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ORIGINAL PAPER

A heuristic method for determining CO_2 efficiency in transportation planning

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Abstract

Background CO_2 emissions are generally considered the most important indicator to determine the global warming effects. Their evaluation in the case of a transportation infrastructure is generally not easy and could be achieved through a separate balance.

Method This paper introduces a new heuristic method for identifying the modifications in the CO_2 emission balance, deriving from a variation in transportation supply. The focus is predominantly on the construction and on the operational phases, which are listed in all their main elements. The method compares the maintenance of the “do-nothing” option with a number of traffic scenarios resulting from the introduction of a new infrastructure and deriving from different policy measures.

Case-study The construction of the Brenner Base Tunnel is used as a case-study for the model, highlighting the role of an enlightened transport policy in the reduction of the CO_2 emissions.

Keywords CO_2 Emissions · Transportation · Heuristic · Brenner railway tunnel

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1 Introduction

The extent and nature of the growing traffic demand in Europe pose several challenges for sustainable transportation, putting pressure on the decision-makers to provide new facilities for both passenger and freight transportation, and hence an ever increasing strain on infrastructure planning policy.

The decline in railway use favours the expansion of road mobility and its infrastructures. In this framework the over-dependence on a limited number of routes has severe impacts on certain areas, generally without adequate compensation for the local communities, which call for measures to mitigate the negative impacts of traffic (congestion, severe crash incidents, large amounts of land wasted and pollution from all motorized traffic modes).

Among the polluting substances, greenhouse gases (GHGs) have steadily assumed a main role. Carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), hydrofluorocarbons (HFC), perfluorinated compounds (PFC), sulphur hexafluoride (SF_6) are the most important among them [39, 51]. However, as CO_2 accounts for about 90% of global GHG emissions [12], it is often used as an overall indicator in heuristic methods.

The CO_2 impacts concern the three environmental, social and economic dimensions of sustainability [11, 41, 50]. Referring to the first one, CO_2 becomes one of the main causes of the global warming [14, 39] as soon as its level exceeds the threshold level of 350 parts per million by volume (ppmv) [18]. The linked environmental consequences are well known: weather changes, temperature increase, sea-level rise, harmful freeze–thaw cycles, precipitation changes, landslides, erosions in coastal areas etc.…

Social sustainability of CO_2 impacts is normally referred to the remarkable influence of these consequences on human life. Among them, a reduction in the agricultural productivity and in the gross domestic product as well as a migration towards more productive areas are included, mostly in the development countries, thus confirming that the unmitigated climate change is incompatible with sustainable development [53]. Other consequences are visible in the life style and in the health of humans, including heat strokes, cardiovascular and respiratory problems [6, 22]. Finally, the economic aspect has been treated in a vast amount of studies [34, 53], including some radical theories that consider the global warming as the most important market failure ever seen [42]. Hence it derives that the determination of the future CO_2 emissions is very relevant if related to the concept of sustainability and its three dimensions.

Even though our understanding of the physical mechanisms of the climate system has progressed rapidly, the use of this knowledge to support transportation decision making, manage risks, and engage stakeholders is still inadequate [45, 48]. Indeed, expressing global warming in monetary terms requires providing a consistent estimation of the effects of higher temperatures within the well-known uncertainty of linking CO_2 and environmental damage. This is the biggest issue in dealing with global warming and the very aspect that sets it apart from other external costs (such as air and noise pollution). As known, the latter are generally converted into monetary units which are purported to express health expenses, property value reduction and other possible costs. Due to this, traditional techniques for monetization hardly apply to the context of CO_2.

Quantifying CO_2 impacts through the Net Present Value (NPV) is challenging, since impacts are difficult to estimate and their apportionment on an annual basis is problematical to apply. Moreover, no distinction between who receives benefits and to whom costs incur can normally be made, thus potentially waiving the principle of social equity (some segments of the community might receive all benefits at the expense of others). A successful attempt of estimating the impacts of greenhouse gas reduction policies through the use of the Benefit-Cost Analysis (BCA) is the use of the MERGE model [7]: the determination of the overall national production of GHGs and other polluting gases in different scenarios with this method showing the effectiveness of a policy that internalizes the costs of the global climate change and the local air pollution.

The Multi-Criteria Evaluation (MCE) is a promising approach when there are significant non-monetary and non-monetisable benefit-and-cost components to a proposed policy or project [11, 27, 28, 36]. This is also the case with GHGs and in particular with CO_2. However, the assessment of the relative level of importance (usually referred to as "weight") of GHGs with respect to other criteria is normally an issue, because the link between emissions and global effects is hard to estimate and quantify. This is obviously a key-step, which may yield flawed results if emissions are assessed using MCE.

In order to determine the CO_2 contribute to the overall impacts, a separate balance analysis is required. This method has already been applied in many fields, namely the industrial [13, 19, 54] as well as the biological [25], agricultural [9] and renewable energy [26] ones.

CO_2 balances kindle considerable interest also within transportation engineering. Von Rozycki [52] considers the variation in CO_2 emissions related to the introduction of the high-speed railway line between Hanover and Würzburg. The study is detailed but it refers only to the environmental footprint of the railway without considering the concurrent trend in road traffic. Tuchschmid [49] proposes a method to quantify the emissions of several pollutant gases (including CO_2) from the construction of high-speed lines in Europe. Being based on macro-scenarios at European level, the study assumes appropriate simplifications at such a scale, which however make the method inapplicable at infrastructure level. An interesting study is carried out to compare the emissions of CO_{2eq} of the high-speed and traditional railway lines connecting London to locations in the North and West of the United Kingdom [31]. Results are based on scenarios for 2070. Also in this case the study dwells on the railway alone without considering the consequences that the new line could have on the road traffic.

Booz Allen Hamilton Ltd. [8] introduces a balance which compares the CO_2 emissions deriving from the London-Edinburgh and the London-Manchester high speed lines with their corresponding air lines over a period of 60 years. The forecast of the CO_2 emissions is provided by the calculation deriving from the construction and the operation phases, the latter being based on the emissions module (i.e. the forecast of future specific emissions) and the demand module (i.e. the forecast of future demand).

Finally, the engineering company of the Italian State Railways [23] proposes a method to forecast the CO_2 emissions that would be generated by a new railway line between Rho and Gallarate. This study is based on well-defined technical and regulatory assumptions and takes into account various stages of the project (preliminary, final, execution, "as built" phases). However, since it lacks a clear description of the methodology, it can hardly be applied elsewhere.

All the afore-mentioned studies being recent, the current interest in the issue among infrastructural planners is confirmed. Nonetheless, most of the methods quoted do not seem flexible enough to be used for assessing the carbon footprint of different transportation systems.

This paper presents a new heuristic method to that end (thoroughly described in section 2), which will be tested on the Brenner Base Tunnel (BBT) currently under construction (section 3).

2 CO_2 balance: description of the method

A CO_2 balance is an analysis intended 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 civil engineering, it consists of four macro-phases over a long time-frame, namely design, construction, operation and decommissioning (Fig. 1). Each of them must be taken into account in order to assess the overall scope.

