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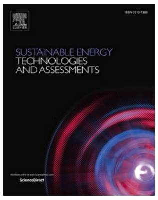

Assessment of railway infrastructure improvements: valuation of costs, energy consumption and emissions

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ABSTRACT

The efficiency of rail freight transport has significant impact on climate change compared to other modes. However, railways still struggle to take larger shares of the growing total transport volumes especially in developing countries, where priority tends to be given to doubling tracks parallel to the existing infrastructure instead of building entirely new optimized alignments. In this context, this paper discusses the lifespan impacts of these two strategies on a real case study in Brazil. We compared the doubling costs of tracks parallel to an existing route and the respective construction costs of 100 new optimized alignments, and the fuel and CO_2-equivalent costs of four pollutants of trains running in 20 services over a timespan. Results show that the CO_2-equivalent costs are significantly lower in the optimized alignments. Scenarios varying the yearly Brazilian economic growth and different monetary CO_2-equivalent values show that 111 and 16 years are required to fuel and emissions compensate for the greater construction costs of the optimized alignments in the respective scenarios of average 1.2% and 4.6% economic growth over the years and CO_2-equivalent values of USD21.9/tonCO_2 and USD944.5/tonCO_2.

Introduction

Considering the need for immediate action in the transport sector to avoid irreversible climate change while also supporting economic development, the renaissance of rail transport is understandable. Global greenhouse gas (GHG) emissions from the transport sector have more than doubled since 1971, and over three quarters of the increase has come from road vehicles [7]. Railways are generally more environmentally friendly than road transport, emitting up to 85% less greenhouse gas emissions than articulated trucks for freight [1]. It is not surprising to find that, between 2005 and 2014, more than 150,000 km of tracks were built worldwide [43].

Despite such rapid expansion of infrastructure, the railways still struggle to take larger shares of the growing total transport volumes, especially in developing countries. In Brazil, for example, the railways account for approximately a third of the total freight traffic [21]. In the case of Brazil, this percentage could be higher if more infrastructure was available. When rail infrastructure does not expand in parallel with demand, other modes will be used and are likely to become congested, which in turn limits the potential for economic growth and generally will result in greater transport derived emissions. Within the railway network, capacity bottlenecks can occur particularly where there is a prevalence of single-track infrastructure, which represents more than 80% of the current railway infrastructure worldwide [41].

Fundamentally, railway capacity can be increased either by building entirely new corridors or doubling single-track lines. Given such high capital costs of rail infrastructure, priority tends to be given to simply doubling alignments parallel to the existing infrastructure. It is considerably cheaper than building completely new lines as new land does not need to be acquired.

Considering that railway upgrades are major projects with high costs and lifespans of 50 to 150 years, design options and specifications must be carefully appraised to ensure the viability and sustainability across the whole life cycle [34]. Traditional appraisal approaches tend to overlook some externalities that have an important impact on the overall sustainability of a project. Even though rail transport is more efficient than its road counterparts, fuel consumption and greenhouse emissions from railway operations are not insignificant, especially in freight which is usually hauled by diesel locomotives. Moreover, energy consumption and emissions are very closely related to the track

