable they have been converted to 2010 € values using the European Harmonised indices of consumer prices (EC, 2012).

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

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 one 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 (2011) estimates that avoidance costs range between €15.09 and €37.72/tCO_2; on the other hand, damage costs range from €14.33 to about €678.88/tCO_2, but in some cases negative values have also been proposed (e.g. Tol, 2005). 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 (see Tables 2 and 3): this is mostly due to the presence of uncertainty. The topic has been extensively treated in Clarkson and Deyes (2002), 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. Since 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" (EC, 2008). 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 (Salling, 2008). 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 (HEVs) 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 (Weiss et al., 2012). 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 under- or overuse of the single infrastructures that generates consequent problems in the whole mobility network (Flyvbjerg et al., 2006). Also in this case no definitive answers can be provided, but the error can be controlled by adopting specific forecasting methods, such as the "four stage model" (Cascetta, 2006; McNally, 2008) and the "input-output" model (Leontief and Costa, 1996).

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 1, 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 over- or underestimating certain aspects. Since 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[7] (Table 1).

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 (Pearce et al., 1996; Watkiss et al., 2005). 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 (Kuik et al., 2007). 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 GDPs of the countries. Earlier studies did not include this aspect in their analyses (Fankhauser, 1995; Tol, 1995), since regional impacts were quantified in local currencies, converted to dollars and then totalled. To avoid these differences, the concept of *Equity Weight* has been introduced (Fankhauser et al., 1997), whose formula could be expressed as:

[7] Interested readers may refer to Litman (2011) for further details.

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

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 formula (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 (Anthoff and Tol, 2007). Firstly, it expresses the kind of welfare function, determining the measure of aversion to inequality between regions; secondly, it is the expression of inequality between different time periods; thirdly, 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 (Hope, 2006b). The consequence is that estimates can differ even by two orders of magnitude due to the equity weight, depending on the region considered (Anthoff et al., 2006).

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 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 (HM Treasury, 2003). Some trustworthy critics voice concerns with the fundamentals of this method: Chichilnisky (1996), for example, considers discounting as a dictatorship of the present generation over the future, whereas Daly and Cobb (1994) 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. (2005), 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 above. 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 €1,000/tCO_2 (Litman, 2011). 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 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 (Maibach et al., 2008). 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 (Nocera and Cavallaro, 2012): 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): firstly, this is the method most often adopted in other environmental analyses of external costs as well, making the results comparable. Secondly, 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 (EC, 2012); the analytical reconstruction of the final prices, as listed in Table 4, is elaborated in Appendix 1.

Lower values are derived from Watkiss et al. (2005). 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. Since 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 (2012) 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 (EC, 2005) for the short term (2010-2020) and CEC (2007) for the long term (2021-2035): both projects have been developed under the supervision of the EU, 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. (2008). 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 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 4. 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 (Wang et al., 2007) 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 BBT

The Brenner Corridor is the central sector of Line 1 of the Trans-European Transport Network (TEN-T) that links Berlin and Palermo with a 2,200 km long high-speed 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, 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, 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 (HS) 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 Brenner Base Tunnel (henceforth, BBT) is a 55 km-long railway tunnel, due to be completed by 2025[8], 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 minutes along the stretch: an intercity train will take only 3 hours to cover the entire distance, compared with the current 5 hours and 30 minutes (BBT SE, 2012).

In general, the impacts that an infrastructure produces on a given territory involve many aspects (Sinha and Labi, 2007): 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).

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

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 (2007). 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 5 describes in detail the most important measures adopted in each of the three scenarios.

"Minimum" is very conservative, since 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 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 eco-tax 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 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, since 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, while 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 6.

The overall CO_2 emissions produced by the construction of the BBT are estimated to be about 2,280 kilotons (kt), of which more than 85% (about 1,940 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[9].

[9] The methods and the parameters adopted to determine these values are fully explained in Nocera et al. (2012).

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 (ProgTrans, 2007). These values are then cross-tabulated with the historical data to determine the yearly future transport demand up to 2035 (Ruffini et al., 2011).

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 formula (2):

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

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[10];
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, formula (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;
p_i is defined as above;
i is the modal index (i=1 for cars; i=2 for HGVs, i=3 for passenger trains; i=4 for freight trains);
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 (Nocera and Cavallaro, 2011). Overall CO_2 emissions deriving from the operational phase are provided in Table 7: 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.

[10] In this analysis, standard trains are powered by electricity and standard road vehicles by diesel technology. According to Cappelli and Pozzi (2011) and to Weiss et al. (2012), alternative sources such as Battery-electric vehicles can be considered economically competitive only after a few decades, and thus are not considered here.
Specific emissions are calculated adopting Tremove (Transport & Mobility Leuven, 2007) and Infras (2010) for train and road emissions, respectively. Interested readers may refer to Nocera et al. (2012), where a detailed description of the values and the methodology is provided.

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 6 and 7, "Trend" provides emissions equal to about 51,100 kt (2,280 + 48,800 kt), whereas "Consensus" limits CO_2 to 45,400 kt (2,280 + 43,150 kt). Finally, since 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 4,400 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", -1,300 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 7) by the corresponding unitary CO_2 price, selecting from the lower, the central and the upper values listed in Table 4. 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 formula (4):

$$E_{co2} = \sum_{k=i}^{n} co_{2k} \cdot u_{hk} \tag{4}$$

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;
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.

Reiterating this formula for each of the three scenarios and for each of the three unitary prices gives rise to a 3x3 matrix, which provides the economic value of CO_2 emissions from 2010 to 2035 in different scenarios (Table 8). As far as the lower unitary value is considered, "Minimum" determines an economic impact of about €1,275 million. This value rises to €1,341 million in "Trend" and lowers to €1,175 million for "Consensus" (Figure 6).

The central unitary values determine a CO_2 economic cost of about €2,635 million in "Minimum", increasing to €2,788 million in "Trend" and reducing to €2,424 million in "Consensus" (Figure 7).

Finally, adopting the upper unitary value (Figure 8), the economic impact of CO_2 is quantified at €4,188 million when using the "Minimum" scenario. The value rises to €4,416 million in "Trend", and lowers to €3,857 million in "Consensus".

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. (2012). 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 €100 million, €211 million or €331 million if the lower, central or upper value is considered; Table 9). 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 to "Minimum" (respectively an increase of about €66 million, €153 million or €228 million, if the lower, central or upper value is considered; Table 9).