The goal of such an analysis is to quantify a system's incoming and outgoing CO_2 emissions in the various phases. The CO_2 balance of a certain project *X* in a given time frame is positive if the overall CO_2 emissions produced (*P*) are lower than the ones generated by the "do-nothing" scenario (*N*). Formally, this assumption can be expressed as follows:

$$BAL_{CO2}(X) = N - P \tag{1}$$

If $BAL_{CO2}(X) > 0$, then $N > P$: the CO_2 emissions of the project are lower than those of the "do-nothing" scenario and hence there is a potential gain for the community. On the contrary, if $BAL_{CO2}(X) < 0$, then the new project system leads to a rise in emissions and its implementation should be discouraged.

2.1 CO_2 emissions for the construction of a new transportation infrastructure

In the field of transportation engineering, the CO_2 balance could be efficiently used in order to evaluate the environmental sustainability of a modified or newly-implemented traffic system or facility. In this last case, this method should take into account the indirect impact that such infrastructures might have in terms of modal distribution of traffic.

To this end a comparison should be made between those scenarios following the building of the planned infrastructure and others, in which no new construction is undertaken. Looking at the phases in Fig. 1, from an operational viewpoint, the emissions resulting both from the design and the decommissioning phases are generally considered as negligible, since the former are of scarce relevance (0,03% in comparison with overall construction phase, [23]) and the latter concern interventions supposed to have a long life.

Also the construction phase seems to play a minor role in the process. In the calibration case chosen in this paper, it accounts only for about 4% overall (Fig. 8) – smaller than the expected error of the methodology to calculate operation emissions. The balance presented should however be applied to a larger amount of cases to make this conclusion generalizable. For this reason, the impacts of the construction phase are examined in short in section 2.2 of this paper.

In this framework, since construction is not to be considered in the "do-nothing" scenario, the terms contained in formula (1) can be expressed as follows:

$$P = C_P + O_P \tag{2}$$

$$N = O_N \tag{3}$$

Where:

P are the total CO_2 emissions related to the project analysed
C_P are the total CO_2 emissions resulting from the construction phase of the project
O_P are the total CO_2 emissions resulting from the operative phase of the project
N are the total CO_2 emissions related to the "do-nothing" scenario
O_N are the total CO_2 emissions resulting from the operative phase of the "do-nothing" scenario.

The emissions resulting from the construction (*C)* and operation (*O*) phases may be further detailed in formulas (4) and (5) (Fig. 2):

$$C = C_{ex} + C_{tr} + C_{pr} + C_{cn} \tag{4}$$

$$O = O_{vh} + O_{up} + O_{io} \tag{5}$$

Where:

C_{ex} are the CO_2 emissions produced by excavation and filling operations
C_{tr} are the CO_2 emissions produced by materials transportation operations
C_{pr} are the CO_2 emissions produced by construction materials production operations
C_{cn} are the CO_2 emissions produced by operations to run the working site
O_{vh} are the CO_2 emissions produced by vehicles
O_{up} are the CO_2 emissions produced by maintenance of the infrastructure

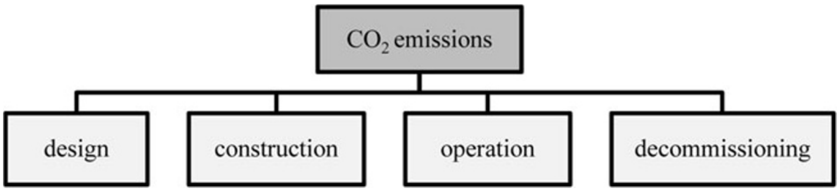
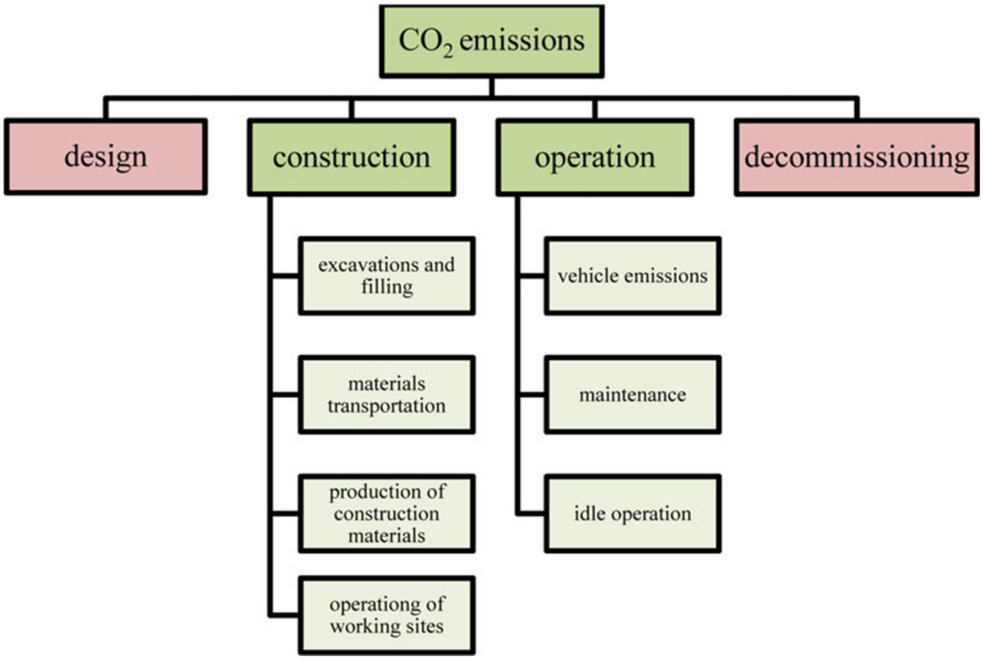


Fig. 1 The phases of a process that yield CO_2 emissions

Fig. 2 CO_2 emissions during the construction and the operation phases of a new infrastructure



O_{io} are the CO_2 emissions produced by idle operation.

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 (2) and (3) can be written as (6) and (7). The choice of the time horizon [1;n] must be well weighed, being based on several factors such as the expected life time of the infrastructure, the reliability of future forecasts etc.

$$P = \sum_{i=1}^{n} P_i = \sum_{j=1}^{m} C_{Pj} + \sum_{i=1}^{n} O_{Pi} \tag{6}$$

$$N = \sum_{i=1}^{n} N_i = \sum_{i=1}^{n} O_{Zi} \tag{7}$$

Sections 2.2 and 2.3 discuss in detail how the terms C and O can be obtained.

2.2 Construction phase

In the construction phase analysis, the calculation of CO_2 emissions is largely linked to the energy consumption, as anthropic CO_2 is released during all energy production and transformation processes that involve combustion. The calculation method proposed is based on a bottom-up approach: it takes into account the final energy consumption of the construction phase and the quantity of materials needed to build the infrastructure. Such data are converted into CO_2 emissions through appropriate factors.