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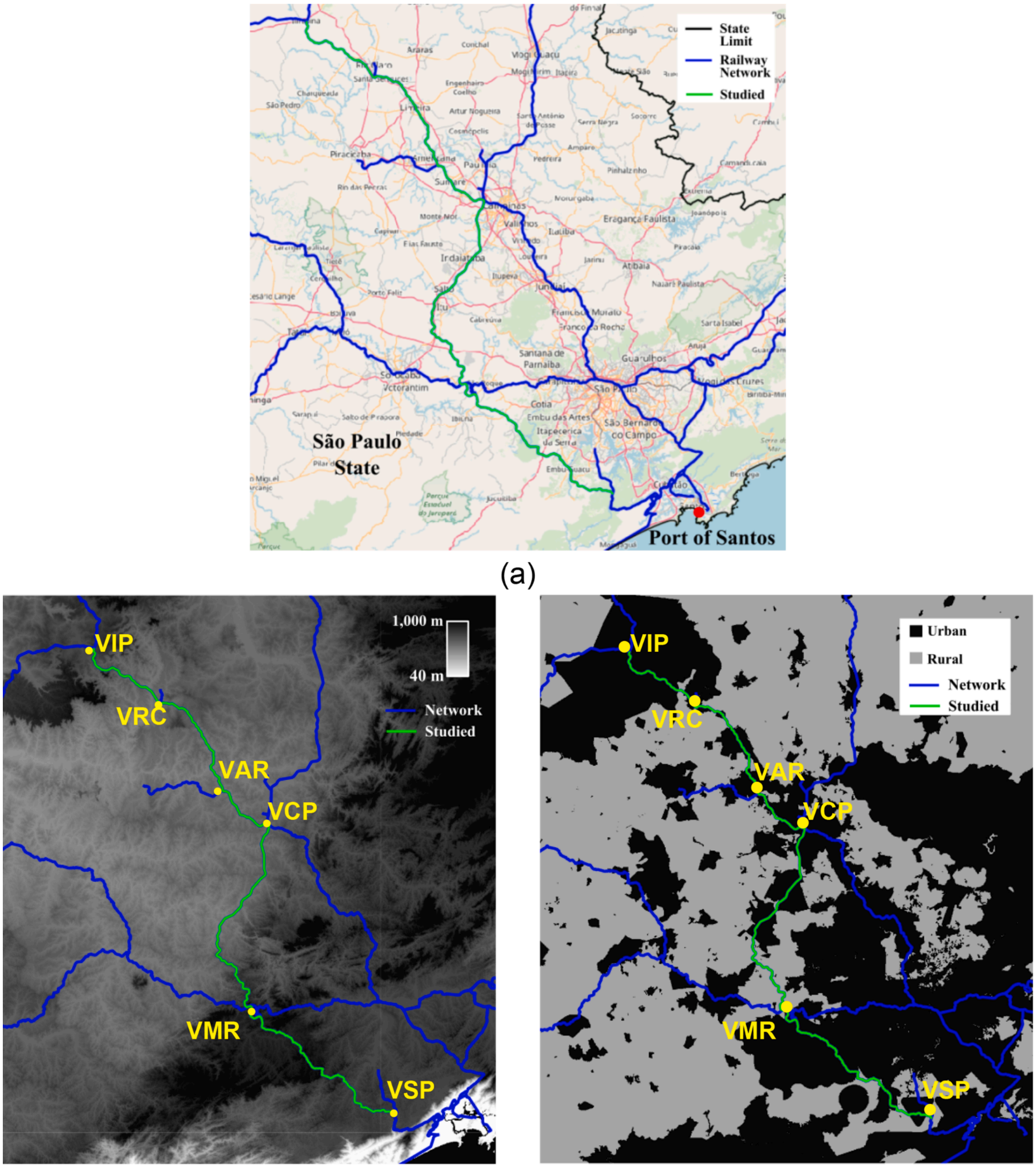

(a)

(b)

(c)

Fig. 1. Railway connection between the Brazilian mid-west and Port of Santos (a) and railway tracks over terrain profile (b) and land use (c).

geometric parameters such as vertical alignment and curvature.

Many railways were constructed over a century ago, and typically were built without consideration of energy consumption when designing their track. An approach therefore is needed to assess the viability of new lines that adds contemporary concerns, such as environmental impacts to the traditional parameters of costs and benefits. The traditionally unidimensional infrastructure capital perspective tends to leave out important aspects of life cycle costs that are difficult to monetize but are essential to account for in the face of climate change. Growing research in the Social Costs of Carbon (SCC) highlights how these parameters should affect decision making by quantifying the economic cost of the emission of an additional tonne of CO_2 or equivalent [32,31].

It follows that the strategic planning of railway infrastructure to increase network capacity in a given region must consider not only the costs associated with construction, rolling stock acquisition, and operations, but also the various externalities imposed during its whole lifecycle. Alternative routes may have greater capital expenditures, but their reduced fuel consumption and emissions may prove cost-beneficial over the long lifespan of railway infrastructure. Therefore, studying them systematically may help countries make improved decisions that lead to sustainable economic growth.

This paper discusses the lifespan impacts of different strategies for expanding railway infrastructure, focusing on fuel consumption and environmental aspects. More specifically, two railway infrastructure strategies are compared: (i) doubling single-track routes parallel to existing tracks; and (ii) designing and building entirely new routes on optimized alignments. In order to improve decision-making policies, a simulation was developed that considered the Net Present Value (NPV) of construction costs, monetary values of fuel consumption, and also the Social Costs of Carbon (SCC). A real case study in Brazil is considered where alternative alignments are simulated such that life cycle costs can be assessed for each new route as compared with the default scenario of doubling the existing track.

Environmental impacts from transport activities have generated

Table 1
Services simulated.

Service	Distance (km)	# Locomotives	Wagons	Total Weight (tonne)	Product	Trains per month	Segments I-inbound O-outbound
1	201	3	80	8,000	Fuel	18	1 2 3 (O)
2	201	2	80	2,600	Empty tanks	28	3 2 1 (I)
3	201	2	60	6,000	Container	12	1 2 3 (O)
4	201	2	50	4,600	Container	9	1 2 3 (O)
5	275	2	79	2,800	Bulk cargo, Fertilizer, Sugar	19	1 2 3 (O)
6	275	2	80	3,600	Bulk cargo, Fertilizer, Sugar	19	1 2 3 (I)
7	360	3	81	9,600	Soybean, Corn, Sugar	22	5 4 3 2 1 (I)
8	360	3	77	8,900	Soybean, Corn, Sugar	20	1 2 3 4 5 (O)
9	401	2	60	6,000	Container	12	1 2 3 4 5 (O)
10	401	2	50	4,600	Container	9	1 2 3 4 5 (O)
11	201	3	80	8,400	Fuel	19	1 2 3 (O)
12	285	2	40	2,600	Empty tanks	4	4 5 (O)
13	234	3	81	9,600	Soybean, Corn, Sugar	22	4 5 (O)
14	234	3	77	8,900	Soybean, Corn, Sugar	20	4 5 (O)
15	130	4	80	6,200	Cellulose	12	5 (O)
16	401	2	50	2,700	Container	42	5 4 3 2 1 (I)
17	401	2	79	2,800	Bulk cargo, Fertilizer, Sugar	19	5 4 3 2 1 (I)
18	401	2	80	3,600	Bulk cargo, Fertilizer, Sugar	19	5 4 3 2 1 (I)
19	130	4	80	2,200	Cellulose	19	5 (I)
20	285	2	40	1,200	Empty tanks	14	3 2 1 (I)

