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

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Abstract

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

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

1. Introduction

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

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

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

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

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

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

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

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

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

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

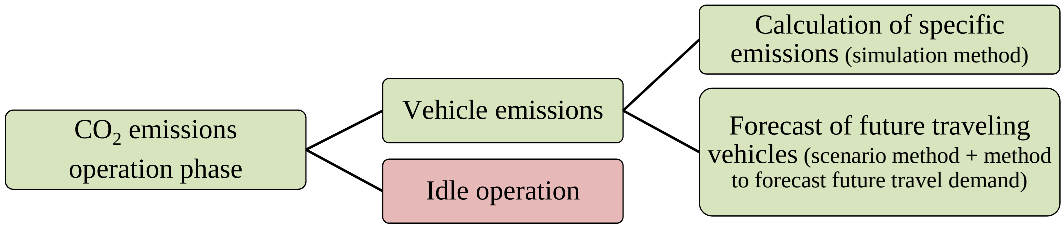

Figure 1: methodology for calculating CO_2 emissions from operation phase of a given infrastructure system

2.1 Simulation method

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

2.1.1 Rail-based simulation method

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

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

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

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

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

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

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

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

$$E_s = r \cdot E_p \qquad 2)$$

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

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

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

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

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

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

2.1.2 Road-based simulation method

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

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

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

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

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

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

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

2.2 Scenario method

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

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

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

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

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

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

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

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

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

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

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

3. The Brenner corridor

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

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

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

3.1 Future scenarios

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

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

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

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

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

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

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

3.2 The Historical Railway Line and the HC Line

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

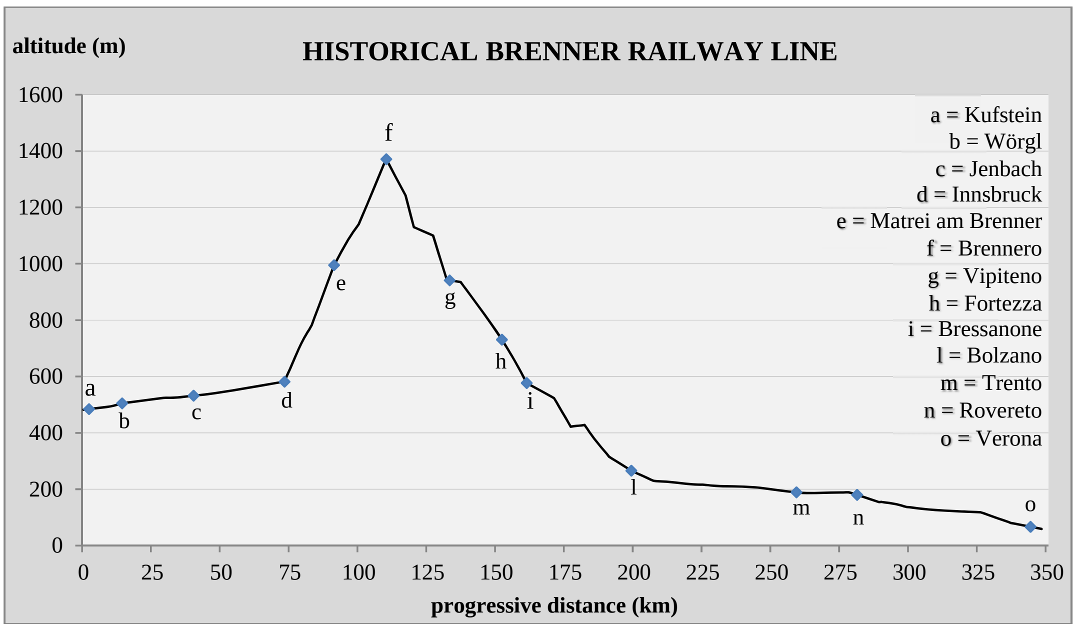

Figure 2: Historical Brenner railway line, profile of the Kufstein-Verona section