It follows that the difference between "Trend" and "Consensus" is respectively €166 million, €364 million, or €559 million if the lower, central or upper value is considered (Figures 9, 10, 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[11]" seems ineffective if not also supported by "push-measures[12]" 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 provides optimal results in terms of CO_2 reduction (Wolfram, 2005); on the other hand, it warns the community that the simple realisation of less polluting infrastructures cannot be enough. It follows that the backing of a solid policy – here including local and national legislation,

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

[12] 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).

voluntary agreements, graduated vehicle taxes, fiscal measures, 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 greenhouse gas 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 carbon dioxide 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, since 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 Brenner Base Tunnel 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 €331 million 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 €228 million. 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 €559 million, 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 (IUAV TTL, 2010). 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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7) TABLES

TABLE 1: 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 - migration, based on socially contingent effects
2) Energy use	- 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., 2005, modified

TABLE 1: Main environmental impacts of CO_2. Source: Watkiss et al., 2005, modified

TABLE 2: DAMAGE COST METHOD. ECONOMIC VALUES 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	IPCC, 1995	€ 1.43		€ 46.56	€ 2.25		€ 60.49
Tol	----	Tol, 2005	€ 0.44	€ 2.80	€ 18.60	€ 0.51	€ 3.25	€ 21.58
ExternE	2005	EC, 2005		€ 9			€ 10.44	
Watkiss	2005	Watkiss et al., 2005	€ 18 *	€ 22	€ 26**	€ 20.88	€ 25.52	€ 30.16
DLR	2006	Krewitt and Schlomann, 2006	€ 15	€ 70	€ 280	€ 17.05	€ 79.58	€ 318.30
HEATCO	2005	Bickel, 2005	€ 22		€ 83	€ 25.52		€ 96.28
Stern review	2006	Stern, 2006	€ 25		€ 71	€ 28.42		€ 80.71
NRC	2009	National Research Council, 2009	€ 0.70	€ 21.50	€ 71.50	€ 0.74	€ 22.70	€ 75.48
Notes: ° The value date is indicated in column "year". * Adopting PAGE model ** Adopting FUND model. Exchange rates taken from Bundesbank, 2012 and Bankenverband, 2012. ^ Conversion to 2010 € values based on EC, 2012								

TABLE 2: Damage Cost method, list of main studies on the economic value of CO_2

TABLE 3: AVOIDANCE COST METHOD. ECONOMIC VALUES 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	Maibach et al., 2000	€ 70	€ 135	€ 200	€ 90.94	€ 175.39	€ 259.84
IPCC	2001	IPCC, 2001		€ 20			€ 25.29	
RECORDIT	2001	Clas, 2002	€ 37*		€ 135†	€ 45.50		€ 166.00
UNITE	2003	Nash, 2003	€ 5	€ 20	38	€ 6.03	€ 24.13	€ 45.84
INFRAS	2004	Maibach et al., 2004	€ 20*		€ 140	€ 23.66		€ 165.65
ExternE	2005	EC, 2005	€ 19		€ 95	€ 22.04		€ 110.20
CEC	2007	CEC, 2007	€ 15♦	€ 65▲	€ 120■	€ 16.70	€ 72.38	€ 133.63
Kuik	2008	Kuik et al., 2008	€ 74□		€ 132■	€ 78.97		€ 140.87
			€ 227□		€ 381■	€ 242.25		€ 406.60

Notes: ° The value date is indicated in column "year". * Short term value † Long term value

^ Conversion to 2010 € values based on EC, 2012 ♦ Year 2010 □ Year 2025 ▲ Year 2030 ■ Year 2050

TABLE 3: Avoidance Cost method, list of main studies on the economic value of CO_2

TABLE 4: CO_2 PRICES ADOPTED HERE FOR THE YEARS 2010-2035			
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

TABLE 4: CO_2 prices (€/tCO_2) adopted here for the years 2010-2035. Lower, central and upper values.

TABLE 5: 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, 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 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 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
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, 2011

TABLE 5: Measures adopted in "Minimum", "Trend" and "Consensus" Scenarios. Source: Nocera and Cavallaro, 2011

TABLE 6: CO_2 EMISSIONS IN THE CONSTRUCTION PHASE OF BBT		
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	1,580.37
	Steel	358.55
	Transportation of the construction materials using trucks	2.51
	Subtotal	*1,941.44*
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		**2,280.35**
Source: Ruffini et al., 2011		

TABLE 6: CO_2 emissions in the construction phase of BBT. Source: Ruffini et al., 2011

TABLE 7: CO_2 EMISSIONS RELATED TO ROAD AND RAIL TRANSPORT (2010-2035)			
Year	**MINIMUM (kt)**	**TREND (kt)**	**CONSENSUS (kt)**
2010	1,535	1,535	1,500
2011	1,555	1,555	1,502
2012	1,581	1,581	1,510
2013	1,608	1,608	1,518
2014	1,635	1,635	1,526
2015	1,663	1,663	1,534
2016	1,690	1,696	1,542
2017	1,715	1,726	1,565
2018	1,741	1,762	1,589
2019	1,767	1,801	1,615
2020	1,793	1,840	1,643
2021	1,805	1,866	1,659
2022	1,817	1,889	1,670
2023	1,829	1,913	1,681
2024	1,840	1,937	1,695
2025	1,852	1,963	1,709
2026	1,873	1,998	1,733
2027	1,885	2,017	1,740
2028	1,897	2,036	1,748
2029	1,909	2,055	1,755
2030	1,921	2,074	1,763
2031	1,934	2,094	1,772
2032	1,946	2,114	1,780
2033	1,959	2,135	1,788
2034	1,972	2,155	1,797
2035	1,984	2,176	1,805
Total	**46,706**	**48,822**	**43,139**
Source: Nocera et al., 2012			

TABLE 7: CO_2 emissions related to road and rail transport. Source: Nocera et al., 2012

TABLE 8: 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	1,275	2,635	4,188
Trend	1,341	2,788	4,416
Consensus	1,175	2,424	3,857

TABLE 8: CO_2 economic values in different scenarios adopting different unitary values

TABLE 9: CO_2 ECONOMIC VALUES RELATED TO THE EMISSIONS IN DIFFERENT SCENARIOS						
	Policies adopted	Emissions (2010-35)	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:	1,275	-----
				central:	2,635	-----
				upper:	4,188	-----
Trend	Continuation of the trend of the last decade, encouraging railway (realisation of BBT) and road traffic	51,100	+4,400	lower:	1,341	+66
				central:	2,788	+153
				upper:	4,416	+228
Consensus	Fulfilment of a sustainable transport policy, encouraging railway traffic (realisation of BBT) and discouraging road traffic	45,400	-1,300	lower:	1,175	-100
				central:	2,424	-211
				upper:	3,857	-331