increased awareness with the growing concerns over climate change, lending themselves to extensive research in the past few years. This work has comprised comprehensive investigations, such as the links between transport volumes, economic growth, and environmental degradation [39,35,2].

In the more specific context of railways, analysis of environmental impacts tends to focus on train performance and energy consumption. These are usually based on modelling techniques that can help understand the relationship between energy requirements and the respective contributions to environmental degradation and their effects to human health. The work of Fernández et al. [13] helps estimate the energy consumption of a train under variable operating situations, while Gould and Niemeier [15] highlighted the use of activity data to model spatial locomotive emissions. On top of that, López et al. [27] and Zhou et al. [44] proposed comprehensive models that estimate railway energy consumption taking life-cycle aspects of infrastructure, rolling stock, and operations into consideration.

Equally important, various authors have published studies on GHG emissions from railway traction. While emissions from railways tend to be relatively small compared to the road sector, they are non-negligible especially in relation to nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM) and their health impacts [25]. The United States Environmental Protection Agency [42] has established emission standards for newly uncontrolled manufactured and remanufactured locomotives, and Johnson et al. [23] and Martire et al. [29] developed emission inventories and developed standards for control of emissions from railway locomotives. More specifically, several studies have looked into the emission factors of different locomotives [14,36,11,17,26,16,38]. These inventories were expanded to India by Annadanam and Kota [4], and in Brazil by Carvalhaes et al. [8].

Finally, the impacts of the design and planning of rail infrastructure in the overall life-cycle costs and emissions have been considered by Dimoula et al. [10], and more specifically on urban heavy rail and high-speed rail by Saxe et al. [37]. This extensive literature on emissions from railway operations, as well as life cycle impacts, are yet to be expanded into non-urban lines and the contexts of emerging economies such as Brazil. Moreover, analyses have so far remained focused on the direct costs associated, where social costs of carbon are playing an increasingly important role in appraisal processes.

After this introduction, the remainder of the paper is organized as follows. Section 2 (Method) describes the method used to quantify the impact that the life-time fuel consumption and pollutant emissions contribute compared to the overall construction costs. Section 3 (Results and discussion) presents and contrasts results. Section 4 (Concluding remarks) draws conclusions and develops policy recommendations.

Method

A model has been developed to calculate the fuel consumption and emissions for potential railway alignments, and to compare these with an established route. The number of years required to compensate the difference between the construction costs of the optimized alignments and track doubling are estimated, taking into account the difference in the NPV of fuel consumption and SCC of CO_2-equivalent emissions over time.

Existing infrastructure and services

The model was applied to a railway route that connects the interior of the Brazilian State of São Paulo to the Port of Santos (see Fig. 1a). This is the main corridor in the country, connecting the most productive farming areas in Brazil to the Port of Santos, the largest in Latin America. It logically follows that the route is also one of the most affected by the capacity and operational constraints imposed by single line tracks.

A major study to improve the capacity between Santa Fé do Sul and the outskirts of the Metropolitan Region of São Paulo was conducted with the doubling of tracks between Itirapina (VIP) and south of the Metropolitan Region of São Paulo (VSP). The project comprised a number of specific upgrades across the section, also replacing ballast and sleepers in order to increase the overall capacity of the system. An Environmental Impact Assessment (EIA) was carried out considering the doubling of the tracks [3]. The study considered the current timetable, train configuration of each service, and the daily transport volume between Itirapina and the outskirts of São Paulo.

In this study, we divided the upgraded section into five segments with known track information taking into consideration the terrain (Fig. 1b), land use (Fig. 1c) and connections to other parts of the network: Segment 1 (S1) between Itirapina (VIP) and Rio Claro (VRC); Segment 2 (S2) between Rio Claro (VRC) and Americana (VAR); Segment 3 (S3) connects Americana (VAR) to Campinas (VCP); Segment 4 (S4) connects Campinas (VCP) to Mairinque (VMR); and Segment 5 (S5) between Mairinque (VMR) and the southwest part of the Metropolitan Region of São Paulo (VSP).