Once the most significant elements of the entire construction process are defined (Fig. 2), these are then broken down into single operations in order to set up the calculation through simplifying assumptions, thus distinguishing relevant aspects from negligible ones.

The accuracy and validity of the results mostly depend on the quality of the data available. Therefore, it is crucial that the entire analysis be based on data as consistent and accurate as possible and capable of covering all the sectors considered. As regards the construction phase, the most useful instruments are the analysis of the available design documentation, an ongoing dialogue with planners, direct observations and surveys.

However, since the analysis is often carried out when the project is still in the assessment phase, there is limited knowledge of the actions and techniques used for construction. To offset this situation, estimates need to be made based on analogy, on the study of the construction techniques, on the information collected from specialised firms and on scientific literature.

Once the final energy consumption for the single construction operations and the quantities of the materials used are obtained, these are converted into CO_2 emissions through the following formula (8) for the construction phase C:

$$C = \sum_{h} f_h \cdot \chi_h + \sum_{k} q_k \cdot \varphi_k \tag{8}$$

Where:

h is the specific energy source
f_h is the final energy consumption obtained from the energy source h
χ_h indicates the CO_2 emission factors for the energy source h

k is the type of material
q_k is the quantity of material k
φk indicates the CO_2 emission factors for the material k.

The emission factors can be estimated using regularly updated methods approved by international scientific bodies such as the Intergovernmental Panel for Climate Change [21]. Databases available in literature [16, 35, 43] contain different values depending on the geographical area considered and on the calculation method used. The conversion factors χ_h for energy consumption vary depending on whether the CO_2 emissions refer to the share of final energy consumed or to the share of primary energy involved in the process.[1] Similarly, as regards the conversion factors φ_k for the construction materials, these vary whether or not the emissions of the primary energy[2] are considered. Consistency is essential when the emission factors to be used are selected: one should always specify whether the calculation is based on primary or final energy. Moreover, area-specific factors related to the geographical setting of the infrastructure should be preferred.

2.3 Operation phase

Operation-related CO_2 emissions must be calculated considering both options of maintaining of the status quo and modifying the existing transportation supply (e.g. by building a new infrastructure). The key elements of the operation phase have already been identified as the number and type of vehicles, maintenance and idle operation (Fig. 2).

One must also determine the territorial scale of reference based on the scope and the repercussions of the infrastructure under consideration. These issues give rise to a series of methodological questions that are normally difficult to work out.

The scenario analysis offers an effective way to address the problem: after forecasting the most likely evolution over time, the pathways leading thereto are explored, as illustrated in Fig. 3.

Estimated trends differ depending on the evolution of the considered parameters. Among these, the most important ones concern the socio-economic conditions (population, GDP), social and technological development and transportation policy (market organization, taxes and tariffs, infrastructure policies, adoption of requirements and bans). These factors determine the growth rates in the various scenarios. Therefore, future traffic flows can be quantified on the basis of historical data, provided that the latter are reliable and of good quality. The next step consists in calculating the CO_2 emissions generated by such scenarios. To do that, the amount of specific emissions per kilometre travelled is multiplied by the number of transiting vehicles according to the formula (9):

$$O_{vh} = \sum_{i=1}^{n} (e_i \cdot v_i \cdot d_i) \qquad (9)$$

Where:

O_{vh}, 1, n have previously been defined
e_i is the specific emission of vehicles and trains in the year considered
v_i is the number of vehicles transiting in the year considered
d_i is the distance covered by vehicle v_i.

The difficulty here lies in determining the trend of the specific traffic-related CO_2 emissions (e_i), especially when the time horizon considered is quite extensive. Literature provides several methods for dealing with this issue (Corinair-IPCC [15], Copert [17] and Ecoinvent [43]). Infras [20] and Tremove [47] are two of the most commonly used software products to forecast future specific emissions on the basis of simple input data (country, region, network, period, fuel and vehicle type, vehicle technology and pollutant type) [20, 47]. Differently from other methodologies that calculate emissions related to the covered distances or use only the tank-to-wheel emissions (i.e. Infras, Copert and Corinair), Tremove considers both the well-to-tank and tank-to-wheel emissions. Even if further researches in the field of specific emissions are required, CO_2 emission models generally provide more accurate results than other forecasts on polluting gases [40], thus making the results more consistent.

3 The case-study: the Brenner base tunnel

The method previously described has been applied to the case study of the Brenner Base Tunnel (BBT), a 55 km long railway infrastructure that, once completed, will connect Austria (Innsbruck) with Italy (Fortezza/Franzensfeste).

The BBT belongs to the central sector of the TEN-T Corridor 1 that connects Berlin with Palermo with a 2,200 km long high-speed railway line. Due to the presence of the Alps, one of the most critical stretches of this line is

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[1] The CO_2 emission factors χ_h for final energy take into account the emissions related only to the energy quantified by the meter, whereas the emission factors χ_h for primary energy take into account also the share of emissions relating to the production, transportation of the energy source considered as well as the production, use and maintenance of the facilities used for its exploitation.

[2] The CO_2 emission factors φ_k for primary energy (also referred to as “grey energy”) take into account the share of emissions generated by the entire process to produce the materials considered, spanning from the extraction of the raw materials to their disposal.

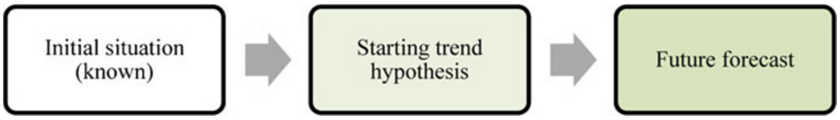


Fig. 3 Outline of the scenario method

the Brenner corridor between Kufstein, a town close to the Austrian-German border, and Verona (Fig. 4).

The Brenner corridor is commonly divided into three sections:

- Northern access route (Munich – Kufstein, Kufstein – Kundl, Kundl – Baumkirchen);
- Brenner Base Tunnel (Innsbruck – Fortezza/Franzensfeste) with the Innsbruck bypass;
- Southern access route (Fortezza/Franzensfeste – Ponte Gardena/Waidbruck, Bolzano/Bozen bypass, Trento bypass, Verona approach).

The entire line will be upgraded in different phases: the works are currently at a more advanced stage in the Northern access route than in the Southern one.

The BBT represents the central sector that links the two parts of the line. The construction phase of the main tunnels began in April 2011 and is planned to be completed by 2022, barring any setbacks.

In calculating the CO_2 emissions of the construction and operation phases, two different spatial scopes were used. While construction-related emissions refer to the realization of the infrastructure (i.e. the 55 km long tunnel: paragraph 3.1), operation-related emissions consider the transnational impact of the tunnel and its effects on the entire line. Therefore, the traffic scenarios (paragraph 3.2) refer to the line as a whole, including all Italian and Austrian sectors between Kufstein and Verona.

3.1 Construction phase

The BBT infrastructure is schematized in Fig. 5.