TABLE 9: CO_2 economic values related to the emissions in different scenarios

8) APPENDIX 1. THE ANALYTICAL DETERMINATION OF CO_2 ECONOMIC VALUES

	LOWER VALUE							CENTRAL VALUE							UPPER 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	$HICP_1$	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**
	£$_{2005}$/tC	€$_{2005}$/tC	€$_{2005}$/tCO_2		€$_{2010}$/tCO_2		€$_{2010}$/tCO_2	***		€$_{2005}$/tCO_2		€$_{2010}$/tCO_2		€$_{2010}$/tCO_2	€$_{2008}$/tCO_2		€$_{2005}$/tCO_2		€$_{2010}$/tCO_2		€$_{2010}$/tCO_2
	(1)	(2)=(1)* 1,4624245	(3)=(2)/ 3,664	(4)	(5)=(3)*(4)	(6)	(7)= (5)*(6)	(8)	(9)	(10)= (8)*(9)	(11)	(12)= (10)*(11)	(13)	(14)= (12)*(13)	(15)	(16)	(17)= (15)*(16)	(18)	(19)= (17)*(18)	(20)	(21)= (19)*(20)
2010	£ 40,00	€ 58,50	€ 15,97	1,16	€ 18,52	€ 0,93	**€ 19,45**	€ 19,00	1,00	€ 19,00	1,16	€ 22,04	€ 1,10	**€ 23,14**	€ 45,00	0,92	€ 41,40	1,16	€ 48,02	€ 2,40	**€ 50,43**
2011	£ 41,00	€ 59,96	€ 16,36	1,16	€ 18,98	€ 0,95	**€ 19,93**	€ 20,90	1,00	€ 20,90	1,16	€ 24,24	€ 1,21	**€ 25,46**	€ 47,50	0,92	€ 43,70	1,16	€ 50,69	€ 2,53	**€ 53,23**
2012	£ 42,00	€ 61,42	€ 16,76	1,16	€ 19,45	€ 0,97	**€ 20,42**	€ 22,80	1,00	€ 22,80	1,16	€ 26,45	€ 1,32	**€ 27,77**	€ 50,00	0,92	€ 46,00	1,16	€ 53,36	€ 2,67	**€ 56,03**
2013	£ 43,00	€ 62,88	€ 17,16	1,16	€ 19,91	€ 1,00	**€ 20,90**	€ 24,70	1,00	€ 24,70	1,16	€ 28,65	€ 1,43	**€ 30,08**	€ 52,50	0,92	€ 48,30	1,16	€ 56,03	€ 2,80	**€ 58,83**
2014	£ 44,00	€ 64,35	€ 17,56	1,16	€ 20,37	€ 1,02	**€ 21,39**	€ 26,60	1,00	€ 26,60	1,16	€ 30,86	€ 1,54	**€ 32,40**	€ 55,00	0,92	€ 50,60	1,16	€ 58,70	€ 2,93	**€ 61,63**
2015	£ 45,00	€ 65,81	€ 17,96	1,16	€ 20,83	€ 1,04	**€ 21,88**	€ 28,50	1,00	€ 28,50	1,16	€ 33,06	€ 1,65	**€ 34,71**	€ 57,50	0,92	€ 52,90	1,16	€ 61,36	€ 3,07	**€ 64,43**
2016	£ 46,00	€ 67,27	€ 18,36	1,16	€ 21,30	€ 1,06	**€ 22,36**	€ 30,40	1,00	€ 30,40	1,16	€ 35,26	€ 1,76	**€ 37,03**	€ 60,00	0,92	€ 55,20	1,16	€ 64,03	€ 3,20	**€ 67,23**
2017	£ 47,00	€ 68,73	€ 18,76	1,16	€ 21,76	€ 1,09	**€ 22,85**	€ 32,30	1,00	€ 32,30	1,16	€ 37,47	€ 1,87	**€ 39,34**	€ 62,50	0,92	€ 57,50	1,16	€ 66,70	€ 3,34	**€ 70,04**
2018	£ 48,00	€ 70,20	€ 19,16	1,16	€ 22,22	€ 1,11	**€ 23,33**	€ 34,20	1,00	€ 34,20	1,16	€ 39,67	€ 1,98	**€ 41,66**	€ 65,00	0,92	€ 59,80	1,16	€ 69,37	€ 3,47	**€ 72,84**
2019	£ 49,00	€ 71,66	€ 19,56	1,16	€ 22,69	€ 1,13	**€ 23,82**	€ 36,10	1,00	€ 36,10	1,16	€ 41,88	€ 2,09	**€ 43,97**	€ 67,50	0,92	€ 62,10	1,16	€ 72,04	€ 3,60	**€ 75,64**
2020	£ 50,00	€ 73,12	€ 19,96	1,16	€ 23,15	€ 1,16	**€ 24,31**	€ 38,00	1,00	€ 38,00	1,16	€ 44,08	€ 2,20	**€ 46,28**	€ 70,00	0,92	€ 64,40	1,16	€ 74,70	€ 3,74	**€ 78,44**
2021	£ 51,50	€ 75,31	€ 20,56	1,16	€ 23,84	€ 1,19	**€ 25,04**	€ 40,70	0,96	€ 39,07	1,16	€ 45,32	€ 2,27	**€ 47,59**	€ 73,00	0,92	€ 67,16	1,16	€ 77,91	€ 3,90	**€ 81,80**
2022	£ 53,00	€ 77,51	€ 21,15	1,16	€ 24,54	€ 1,23	**€ 25,77**	€ 43,40	0,96	€ 41,66	1,16	€ 48,33	€ 2,42	**€ 50,75**	€ 76,00	0,92	€ 69,92	1,16	€ 81,11	€ 4,06	**€ 85,16**
2023	£ 54,50	€ 79,70	€ 21,75	1,16	€ 25,23	€ 1,26	**€ 26,49**	€ 46,10	0,96	€ 44,26	1,16	€ 51,34	€ 2,57	**€ 53,90**	€ 79,00	0,92	€ 72,68	1,16	€ 84,31	€ 4,22	**€ 88,52**
2024	£ 56,00	€ 81,90	€ 22,35	1,16	€ 25,93	€ 1,30	**€ 27,22**	€ 48,80	0,96	€ 46,85	1,16	€ 54,34	€ 2,72	**€ 57,06**	€ 82,00	0,92	€ 75,44	1,16	€ 87,51	€ 4,38	**€ 91,89**
2025	£ 57,50	€ 84,09	€ 22,95	1,16	€ 26,62	€ 1,33	**€ 27,95**	€ 51,50	0,96	€ 49,44	1,16	€ 57,35	€ 2,87	**€ 60,22**	€ 85,00	0,92	€ 78,20	1,16	€ 90,71	€ 4,54	**€ 95,25**
2026	£ 59,00	€ 86,28	€ 23,55	1,16	€ 27,32	€ 1,37	**€ 28,68**	€ 54,20	0,96	€ 52,03	1,16	€ 60,36	€ 3,02	**€ 63,37**	€ 88,00	0,92	€ 80,96	1,16	€ 93,91	€ 4,70	**€ 98,61**
2027	£ 60,50	€ 88,48	€ 24,15	1,16	€ 28,01	€ 1,40	**€ 29,41**	€ 56,90	0,96	€ 54,62	1,16	€ 63,36	€ 3,17	**€ 66,53**	€ 91,00	0,92	€ 83,72	1,16	€ 97,12	€ 4,86	**€ 101,97**
2028	£ 62,00	€ 90,67	€ 24,75	1,16	€ 28,71	€ 1,44	**€ 30,14**	€ 59,60	0,96	€ 57,22	1,16	€ 66,37	€ 3,32	**€ 69,69**	€ 94,00	0,92	€ 86,48	1,16	€ 100,32	€ 5,02	**€ 105,33**
2029	£ 63,50	€ 92,86	€ 25,34	1,16	€ 29,40	€ 1,47	**€ 30,87**	€ 62,30	0,96	€ 59,81	1,16	€ 69,38	€ 3,47	**€ 72,85**	€ 97,00	0,92	€ 89,24	1,16	€ 103,52	€ 5,18	**€ 108,69**
2030	£ 65,00	€ 95,06	€ 25,94	1,16	€ 30,09	€ 1,50	**€ 31,60**	€ 65,00	0,96	€ 62,40	1,16	€ 72,38	€ 3,62	**€ 76,00**	€ 100,00	0,92	€ 92,00	1,16	€ 106,72	€ 5,34	**€ 112,06**
2031	£ 67,50	€ 98,71	€ 26,94	1,16	€ 31,25	€ 1,56	**€ 32,81**	€ 67,75	0,96	€ 65,04	1,16	€ 75,45	€ 3,77	**€ 79,22**	€ 103,50	0,92	€ 95,22	1,16	€ 110,46	€ 5,52	**€ 115,98**
2032	£ 70,00	€ 102,37	€ 27,94	1,16	€ 32,41	€ 1,62	**€ 34,03**	€ 70,50	0,96	€ 67,68	1,16	€ 78,51	€ 3,93	**€ 82,43**	€ 104,67	0,92	€ 96,29	1,16	€ 111,70	€ 5,59	**€ 117,29**
2033	£ 72,50	€ 106,03	€ 28,94	1,16	€ 33,57	€ 1,68	**€ 35,25**	€ 73,25	0,96	€ 70,32	1,16	€ 81,57	€ 4,08	**€ 85,65**	€ 108,17	0,92	€ 99,51	1,16	€ 115,44	€ 5,77	**€ 121,21**
2034	£ 75,00	€ 109,68	€ 29,93	1,16	€ 34,72	€ 1,74	**€ 36,46**	€ 76,00	0,96	€ 72,96	1,16	€ 84,63	€ 4,23	**€ 88,87**	€ 111,67	0,92	€ 102,73	1,16	€ 119,17	€ 5,96	**€ 125,13**
2035	£ 77,50	€ 113,34	€ 30,93	1,16	€ 35,88	€ 1,79	**€ 37,68**	€ 78,75	0,96	€ 75,60	1,16	€ 87,70	€ 4,38	**€ 92,08**	€ 115,17	0,92	€ 105,95	1,16	€ 122,91	€ 6,15	**€ 129,05**