Timetable and train configuration data were found in the 2019

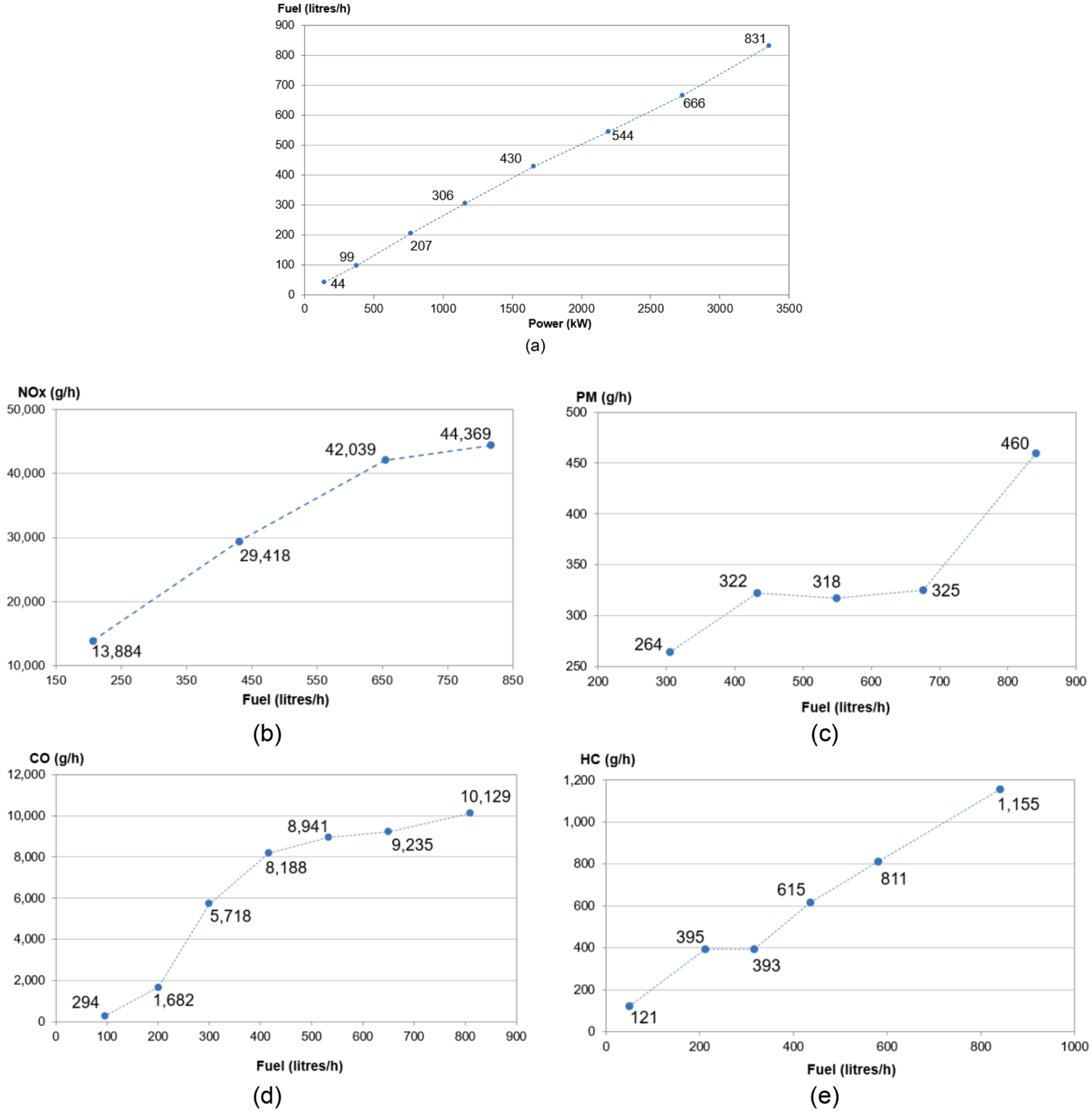

Fig. 2. Fuel consumption (a), and emission factor of NOx (b), PM (c), CO (d) and HC (e) of GE Dash 9 as a function of fuel consumption ([15,14], adapted).

annual report of the Brazilian National Agency for Land Transport [6]. A set of 20 services that run regularly through the 5 segments were simulated using the existing tracks in order to estimate fuel consumption and emissions under the assumption that the geometric parameters remain the same. These 20 services were simulated in new alignments obtained by an optimization model based on a Parallel Genetic Algorithm proposed by Isler and Widmer [19] to find the route that minimizes the overall construction costs of railway infrastructure, which included the costs of track elements (rails, sleepers etc.), land acquisition, earthwork, and tunnels and bridges.