Main tubes, exploratory tunnels, side tunnels, multi-purpose areas, lateral access and the interconnections with

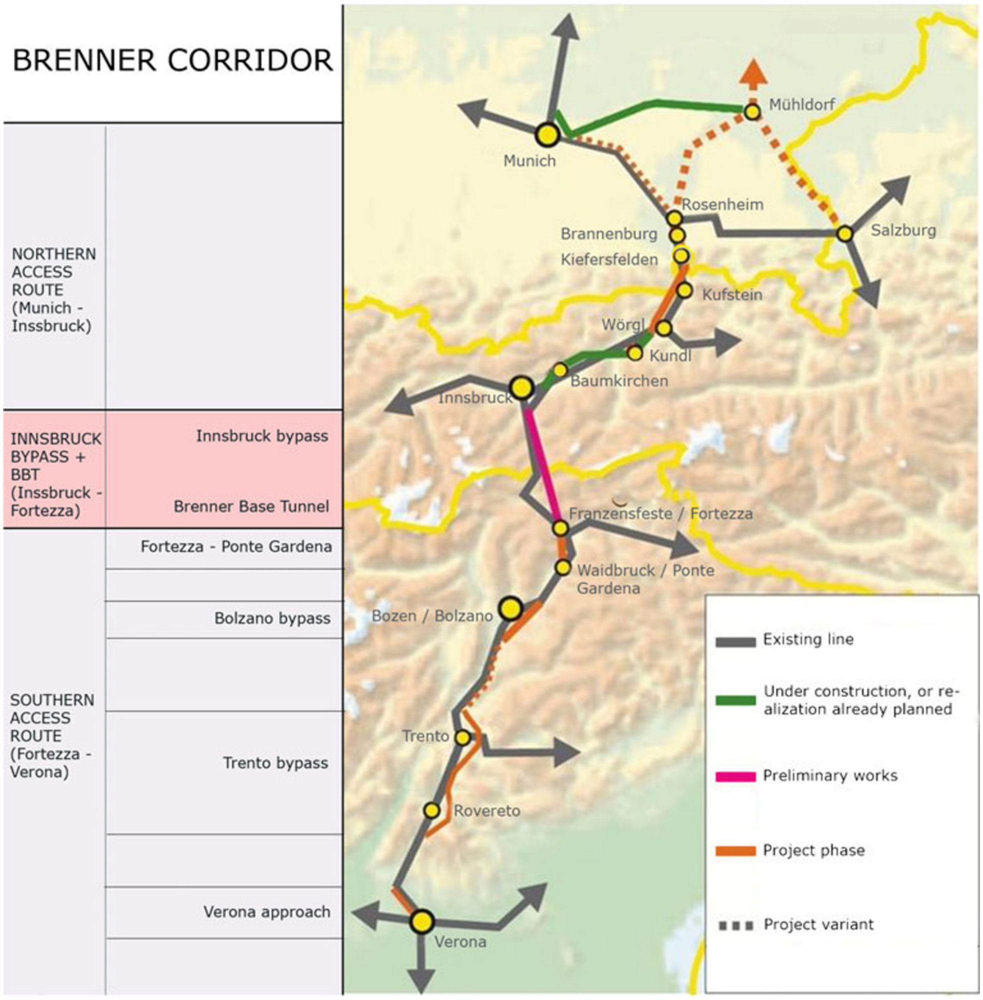
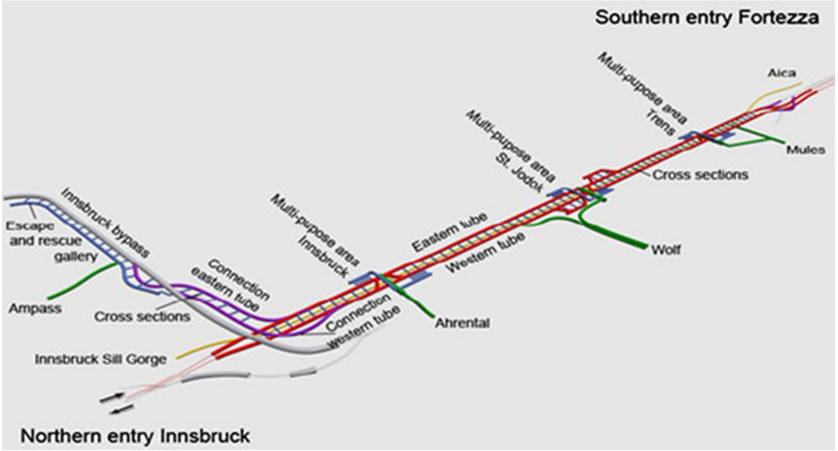


Fig. 4 Munich-Verona railway line. Realization of the access routes. Source: [10], elaborated

Fig. 5 Overview of the Brenner Base Tunnel system. Source: [5], elaborated



Fortezza and the Innsbruck bypass are the components considered during the calculation phase. In the following analysis, most of the data and values derive from the final design drawn up by BBT SE [4]. Figure 2 lists the main process elements that should be taken into account in the CO_2 balance of the construction of a tunnel. The largest energy consumption and consequently the CO_2 emission peak are normally generated during the excavation phase, the transportation of the spoil to the deposits, the production of the materials used to coat the tunnels and the running of the working sites [33]. These elements have been specified into the sub-process elements listed in Table 1.

In the case of the BBT, the tunnel is excavated using the conventional method with excavators and rock blasting, and the mechanical method with the Tunnel Boring Machine (TBM). The method to be used is chosen on the basis of the geological and geotechnical surveys and the cross section, as well as on the length and gradient of the tunnel section to be built. The calculation estimates mainly the energy consumption of the machines used. In the conventional excavation, also the CO_2 released during rock blasting is factored in. Likewise, in the mechanical excavation, the CO_2 emissions resulting from the production of TBMs and their transportation from the production to the working sites are included.

Table 1 Main process elements of the analysis. Source: [33], elaborated

Main process elements	Sub-process elements
Boring works	Conventional excavation
	Mechanical excavation
	Manufacturing of TBMs
	Transportation of TBMs
	Rock blasting
Transportation of the spoil	Transportation using belt
	Transportation using trucks
Production of the construction materials	Concrete
	Steel
	Transportation of the construction materials using trucks
Working sites	Ventilation and the cooling of the tunnels
	Water treatment plants
	Functioning of the offices and the mechanic shops
	Lighting of the tunnels
	Lighting of the external areas

Table 2 CO_2 emissions in the construction phase of the BBT

Main process elements	Sub-process elements	CO_2 [kt]
Boring works	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 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
Working sites	Ventilation and cooling of the tunnels	150.71
	Water treatment plants	14.26
	Functioning of the offices and the mechanical shops	1.48
	Lighting of the tunnels	8.75
	Lighting of the external areas	13.19
	Subtotal	188.39
Total		2,280.35
Total (rounded)		2,280

Table 3 Measures to discourage the use of road transportation adopted in "minimum", "trend" and "consensus" scenarios. Source: [32], elaborated