Note:

*1 £ = 1.4624245 € (Bank of Italy, 2012)

** 1 tC = 3.664 tCO_2 (IPCC, 1995)

*** €$_{2005}$/tCO_2 for years 2010-2020; €$_{2007}$/tCO_2 for years 2021-2035

$HICP_1$ = Harmonised indices of consumer prices adjusted to 2010 values (EC, 2012)
$HICP_2$ = Harmonised indices of consumer prices adjusted to 2005 values (EC, 2012)

° Watkiss et al. (2005)

°° ExternE (2005) for the years 2010-2020; CEC (2007) for the years 2020-2035

°°° Maibach et al. (2008)

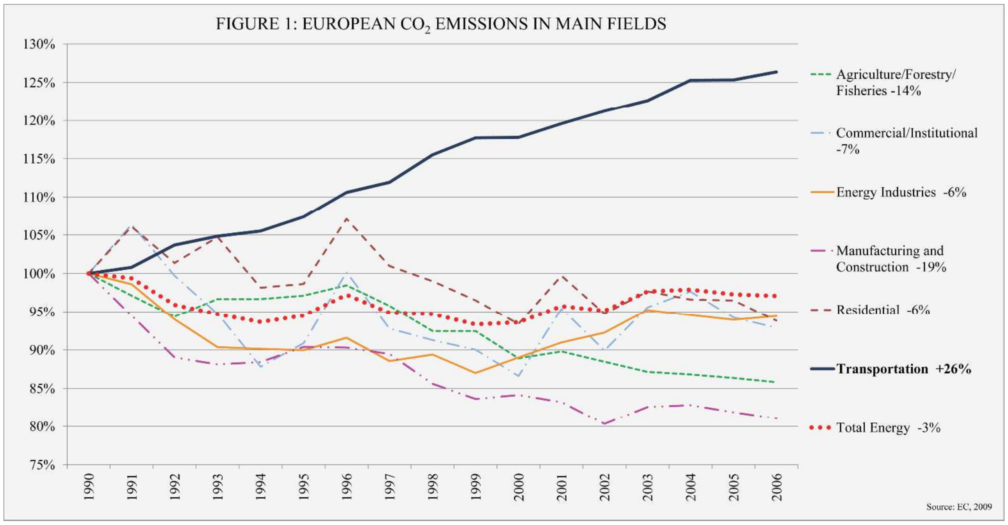

FIGURE 1: European CO2 emissions in main fields. Source: EC, 2009
384x198mm (300 x 300 DPI)