In summary, the Genetic Algorithm creates a set of alignments that satisfies slope and curvature constraints and defines them as individuals of a population. These individuals are submitted to crossover and mutation operators that change the horizontal and vertical intersection points of the initial alignments. After assessing their overall costs, these individuals are ranked and those more adapted remain in the population, while the others are excluded. The population is changed until a stopping criterion is reached and a near-optimal alignment is obtained between the proposed start and end points of the route. The parameters presented by [19] were used in this paper to obtain the optimized alignments (refer to HPT in Table 1 of [19]), except by gauge (1,600 mm), average speed (80 km/h) and minimum horizontal radius (520 m).

Table 1 describes each service in terms of traveled distance, number of tractive units and wagons, total weight, products transported, and frequency. It is worth noting that some of the services carry products uphill from the port to the countryside (inbound) which results in distinct tractive efforts. The monthly number of trains per service was calculated from a total demand of 545,000 tonnes/year, and proportionally distributed according to train tonnage informed by ALL [3]. All simulations used standard General Electric (GE) diesel electric Dash 9 locomotives with 3,000 kW of tractive power and 80 km/h speed limit.

Estimation of fuel consumption and pollutants emissions

A single train simulator developed by Lu et al. [28] was used to estimate the travel time and energy consumption of the 20 services between Itirapina and Mairinque. The tool provides not only the energy consumption but also the travel time required to deliver the desired speed. The emissions were estimated on the basis of factors of the following pollutants: oxides of nitrogen (NOx); carbon monoxide (CO); particulate matter (PM); and hydrocarbons (HC).

The Intergovernmental Panel on Climate Change (IPCC) recommends three different approaches to quantify GHG emissions in the transportation sector [24]. The Tier 1 method is based on the amount of fuel combusted and default emission factors provided by the IPCC [12]. Tier 2 is similar to the first except by considering the carbon contents of the fuel, and Tier 3 is encouraged by the IPCC as it considers the country-specific emission factors for locomotives [24].

As Brazil does not have reliable emission factor data for its locomotive fleet, estimates were generated in two stages. Firstly, tractive power was converted into fuel consumption using models by Fritz [14] and Gould and Niemeier [15], illustrated in Fig. 2a. Secondly, fuel consumption data was used to generate pollutant emissions levels based on Fritz [14], as shown in Fig. 2(b)-(e).

The emission of the i-th pollutant (NOx, CO, PM and HC) in the j-th route was calculated according to Eq. (1) referring $j = P$ to the alignment parallel to the existing infrastructure and $j = \{1, \cdots, 100\}$ to the optimized alignments obtained by the Parallel Genetic Algorithm.

$$E_{i,j} = \sum_{s} EF_i \cdot TT_{j,s} \forall i = \{NOx, CO, PM, HC\}, j = \{1, \cdots, 100; P\} \tag{1}$$

where $E_{i,j}$ is the overall emission of the i-th pollutant (NOx, HC, PM and CO) of the j-th alignment, EF_i (g/h) is the emission factor of the i-th pollutant retrieved from Fig. 2(b)-(e) and $TT_{j,s}$ (hours) is the travel time of service s described in Table 1 running on alignment j, obtained in the simulations. In order to properly perform a life cycle analysis of railway infrastructure improvement projects, the estimated NOx, CO, PM and HC emissions were converted to CO_2-equivalent for track doubling of the existing alignment ($CO_2e_{i,P}$) and in each optimized alignment ($CO_2e_{i,j} \forall j = \{1, \cdots, 100\}$) by means of specific factors of each pollutant as described in Eq. (2).

$$CO_2e_{i,j} = E_{i,j} \cdot CO_2e_i^{factor} \forall i = \{NOx, CO, PM, HC\}, j = \{1, \cdots, 100, P\} \tag{2}$$

where $CO_2e_{i,j}$ is the emission of CO_2-equivalent of i-th pollutant (NOx, CO, PM and HC) of trains running on alignment j (tonnes); $E_{i,j}$ is the estimated emission of pollutant i regarding alignment j from Eq. (2) (tonnes); and $CO_2e_i^{factor}$ is the CO_2 equivalency factor to the pollutant i (tonnes of CO_2 per tonnes of pollutant). In this paper we considered the following values to the $CO_2e_i^{factor}$: 298 for NOx (USEPA, 2020); 2 for CO [18]; 330 for PM (USEPA, 2020); and 36 for HC (USEPA, 2020).

Assessment of construction costs, fuel consumption and emissions

This paper considers not only the capital costs of building new railway alignments, but also the operational costs consisting of fuel consumption and environmental impacts measured by the monetised values of CO_2-equivalent emissions. Let CC_P be the estimated construction cost of the infrastructure parallel to the existing railway and CC_j the estimated construction cost of the j-th optimized alignment. We consider that monetary values of fuel consumption required to provide the energy to the train engines and of pollutant emissions caused by the operation of trains over a period of time in the optimized alignments would be lower than those of operating trains running parallel to the existing tracks. It logically follows that there is a time horizon in which the savings in fuel and emissions of a given optimized alignment will compensate for the greater construction costs of the optimized alignment.