Measures to discourage the use of road transportation	Minimum	Trend	Consensus
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 under infrastructural costs up to 2015	Highway tolls at the same level as infrastructural costs up to 2015	Highway tolls higher than infrastructural costs (+15% in comparison with trend scenario); harmonization of tolls in all the Alpine arc
Road traffic ban	No ban along Brenner highway, maintenance of Sunday and nocturnal bans, use of dosage systems	No ban along Brenner highway, maintenance of Sunday and nocturnal bans, use of dosage systems	Implementation of social and security prescriptions, no ban along Brenner highway, maintenance of Sunday and nocturnal bans, use of dosage systems
Speed-limits	No changes	No changes	More controls, reductions of a good 8%
Tax on mineral oil	Uniform tax rate on all the EU countries based on present value	Uniform tax rate on all the EU countries based on present value	Uniform tax rate on all the EU countries higher than present value; introduction of an eco-tax
Enforcement of roads	Enforcement of highways (but not along Alps)	Enforcement of highways (but not along Alps)	Investments only for national programs or for TEN-T to reduce bottlenecks

The materials used to build the infrastructure are mainly cement and steel, with the latter used mostly for anchoring, building bridges and the production of reinforced concrete. Emissions due to the use of plastic material for the piping and other finishing materials are assumed to be negligible.

The transportation of the construction materials and the spoil to the deposits is then considered: a distinction is made between belt and truck method on account of the different energy consumption of the two forms of transportation.

The CO_2 emissions related to the construction site include those generated by the tunnel ventilation and cooling systems, the water treatment plants, the mechanical shops and offices. Finally, the contribution of the lighting of the tunnels and external areas are considered.

Table 4 Measures to encourage the use of rail transportation adopted in "minimum", "trend" and "consensus" scenarios. Source: [32], elaborated

Measures to encourage the use of rail transportation	Minimum	Trend	Consensus
Intermodality	Considerable improvement, reduction of technical and administrative barriers	Considerable improvement, reduction of technical and administrative barriers	Considerable improvement, reduction of technical and administrative barriers, optimization of the rail services
Rolling highway	At 2004 level	At 2004 level	At 2003 level
Railroad costs	Slight reduction (−5% for goods)	Slight reduction (−5% for goods)	Considerable reduction
Subsidies	Reduction for profitless transports	Reduction for profitless transports	Slight reduction, but not related to profitless transports. Rail is more funded
Railway traffic market rules	Slight liberalization and broad privatization of freight and passenger transport	Slight liberalization and broad privatization of freight and passenger	Slight liberalization and broad privatization of freight and passenger
Enforcement of railway lines	Realization of Gotthard, Moncenisio and Lötschberg base tunnels	Realization of BRENNER, Gotthard, Moncenisio and Lötschberg base tunnels. In 2025 TEN-T are realized	Realization of BRENNER, Gotthard, Moncenisio and Lötschberg base tunnels. In 2025 TEN-T are realized
Telematics	Introduction of ERTMS systems for high-capacity lines until 2025	Introduction of ERTMS systems for high-capacity lines until 2025	Introduction of ERTMS systems for all high-capacity lines until 2015
Average rail speed	Slight changes in comparison with current speed	In comparison with current speeds: +3% up to 2015, further + 2% up to 2025	In comparison with trend scenario: +3% up to 2015, further + 2% up to 2025

Table 5 Overview of results of the mean annual variations of traffic along the Brenner axis. Source: [37], elaborated

	Brenner growth rates - Freight						Brenner growth rates - Passengers					
	Minimum		Trend		Consensus		Minimum		Trend		Consensus	
	Road	Rail	Road	Rail	Road	Rail	Road	Rail	Road	Rail	Road	Rail
2009–2015	1.9%	3.1%	1.9%	3.1%	0.1%	3.1%	1.2%	3.1%	1.2%	3.1%	0.7%	3.1%
2016–2020	1.5%	2.1%	1.5%	7.7%	−0.1%	8.6%	1.9%	2.1%	1.9%	4.8%	2.2%	5.3%
2021–2025	1.5%	2.1%	1.3%	6.9%	−0.6%	7.4%	1.9%	2.1%	1.9%	4.5%	2.2%	5.0%
2026–2030	1.0%	1.2%	1.4%	1.9%	0.0%	2.3%	1.5%	1.7%	1.4%	3.8%	1.5%	4.2%
2031–2035	1.0%	1.2%	1.4%	1.9%	0.0%	2.3%	1.5%	1.7%	1.4%	3.8%	1.5%	4.2%

After calculating the energy consumption [33], values are converted into CO_2 emissions by applying the following emission factors X_h, expressed in kg CO_2/kWh:

X_g=0.202 for energy obtained from natural gas [21];
X_d=0.267 for energy obtained from diesel oil [21];
$X_{el,IT}$=0.435 for electricity generated in Italy [44];
$X_{el,A}$=0.216 for electricity generated in Austria [44].

The emissions resulting from the combustion of crude oil derivatives are calculated by referring to the guidelines provided by the IPCC [21], while the calculation of the emissions deriving from electricity are based on Terna's studies [44]. Since about 60% of the infrastructure is located in Austria and the remaining 40% is in Italy, the combined average of the energy mix of both countries was considered.

Specific emission factors (φ_k) are then provided for the construction materials. The data about concrete are provided by BBT SE, while the data about steel are provided by the Munich-based FFE research centre [16], as specific values are not available for Italy and Austria. Emission factors are expressed in kg CO_2/t:

$\varphi_{steel,\ structural}$=1.980 [16];
$\varphi_{steel,\ machines}$=1.449 [16];
$\varphi_{portland\ cement}$=622;
$\varphi_{pozzolanic\ cement}$=576.

Both factors (X_h and φ_k) estimate the CO_2 emissions resulting from the consumption of primary energy, taking into account the emissions related to the entire process and not only to the final energy, as described in footnotes 1 and 2.

Table 6 Traffic demand along the Brenner axis in 2008. Sources: [1, 29], elaborated

Traffic along the Brenner axis [vehicles/year]				
Country/Vehicle	HGVs	Freight trains	Cars	Passenger trains
ITALY	4,256,697	48,600	10,095,536	15,500
AUSTRIA	2,882,743	47,100	11,390,190	15,900

Energy consumption and material quantities are converted into CO_2 emissions using CO_2 emission factors (formula 8). The total amount of CO_2 associated with the BBT construction phase is about 2,280 kt (Table 2).

3.2 Operation phase

Recalling Fig. 2, emissions in the operation phase arise from vehicles, maintenance and idle operation. The last two factors are not calculated as their overall emissions are considered negligible in comparison with the vehicle emissions.

The calculation is based on a study by ProgTrans [37], which analyses the evolution of transportation along the Brenner axis (i.e. the Brenner rail line and the Brenner highway) up to 2030 in terms of average annual variations in freight and passenger traffic, by the development of six different scenarios.

3.2.1 The future traffic demand

In order to determine the future traffic demand and to provide the possible growth rates, ProgTrans adopts a classical four-stage model [30]. An area which includes 37 countries (all EU countries – except for Malta and Cyprus – , Switzerland, Norway and South-East European countries) is analysed: most of them are considered on NUTS 0-level, except for Austria, Germany, Italy, France, Netherlands, Belgium and Switzerland (NUTS 2) and the Alpine area (NUTS 3).