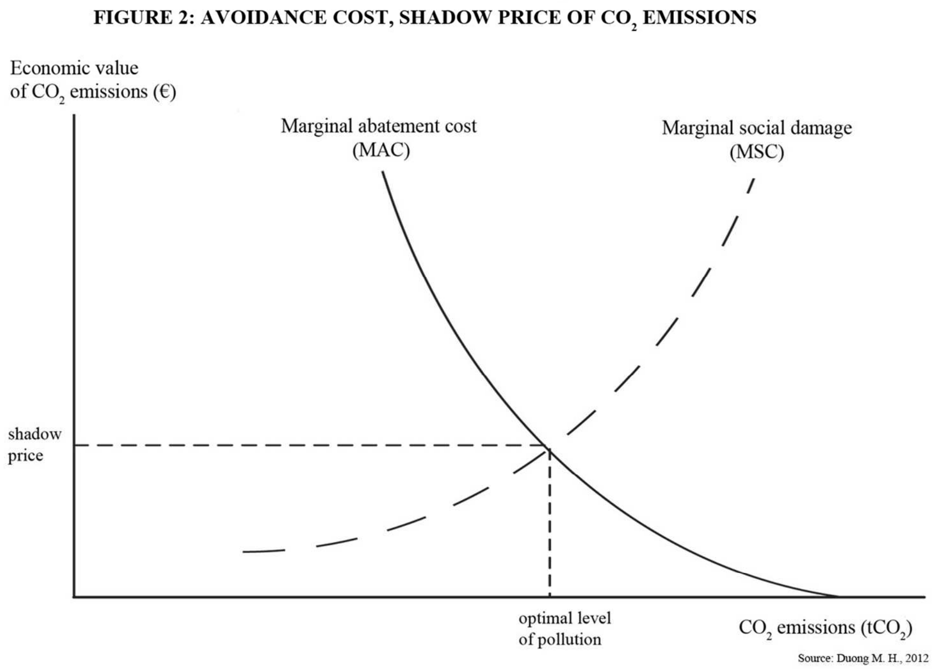

FIGURE 2: Shadow price of CO2 emissions as the intersection between marginal abatement costs and social damage curves. Source: Duong (2012)
119x82mm (300 x 300 DPI)

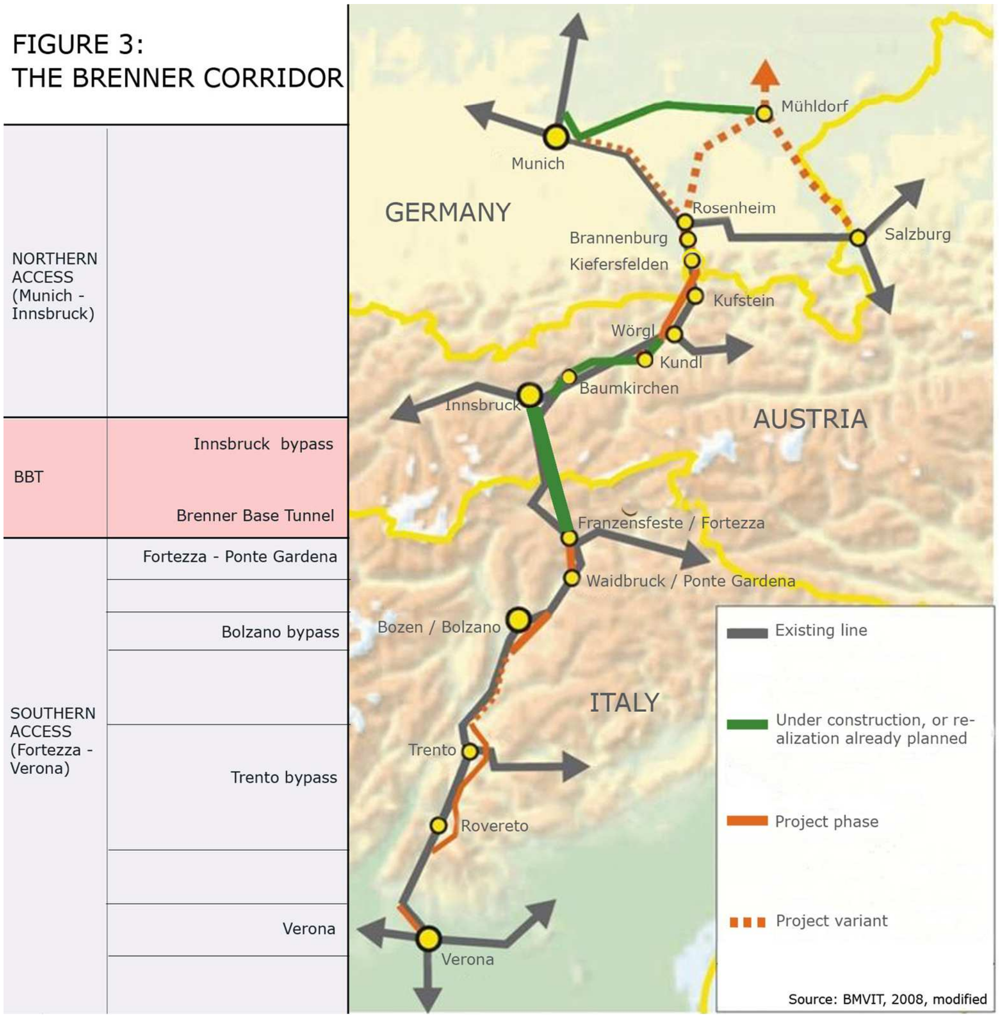

FIGURE 3: Munich-Verona HS railway line. Source: BMVIT (2008), modified
139x140mm (300 x 300 DPI)