In order to estimate this time horizon, the demand for services was considered by the monthly number of trains (Table 1) on an annual basis, and then extrapolated through a time period given an estimated demand growth. For the first four years the demand growth was estimated based on the information of ALL [3] and the growth of the following years was parametrized by the time series of the Brazilian Gross Domestic Product (GPD) as presented in Table 2 [22]. Given the Brazilian GDP average growth from 1997 to 2019, three scenarios were considered: optimistic (4.6%); realistic (2.3%), equals the average growth of the past 22 years; and conservative (1.2%).

Table 2
Estimated demand growth adapted from ALL [3].

Year	Tonnes/year	Demand Growth
1	545,000	0
2	666,111	22%
3	787,222	18%
4	1,090,000	38%
5 and following	–	Brazilian GDP based scenarios Optimistic (4.6%) Realistic (2.3%) Conservative (1.2%)

*Average growth from year 1 to 4.

For each alignment a life cycle assessment was performed that considered the Net Present Value (NPV) of the fuel consumption and pollutant emissions in terms of CO_2-equivalent given a specific discount rate and the average demand growth of Table 2. Then, for each alignment (optimized by the GA and parallel to the existing tracks) and for each year of the life cycle analysis, the total fuel consumption and the overall CO_2-equivalent emissions of all the services were calculated based on the cumulative demand growth rate of a given year. The monetary value of the fuel consumption based on a fuel price and an inflation rate per year was calculated, as well as the CO_2-equivalent emission cost, also known as Social Costs of Carbon (SCC). The NPV of the monetary values of fuel consumption and CO_2-equivalent emissions on a given year are presented in Eq. (3) and Eq. (4) respectively.

$$NPVF_j^t = \sum_{s} FC_{j,s} \cdot FP \cdot \frac{(1+FIR)^t}{(1+r)^t} \forall j = \{1, \cdots, 100; P\} \tag{3}$$

where $NPVF_j^t$ is the Net Present Value of the fuel consumption of trains running in alignment j on a given year t (BRL); FC_s is the fuel consumption of a service s; FP is the baseline fuel price; FIR is the fuel inflation rate; r is the discount rate; and t is the year. The fuel cost baseline (FP) was considered equal BRL2.5/litre and the inflation rate (FIR) was set equal to 1.0% per year based on the time series of ANP [5].

$$NPVCO_{2j}^t = \sum_{i} CO_2e_{i,j} \cdot SCC_{CO_2e} \cdot \frac{(1+g)^t}{(1+r)^t} \forall j = \{1, \cdots, 100\} \tag{4}$$

where $NPVCO_{2j}^t$ is the Net Present Value of the overall emissions of the trains running on alignment j during year t (BRL); SCC_{CO_2e} is the Social Carbon Cost (SCC) of the CO_2-equivalent emissions; and g is the demand growth rate.

A few studies have assessed the valuation of Social Cost of Carbon worldwide and found very distinct values. Tol [40] provided an extensive review of Global SCC studies (GSCC) from 1982 to 2006 and found values ranging from USD1.5/tonCO_2 [30] to USD2,400/tonCO_2 [9] in the so-called realistic scenarios. More recently, Nordhaus [31] updated these estimations in the world levels considering fixed discount rates of 2.5%, 3%, 4% and 5% from 2010 to 2050. Ricke et al. [33] estimated the GSCC and presented values to the country level by the CSCC (Country Social Cost of Carbon) with adjusted discount rates over time and fixed discount rate of 3% per country and on a world basis.

Given the wide range of estimations from different sources, we considered a sensitivity analysis with different values from recent sources at a 3% fixed discount rate. The GSCC of USD42/tonneCO_2 proposed by IAWG [20] were applied, while the GSCC values of USD83.7/tonneCO_2 for 2020 and USD156.6/tonneCO_2 for 2050

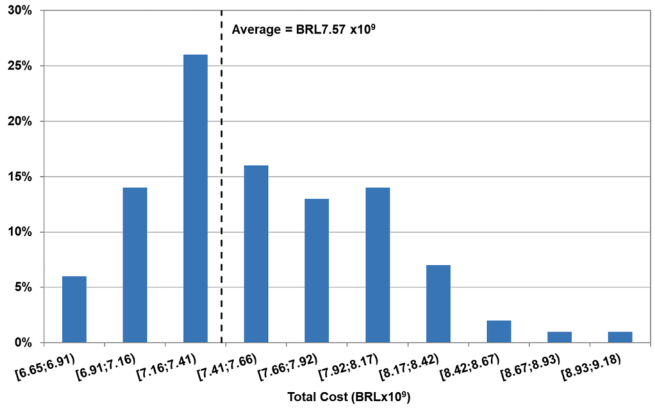

Fig. 3. Construction costs of the 100 optimized alignments.

presented by Nordhaus [31], and USD21.9/tonneCO_2 and USD944.5/tonneCO_2 proposed by Ricke et al. [33][1] to the Brazilian CSCC were considered, respectively. Consider currency conversion of 4.25 Brazilian Reais per US Dollar.