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

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

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

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

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

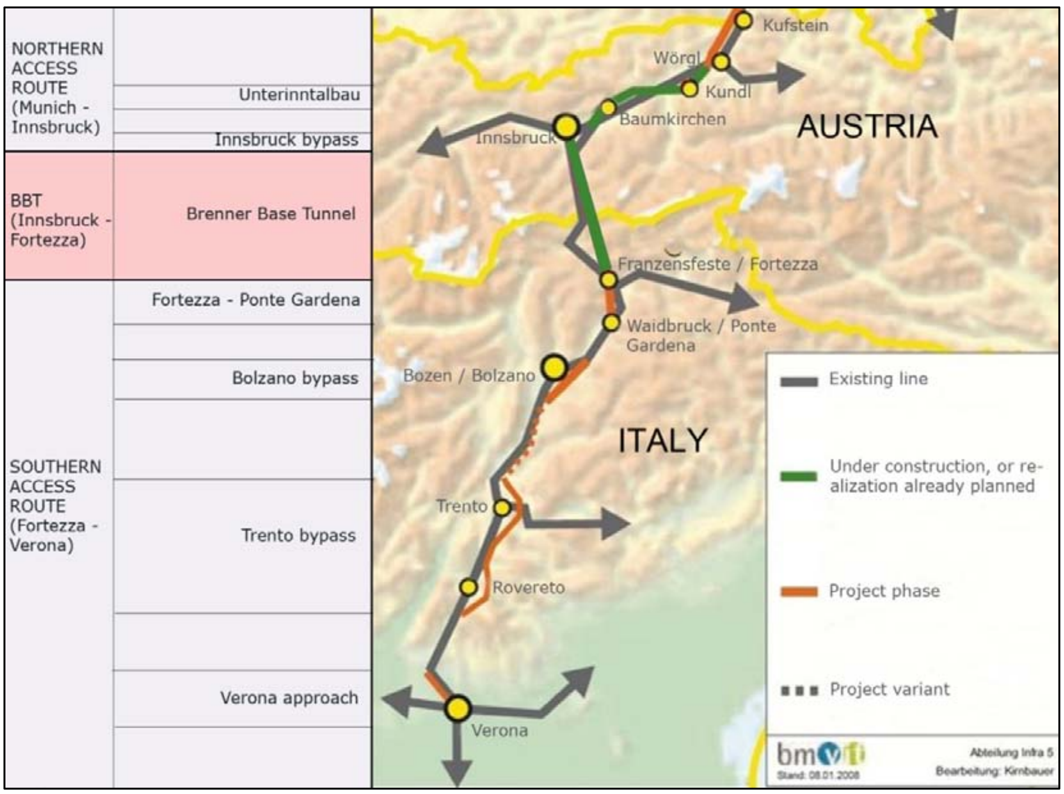

Figure 3: HC line Munich-Verona, Kufstein-Verona section. Source: BMVIT, 2008, modified

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

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

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

Table 2: Technical characteristics of the typical trains

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

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

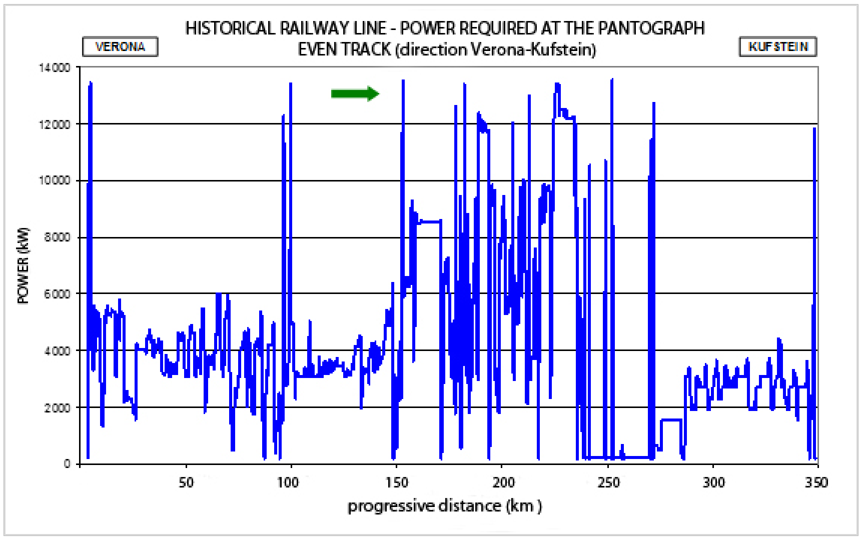

Figure 4: Power required by a typical train for the historical line. Source: Atos progetti, 2009