The traffic generation is calculated depending on five main parameters: socioeconomic tendencies, technological development, transportation policies, social changes (for passengers) and development of transportation economy and logistics (for goods).[3]

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[3] In detail, three main fields are considered among the socioeconomic tendencies: the division in different classes of age of the overall population, the gross domestic product and the import/export business. The social aspects involve mostly the life style of the families and its changes in the next years. The main differences among the hypothesis introduced are related to the transportation field: different market regulations, fiscal and infrastructural policies, prescriptions and bans.

Table 7 Traffic along the Brenner axis. Forecast for 2035 [vehicles/year]. Source: [38]; elaborated

	Italy				Austria			
Scenario	HGVs	Freight trains	Cars	Pax trains	HGVs	Freight trains	Cars	Pax trains
MINIMUM	6,280,857	85,033	15,328,854	28,350	4,253,555	82,409	17,294,631	29,081
TREND	6,444,440	148,676	15,193,468	43,608	4,364,338	144,087	17,141,882	44,733
CONSENSUS	4,142,902	164,345	15,172,896	49,900	2,805,678	159,273	17,118,672	51,188

The distribution is provided by the use of an origin–destination matrix, which includes 296 traffic cells. The modal choice is based on the generalized costs, which include both the distance costs and the travel costs. The former are meant as the sum of the costs necessary to transport a freight train or a HGV (freight transportation) or a person (passenger transportation) for a kilometre; the latter include fixed costs for the exercise of a transportation system (HGVs, freight trains, passenger trains or cars), energy and tracing costs and tolls.[4]

Finally, the route assignment is developed for both road and rail traffics. The former is obtained through TRIBUT [2], a capacity restraint method based on a bicriterion path search algorithm which includes times and costs as parameters. The latter is calculated through a procedure which takes into account the aggregate travel time of four different systems [37]: three of them are related to the passenger transportation (namely high speed, intercity/eurocity and regional trains), while the fourth is linked with good transportation (freight trains).

At the end of this method, six different scenarios are determined. Only three of them are included in the balance, as the assumptions of the other three are deemed either unlikely (two of them consider the new Gotthard Base Tunnel not in use – even though it is currently at an advanced stage of construction) or incomplete (forecasts considered freight traffic only). Three scenarios are therefore taken into account, in this paper called “minimum”, “trend” and “consensus”, whose main points are shown in Tables 3 and 4.

The “minimum” scenario coincides with the maintenance of the do-nothing, i.e. the BBT is not built, while both the “trend” and “consensus” scenarios are based on the construction of the tunnel.

The difference between these last two scenarios lies in the transportation policies. The continuation of the trend of the last decade is considered in the “trend” scenario, namely a market liberalisation that boosts road traffic. This policy should encourage the development of rail transportation. At the same time, the absence of measures to discourage the use of road vehicles should cause also a demand increase of HGVs and cars. It follows that an higher amount of overall traffic is generated, if compared with the two other scenarios.

The latter (“consensus” scenario) foresees a series of actions to foster the growth of railway traffic and encourage the simultaneous reduction of road traffic. The following measures are introduced in order to reach the complete internalization of external costs: in the field of tax policy, the increase of tolls (Austrian tolls are assumed to reach the Swiss ones) for all the types of vehicles and the funding of the railway mode. The introduction of an eco-tax for mineral oil and the reduction of transportation subsidies are also forecasted. Related to the infrastructural policy, the improvement of the high-speed rail line (with subsequent reduction of travel time), the development of the rolling highway and the modernization of the materials are scheduled. In relation to the road empowerment, only the most critic bottlenecks are solved (no further construction of road segments between the Alpine highways).

Finally, a scenario which includes only restriction to the circulation of the vehicles is considered unrealistic and therefore not analysed here: it foresees only constrictions to the free circulation, thus being against the important principle of “social equity” promoted by the EU in the development of its transportation policy.

Originally up to 2030, the forecasts were extended to 2035, thus determining a time horizon for the Brenner Base Tunnel of 25 years (Table 5). The values shown are mean annual growth rates.

As above mentioned, the growth of rail traffic (both for passengers and goods) in the “consensus” and “trend”

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[4] In order to ease the comprehension of the modal choice, the values of the costs in the scenarios analyzed in this article are here provided. In “trend” scenario, the values are as follows: for the goods, the distance costs are 34.10 € for every freight train and kilometre, reduced to 31.90 € from 2015, and 0.57 € for every HGV; time costs are, respectively, 68.20 and 34.10 €. This value considers a type-train of 420 t up to 2015 and of 500 t train from 2015; HGVs are divided in 10 classes, considering the different goods transported; the capacity is supposed stable up to 2035. For the passengers, the distance costs are currently 0.085 € for every train passenger and 0.10 € for every car passenger; time costs are 9.15 € both for rail and road. In “consensus” scenario, the values are as follows: for the goods, the distance costs are the same as in “trend” scenario for rail; only the capacity of the type freight train is supposed to change, being 425 t up to 2015, 550 t in 2015 and 605 t in 2025. For road freight transportation, costs increase to 0.68 € for every HGV from 2015 to 0.75 € from 2025. The capacity as well as the time costs are the same as in the “trend” scenario.

Table 8 Calculation of the trend in CO_2 emissions for road traffic. Source: [20, 47], elaborated

Road			Rail	
Year	Automobiles [g/veh km]	Trucks [g/veh km]	Pax trains [g/veh km]	Freight trains [g/veh km]
1990	186	855	5,890	14,860
1995	180	796	5,730	13,830
2000	174	720	5,440	12,670
2005	167	718	5,200	10,960
2010	160	717	4,970	9,260
2015	155	710	4,930	8,970
2020	151	703	4,900	8,680
2025	143	680	4,850	8,290
2030	137	671	4,770	7,820
2035	131	663	4,700	7,400

scenarios is due to the introduction of the BBT and the high speed rail line. They allow the use of new tracks, thus implementing the overall railway capacity and rationalizing the line already existing. The growth rate of freight rail transportation is higher than the passenger one. This result can be explained by the nature of BBT, which is supposed to introduce about 400 new trains per day: according to the traffic simulations developed by BBT SE, about 75% of them will be introduced for freight transportation and the leftover for passengers [3]. This is the reason for which the expected growth rates of rail freight transportation are much higher than passengers'. Indirectly, it justifies also the difference between road passenger traffic of "consensus" and "trend" scenarios.

The number of vehicles circulating up to 2035 is then obtained by multiplying the rates listed above by the historical data [1, 29; Table 6]. The analysis considers both freight and passenger traffic on road and rail. By way of example, Table 7 shows the data for 2035 alone.

3.2.2 The future specific emissions

The Infras Handbook and the Tremove software applications are used to determine the average specific emissions for road and railway traffic respectively [20, 47]. Both software applications provide the trend of the specific emissions over five-year periods (Table 8).