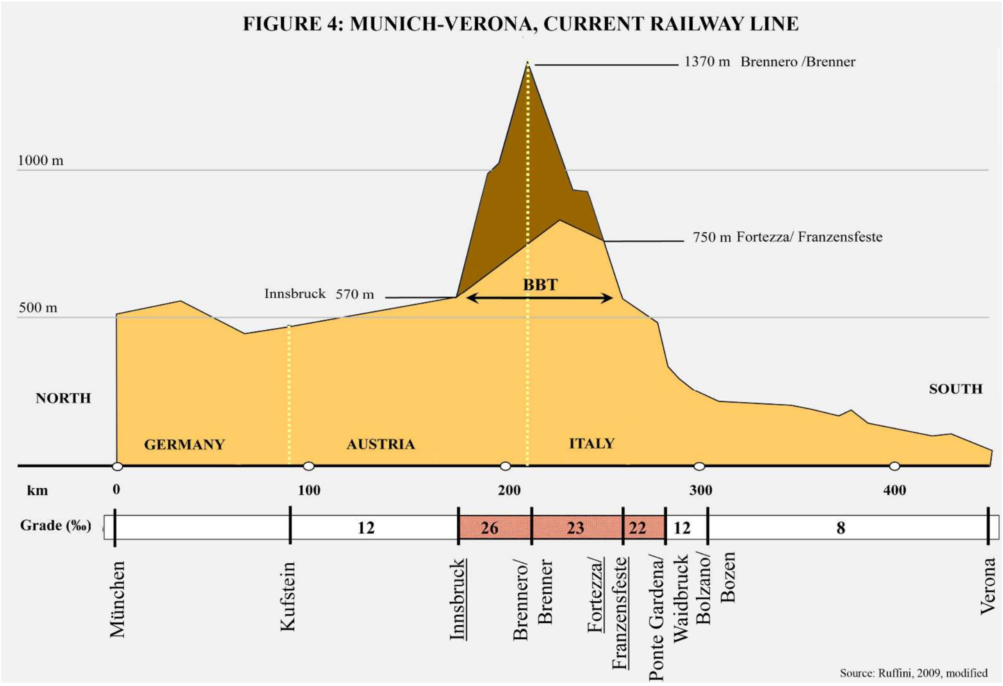

FIGURE 4: Munich-Verona, current railway line. Source: Ruffini (2009), modified
275x187mm (300 x 300 DPI)

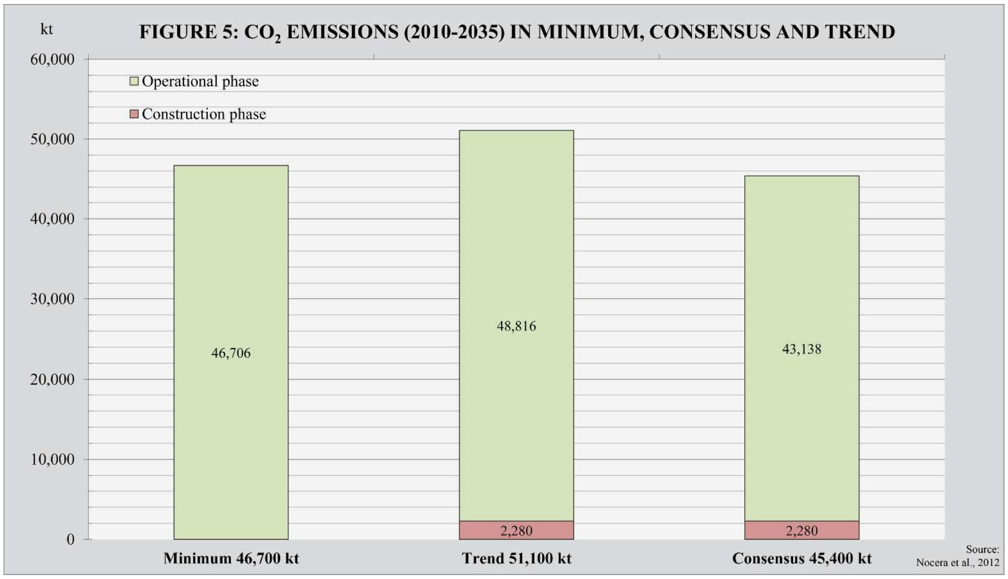

FIGURE 5: CO2 emissions in “Minimum”, “Trend” and “Consensus” for the years 2010-2035. Source: Nocera et al. (2012)
384x219mm (300 x 300 DPI)

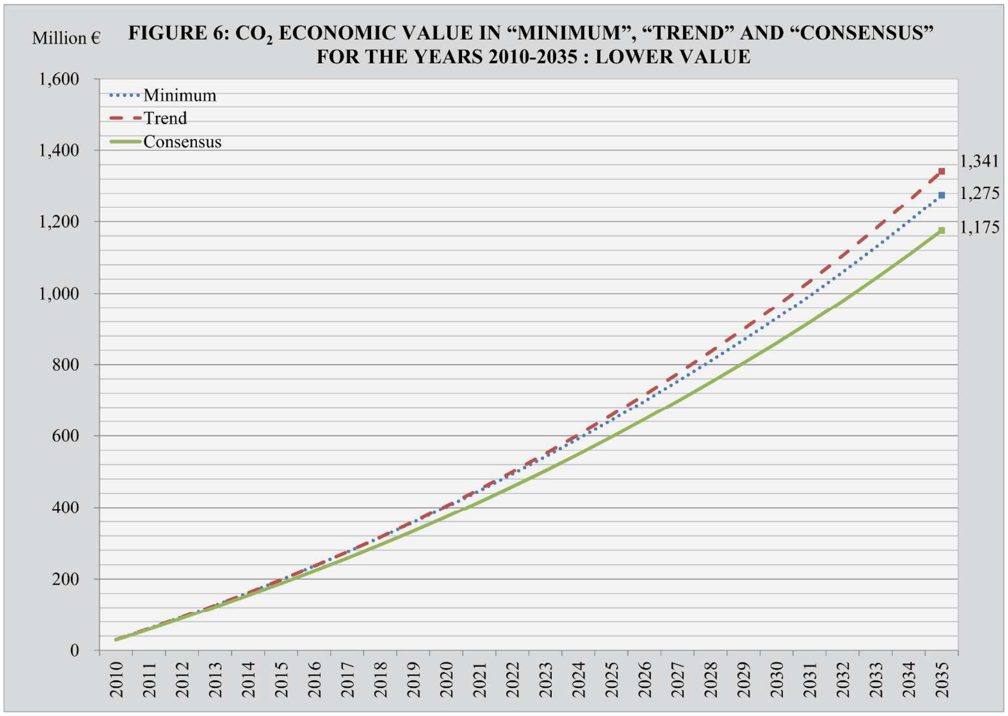

FIGURE 6: CO2 economic value in "Minimum", "Trend" and "Consensus" (2010-2035): lower value
365x258mm (300 x 300 DPI)