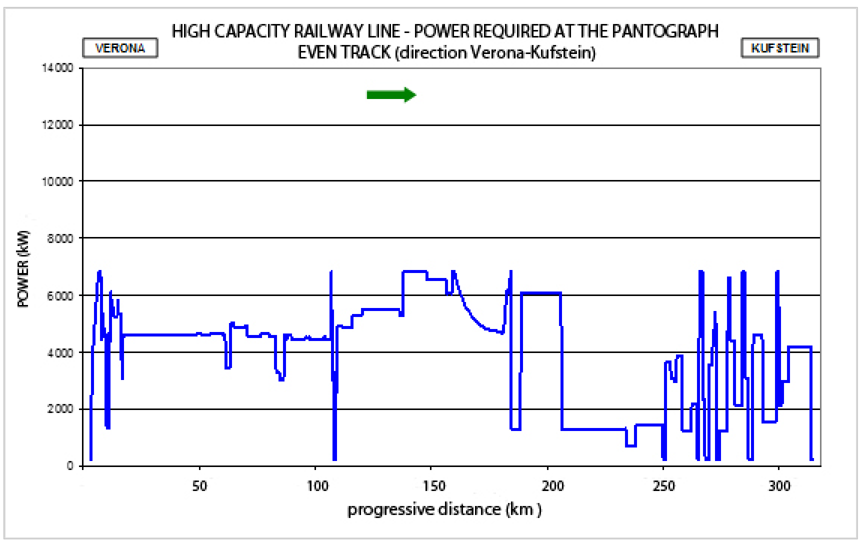

Figure 5: Power required by a typical train for the HC lines. Source: Atos progetti, 2009