Finally, in order to assess the strategy of infrastructure improvement based on the construction of new optimized alignments, the number of years required to compensate for the difference of costs of a new optimized alignment and the parallel to the existing infrastructure ($CC_j - CC_P$) was calculated. It used the NPV of the summed monetary values of fuel consumption and CO_2-equivalent of the optimized alignments subtracted by the equivalent values regarding the duplication along the existing tracks.

Therefore, Eq. (5) on the variable number of years t for each j-th optimized alignment was solved. It is important to highlight that the construction costs of both alignments were not discounted over a period of time, and the infrastructure maintenance and other benefits of operating the trains besides the fuel and emissions (capacity increment, induced demand, maintenance cost, and travel time savings) were not included in the time horizon estimation as these costs and benefits were considered to be equal for both the parallel or the optimized alignments.

$$CC_j - CC_P = \sum_t \left(NPVF_j^t + NPVCO_{2j}^t\right) - \sum_t \left(NPVF_P^t + NPVCO_{2P}^t\right) \forall j = \{1, \cdots, 100\} \tag{5}$$

Results and discussion

Optimized alignments

The application of the Genetic Algorithm described by Isler et al. [19] resulted in 100 different alignments connecting the start and end points of each segment previously described. The construction costs of the optimized alignments are shown in histogram of Fig. 3 while the average cost and cost per km of each of the five segments are shown in Fig. 4.

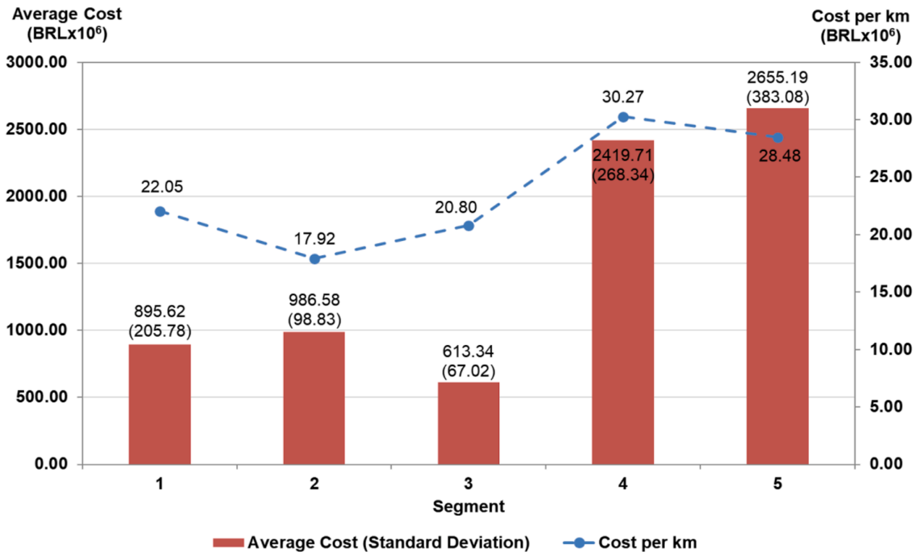

Fig. 4. Average construction cost and cost per km, per section of the optimized alignments.

The minimum cost obtained by the optimization method is BRL6.65x10^9, while the most expensive alignment amounted to BRL9.18x10^9. The average cost to build a new optimized alignment is BRL7.57x10^9 with a standard deviation of BRL0.48x10^9 (coefficient of variation equals 6.4%). The average cost per km to double a single track line in Brazil was based on the guidelines of ANTT of BRL2.8x10^6/km. This lower value compared to the estimations of the new alignments is mainly due to the fact that no expropriation is required and the lower earthwork costs.

The average length of Segment 1 to Segment 5 are 40.95 km, 55.55 km, 30.51 km, 80.1 km, and 93.42 km, respectively. In particular, the average cost per km ranges from BRL17.92x10^6/km to BRL30.27x10^6/km. It is worth noting that the standard deviation of the costs per segment varies from 10% to 14% between Segment 2 to Segment 5, except for Section 1 (Introduction) with standard deviation of 23% of the average cost. Moreover, the average cost per km of the entire alignment is BRL25.2x10^6/km and standard deviation of BRL1.8x10^6/km.

Fig. 5 illustrates the optimized alignments over the existing track per segment. In Segment 1 the estimated alignments were close to the existing one, which indicate that track doubling is already reasonable from the point of view of the geometric parameters. However, Segments 2, 3, 4 and 5 resulted in alignments with configuration different from the existing tracks.