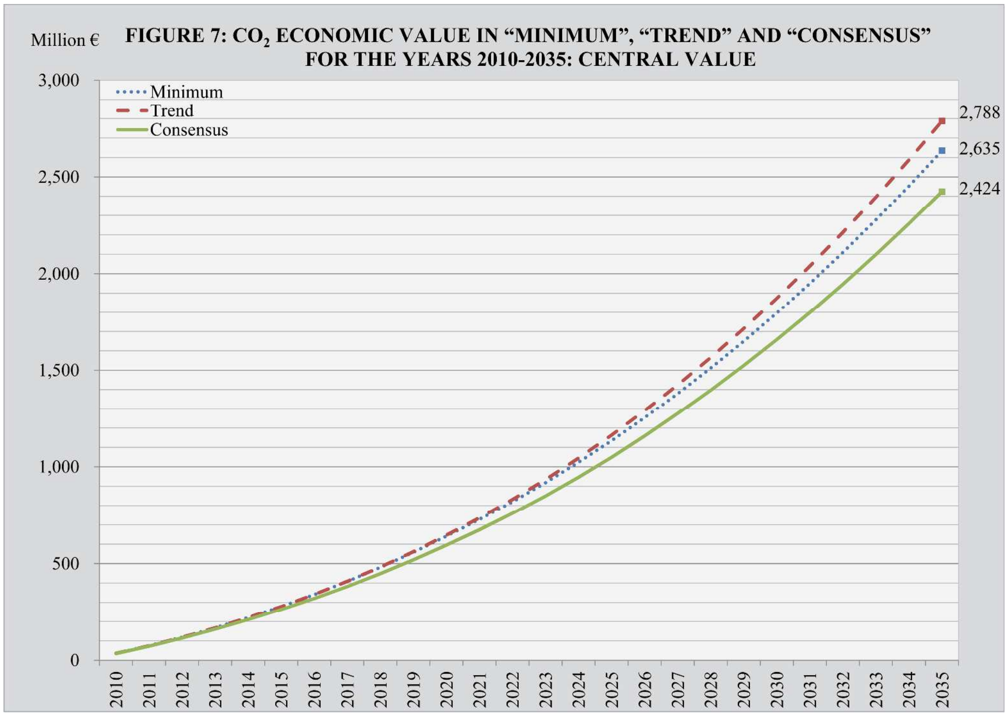

FIGURE 7: CO2 economic value in "Minimum", "Trend" and "Consensus" (2010-2035): central value
365x258mm (300 x 300 DPI)

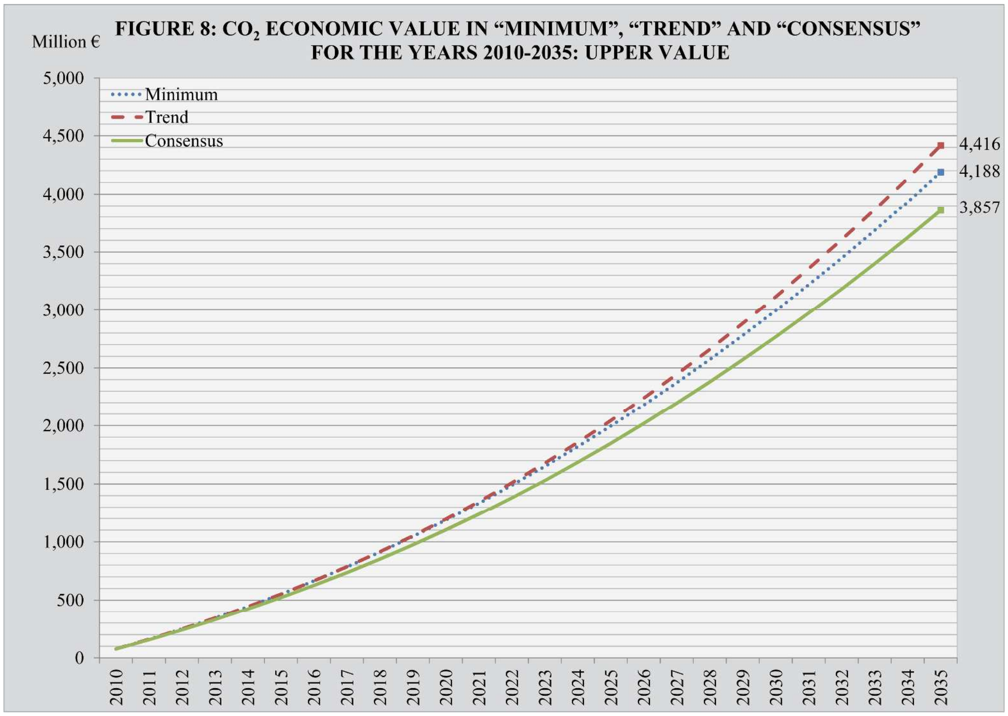

FIGURE 8: CO2 economic value in "Minimum", "Trend" and "Consensus" (2010-2035): upper value
365x258mm (300 x 300 DPI)

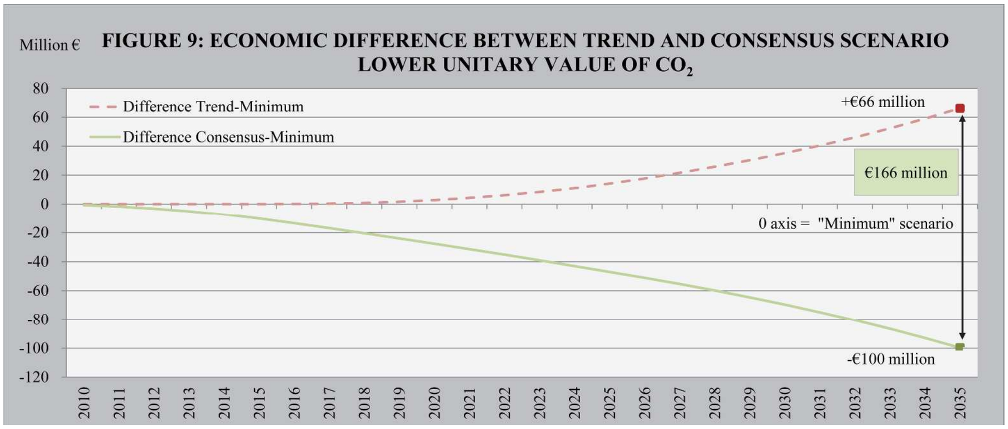

FIGURE 9: Economic difference between “Trend” and “Consensus”: lower unitary value of CO2
306x129mm (300 x 300 DPI)