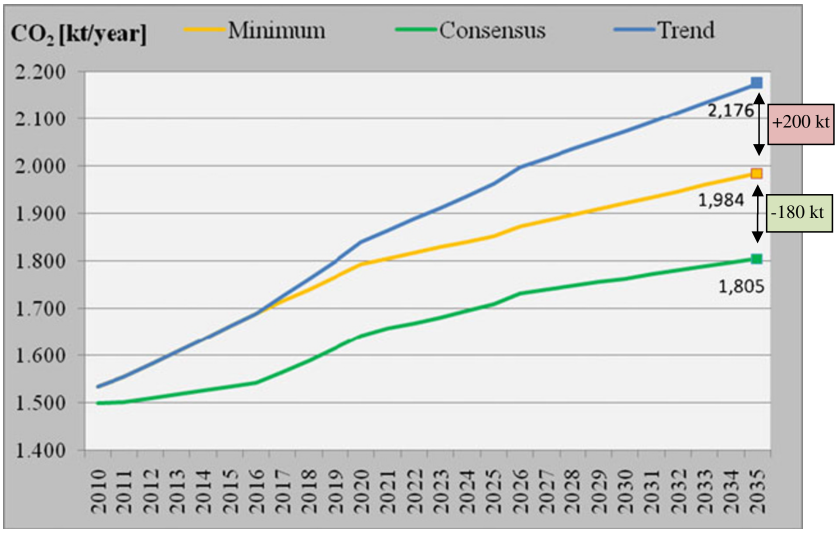
Tremove software includes the following parameters: country, region, network, period, fuel type, vehicle type, vehicle technology, pollutant type. Each of them requires a choice among several possibilities: for example, referring to the vehicle technology, the choice is among passenger train, bus, car, heavy duty truck >32 t, heavy duty truck 6–32 t, heavy duty truck 3.5–7.5 t, heavy duty truck 7.5–16 t, light duty truck, moped, motorcycle, van, plane, freight train, inland ship, metro/tram [24].

Infras handbook considers the following parameters: country, vehicle type, polluting gases, year, fleet composition,

Table 9 CO_2 emissions produced by road and railway traffic. Kufstein-Verona section. Source: [38], elaborated

Year	Minimum CO_2 emissions (kt)	Trend CO_2 emissions (kt)	Consensus CO_2 emissions (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
Total (rounded)	46,700	48,800	43,150

Fig. 6 CO_2 emissions in the various scenarios: yearly variations. Source: [38], elaborated



network, level of service, speed limit, parameters for hot emissions factors and cold start access [46]. The evaluation of the specific emissions is based on the type-vehicle. Two trains (one for each railway line) are considered for the freight transportation: the one going through the existing line has two locomotives, a max speed of 100 km/h, an overall weight of 1,200 t. The other one has only one locomotive and same attributes. The train for passengers is an Intercity express type 1 (length: 200 m, average number of passengers: 400; gross weight: 435 t). Data are extracted from an exercise document of the Monaco-Verona line, provided by BBT SE.

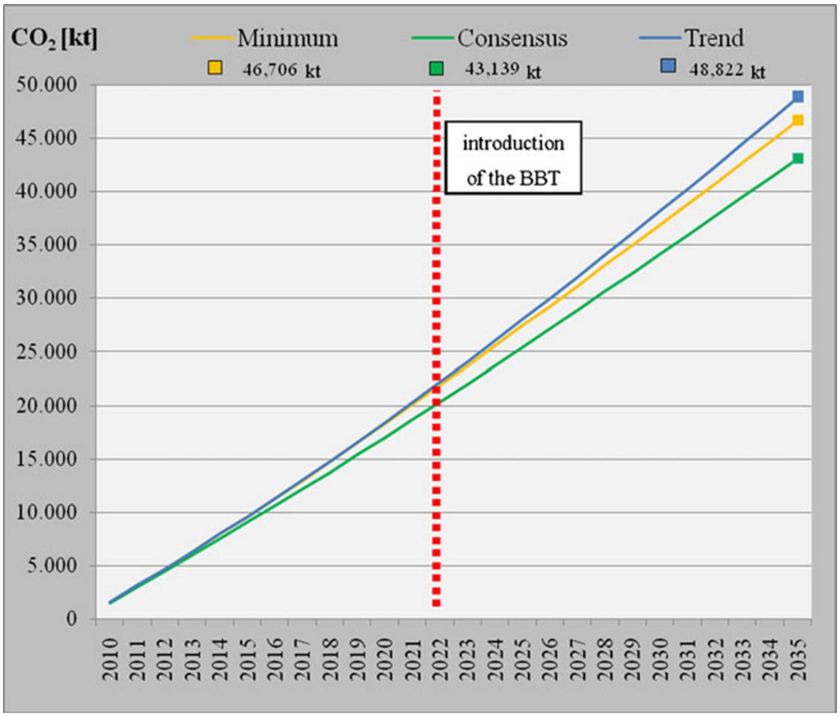
For the road, the standard vehicle for goods is an HGV of 32 t. Average speed is 80 km/h and it is powered by diesel. The class of the engine depends on the year considered. The standard vehicle for passengers is a car with an engine of 1,600 cc. Maximum speed is 130 km/h and it is powered by diesel. Also in this case, the class of the engine depends on the year considered.

The constant decreasing values presented in Table 8 are due to the progress in the technology field, which grants the development of more efficient engines and vehicles.

3.2.3 The future overall emissions

The total emissions in the various scenarios were obtained for the years 2010–2035 by multiplying the number of vehicles by the mean specific emissions and by the distances travelled (formula 9).

Fig. 7 CO_2 emissions in the various scenarios: aggregate variations 2010–2035



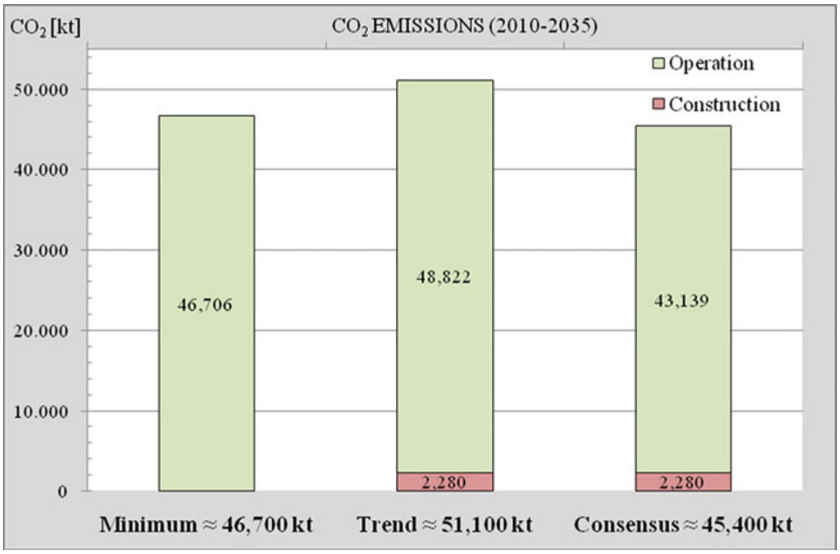


Fig. 8 CO$_2$ emissions in the various scenarios, as a sum of construction and operation phases. Years: 2010–2035

Distances were calculated using www.viamichelin.it for road, http://pedaggio2004.rfi.it for the Italian sector of the railway line and www.oebb.at for the Austrian one. From these calculations, the road distance for the Italian rail and road stretches (Verona-Brenner) are, respectively, 220 and 226 km; for the Austrian one (Brenner-Kufstein), respectively 111 and 106.