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

Table 3: Energy consumption of typical trains

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

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

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

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

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

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

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

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

RAILWAY SIMULATION METHOD – SUMMARY TABLE

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

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

3.3 The Highway

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

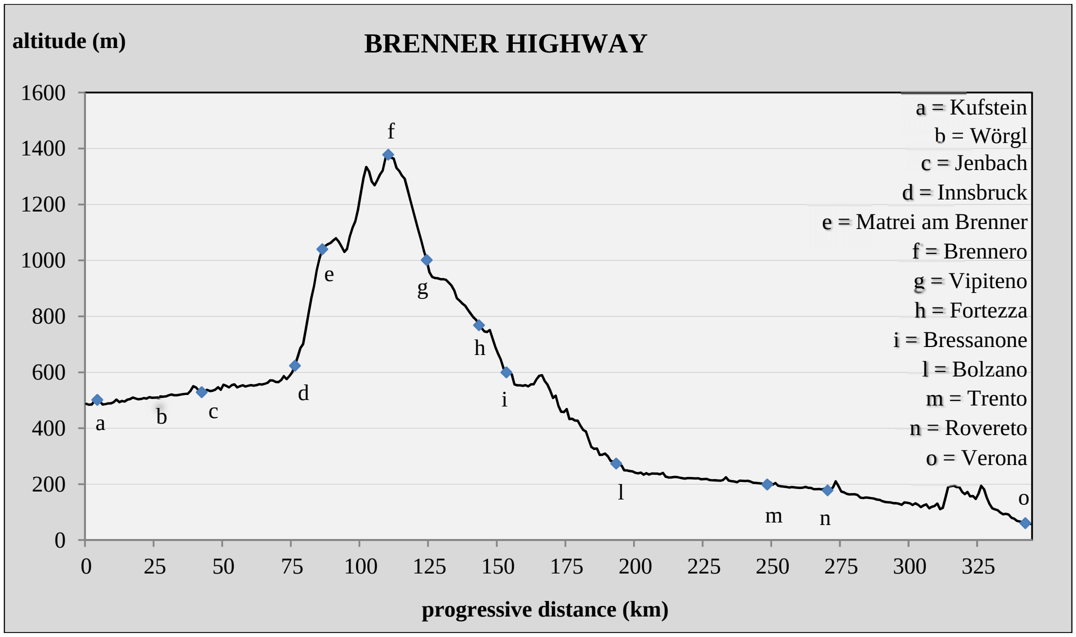

Figure 6: Profile of the Brenner highway

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

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

Table 5: Characteristics of the typical vehicle for road transport

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

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

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

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

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

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

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

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

3.4 Results and discussion

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

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

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

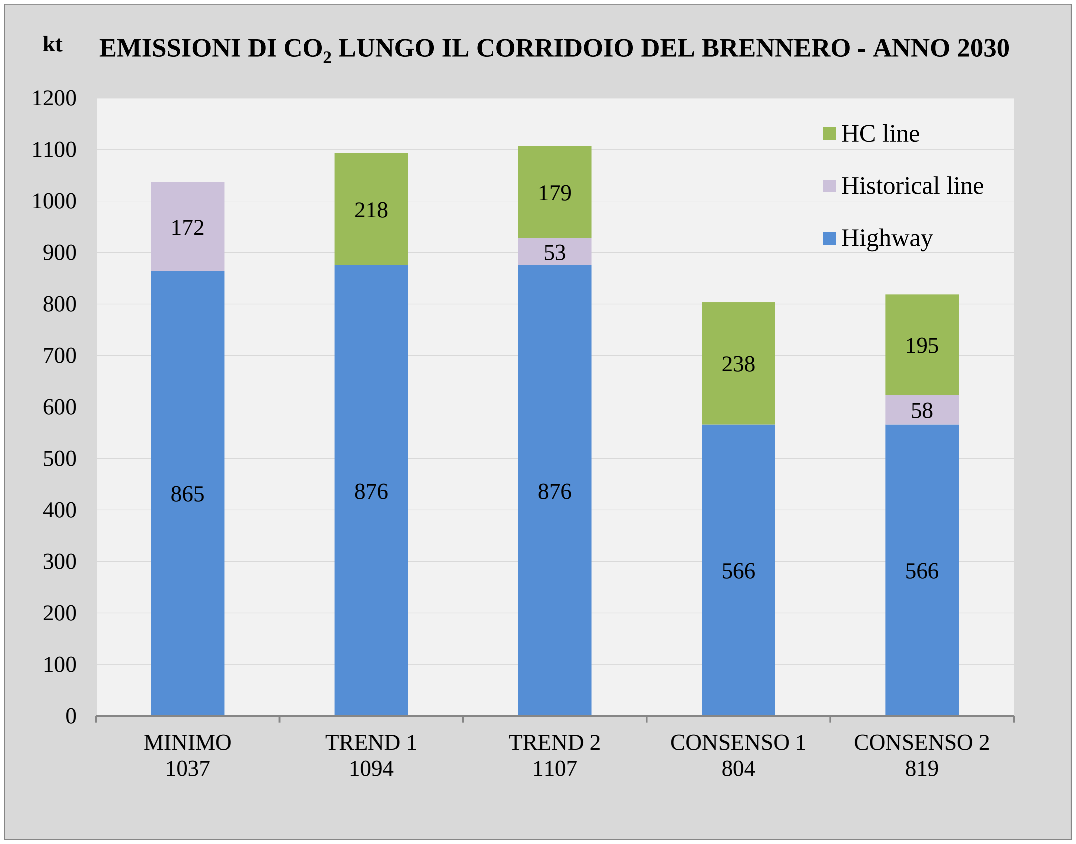

Figure 7: CO_2 emissions along the Brenner corridor, 2030

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

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

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

BRENNER CORRIDOR - CO_2 EMISSIONS PER TON OF FREIGHT (2030)			
Mode	*Infrastructure*	*CO_2 specific emissions*	*Variation*
		kg CO_2 / t_{net}	%
Road	Highway	18.3	----
Rail	Historical line	8.8	-48.2%
	HC line	6.6	-62.5%

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

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

4. Conclusions

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

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

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

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

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

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

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6. Appendix 1

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

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