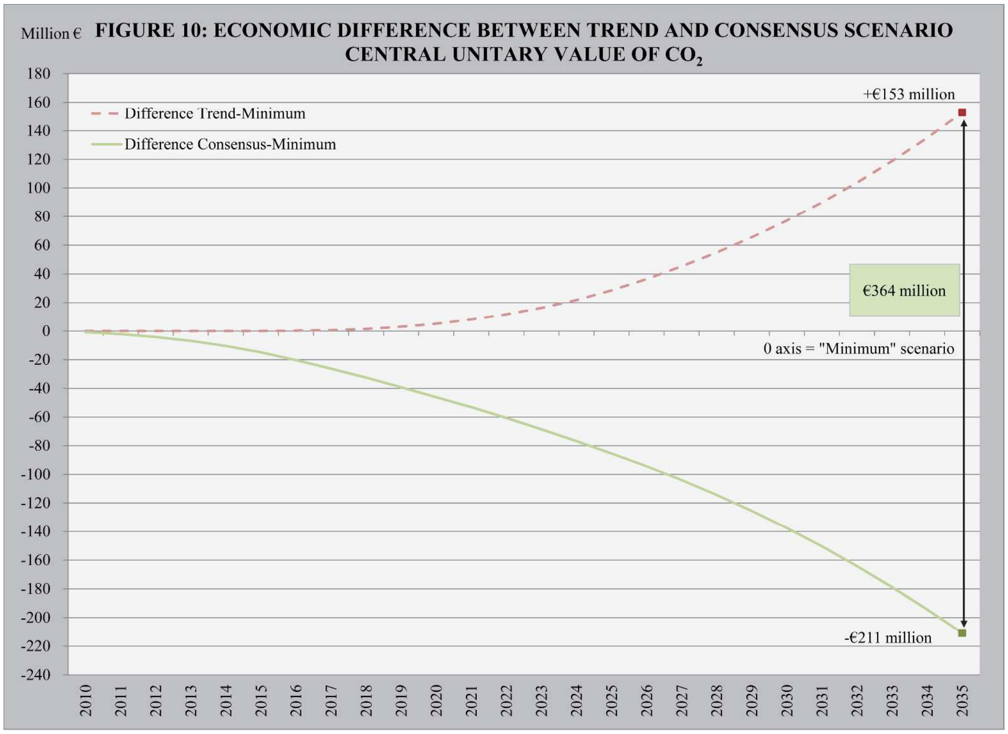

FIGURE 10: Economic difference between “Trend” and “Consensus”: central unitary value of CO2
306x223mm (300 x 300 DPI)

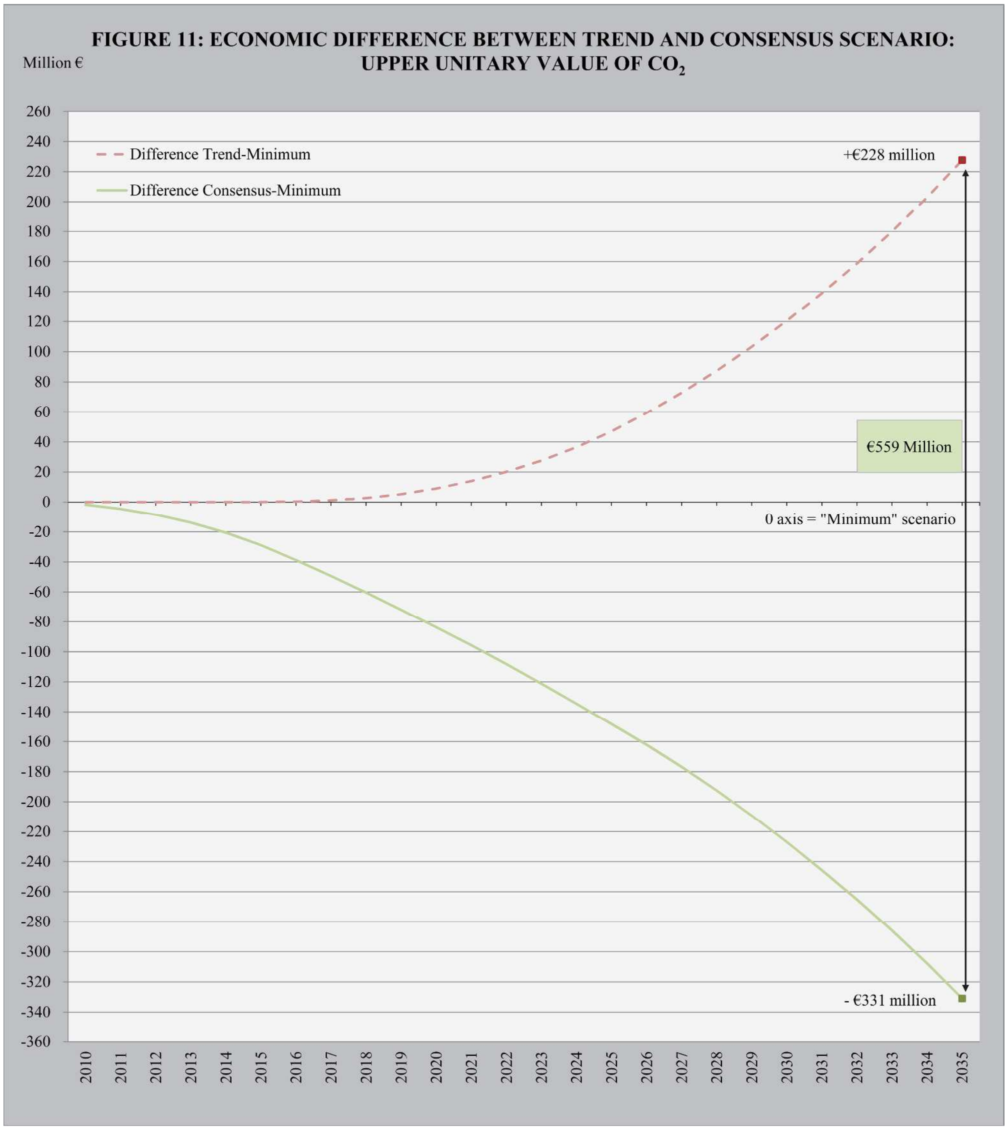

FIGURE 11: Economic difference between “Trend” and “Consensus”: upper unitary value of CO2
307x344mm (300 x 300 DPI)