As soon as all these data are known it is possible to determine the yearly overall CO$_2$ emissions by using the method described in section 2 (Table 9).

Table 9 shows that the overall lowest CO$_2$ emissions (about 43,150 kt) are forecasted in the “consensus” scenario, followed by the “minimum” and “trend” scenarios, with about 46,700 kt and 48,800 kt respectively.

As the year of reference increases, the difference in the emissions between the scenario without tunnel and the two scenarios with tunnel increases as well. In 2035, the “consensus” scenario produces about 180 kt CO$_2$ emissions less than the “minimum” scenario, while the “trend” scenario implies an increase in emissions of about 200 kt (Fig. 6).

Three aspects need here a further explanation.

First, although the BBT is expected to be working only by 2022, the variations in CO$_2$ emissions between the “consensus” scenario on the one side, and the “trend” and “minimum” scenarios on the other, are already visible starting from 2010 on. This is mainly due to a supposed different behaviour of freight operators: ProgTrans forecasts [37] consider the traffic support policy (as described above) to be strictly linked to the opening of the tunnel. Some of these measures are supposed to be put into force already in 2010 in order to obtain a gradual but constant shift from road to rail (“consensus” scenario) or a gradual growth of traffic rail (“trend” scenario). Both these conditions are supposed to be fully realized in the first operation year of the tunnel (believed 2022). In this year, at these traffic growth rates the current Brenner railway line by itself would not have the capacity to serve the demand of neither of these two scenarios.

Second, “minimum” and “trend” scenarios show the same rise between 2010 and 2015. This should be considered an expected result, as both call for the same traffic growth forecasts (Table 5).

Third, the overall trend in the “consensus” and “minimum” scenarios seems to have a similar shape in the years 2016–2035 (Fig. 6). This is mostly an undesired visual impression: a rough data comparison can confirm this statement.[5] This means that the two curves are divergent and the difference in CO$_2$ emissions is progressively increasing.

The overall CO$_2$ emissions for the years 2010–2035 deriving from the operation phase (Fig. 7) confirm these considerations, showing how the main differences in the three scenarios are broader after the opening of the BBT (2022).

3.3 Result comparison

Table 9 and Fig. 8 show the impacts of the BBT on CO$_2$ emissions, which are supposed to be about 46,700 kt in the do-nothing case (“minimum” scenario). If the tunnel is realized, future emissions will depend on the policies adopted. If the support measures for the railway are adequate, the road traffic is likely to decrease and the overall CO$_2$ emissions are expected to be lower than in the “minimum” scenario. They will amount to about 45,400 kt, equal to the sum of the emissions resulting from the construction of the tunnel

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[5] In 2021, CO$_2$ emissions are supposed to be 1,696 kt for the “trend” and 1,542 for the “consensus” scenario – it makes a difference of 144 kt. In 2035 this difference rises up to 371 kt–2,176 kt in “trend” and 1,805 kt in “consensus” scenarios.

(2,280 kt) and from the "consensus" scenario (about 43,150 kt). Therefore, recalling formula (1), $BAL_{CO2}(BBT) > 0$.

On the other hand, if policies adopted continue the current trend, rail and especially road traffic will further increase. As a consequence, also emissions are expected to grow and reach about 51,100 kt, which is the sum of the emissions resulting from the tunnel construction (2,280 kt) and the "trend" scenario (about 48,800 kt). In this case $BAL_{CO2}(BBT) < 0$.

Figure 8 shows that the construction of the BBT does not necessarily imply a reduction in CO_2 emissions; indeed, the tunnel might lead to a considerable increase due to the traffic demand growth, as evidenced by the "trend" scenario, which yielded 4,400 kt CO_2 more than the "minimum" one. Only if duly supported by a correct policy favouring railways the tunnel will help cut CO_2 emissions ("consensus" scenario, −1,300 kt).

As far as "minimum" and "consensus" scenario are concerned, the overall CO_2 emissions are cut only by about 3%. This value could be considered disappointing if taken by itself. It should rather be taken into account in connection with its relative traffic demand: in the period 2010–2035, a 29% emission increase in the "minimum" scenario (1,535–1,984 kt) is for instance accompanied from a 75% freight railway increase (51,660–85,033 trains).

As well, in "consensus" scenario the emissions are supposed to grow from 1,500 kt (in 2010) to 1,805 kt (in 2035, +20%), but the overall amount of freight trains circulating should treble (51,660 in 2010 and 164,345 in 2035) and is almost double than in "minimum" scenario. Similar considerations can be stated for the other traffic modes analysed.

4 Values and faults of the method described

The method described in this paper was conceived to relate carbon dioxide emissions to modifications in the transportation supply. It can be used either as an independent tool or within a Multi-Criteria Evaluation.

In both cases, further research is required on the interaction between the effects of the simplifications adopted and the accuracy of the model results. Particularly, as the impact of the emissions depends from a certain number of key variables (here identified with the estimation of overall road traffic, its modal shift, and the technological improvement of the vehicles circulating), the extension of the time frame at stake makes hard quantifying model uncertainty, thus denying an important information for decision-making.

If the construction of a new infrastructure is included in the process, then the considerable width of the time frame cannot be avoided and should be retained as a model feature. This obviously makes the estimation of the evolution of the key-variables not reliable on *ex-post* evaluations. As in any forecast, however, the containment of the referential period makes the control of the results easier.

The Brenner Base Tunnel was here reported as a case study. The main benefit from the construction of this infrastructure should be considered the time reduction for the connections between the cities along the stretch of the Munich-Verona high speed line at a lower average pollution rate. In mere terms of carbon dioxide, however, the results reveal that the effect of the tunnel may be strengthened if added to an adequate policy in favour of the railway and that the amounts of CO_2 produced should not be considered by themselves but in connection with their relative travel demand.

Though it probably needs to be further refined and some of its limitations need to be better understood, the necessary changes having been made, the method described herein is considered to be fully applicable throughout transportation planning. In fact, it may cover all the cases of implementation of new systems, changes in existing systems, or construction of new infrastructures. Its hypotheses are sufficiently flexible, and the number of equations and assumptions used was kept as small as possible. The model only requires that input data be adequately detailed in terms of vehicle shares, fuel consumption per vehicle and distance travelled – a result that can be achieved from planners, decision-makers and stakeholders by allocating adequate resources for data collection.

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