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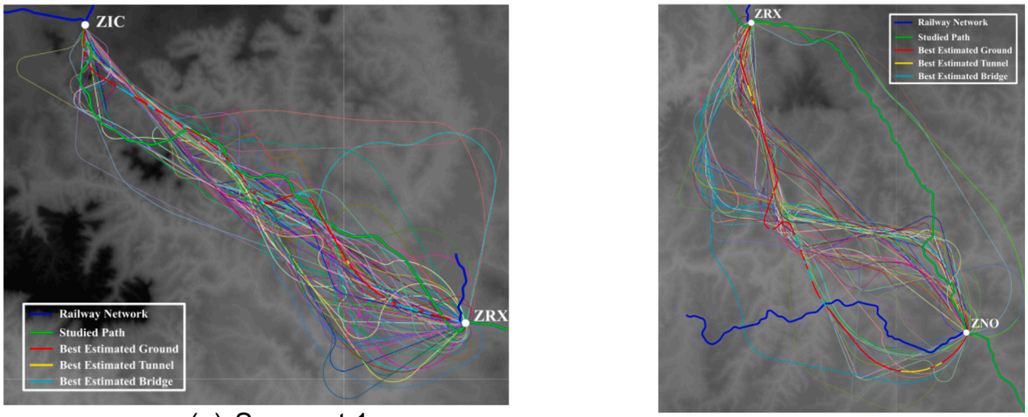
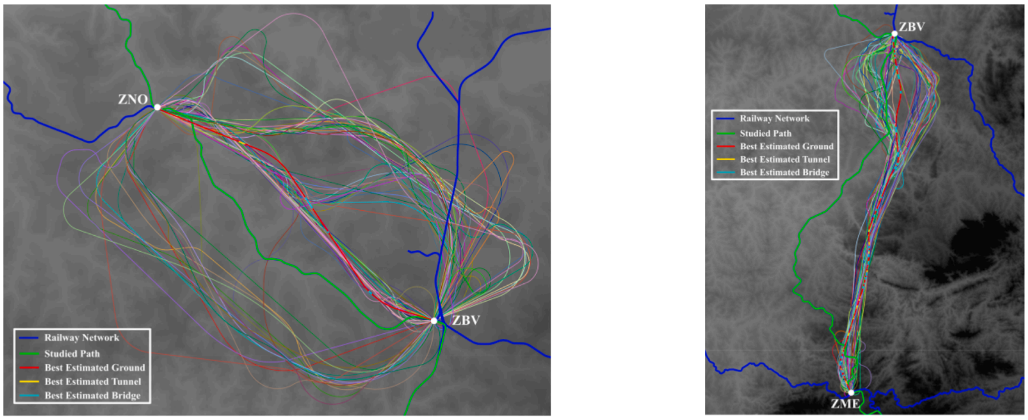
[1] Median with the following parameters of the Supplementary Data 1: run=bhm_lr; dmgfuncpar=estimates; climate=expected; SSP=SSP2; RCP=rcp60; N=1; ISO3=BRA and WLD; prtp=NA; eta=NA; dr=3.



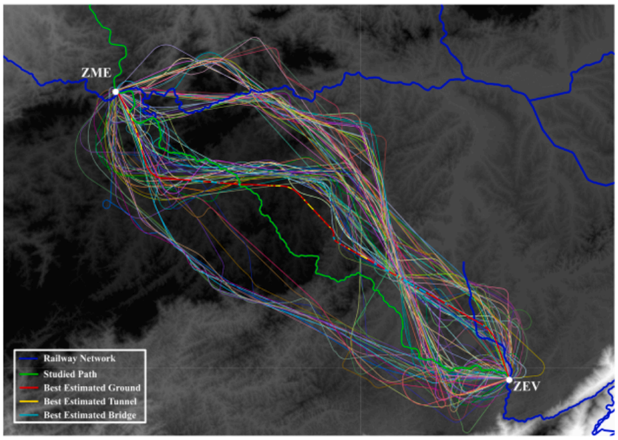
(a) Segment 1

(b) Segment 2



(c) Segment 3

(d) Segment 4



(e) Segment 5

Fig. 5. Estimated alignments in Segments 1 (a), 2 (b), 3 (c), 4 (d) and 5 (e) in comparison to existing tracks.

Pollutant emissions

Using the energy consumption estimates, fuel consumption and pollutant emission (NOx, CO, PM and HC) were calculated for those services running in the existing alignment and compared with the results with those provided by the EIA described by ALL [3]. The comparison resulted in maximum deviation of 0.10% between the total emissions of the simulation compared to that presented by the EIA, which indicates a high level of confidence in the models.

Following the calibration procedure, the 20 services were simulated using both the track doubling and the optimized alignment scenarios. Figs. 6 to 10 illustrate the total energy consumption, NOx, CO, PM and HC emissions of trains running in each simulated service described in Table 1 compared to the overall alignment costs of the GA results. The illustrations also represent the cost, energy consumption and pollutant emissions of the services running in the track parallel to the existing infrastructure.

As expected, optimized alignments resulted in higher construction costs but lower fuel consumption and, thus, emissions of all the pollutant types. From Fig. 6, the amount of fuel required to run the 20 services in the alignment with the lowest construction cost is 315.1x10^3 litres, and 222.60x10^3 litres for the estimated alignment with the lowest fuel consumption. The consumption to run these services in the non-optimized doubled tracks is 1,489.3x10^3 litres. This represents

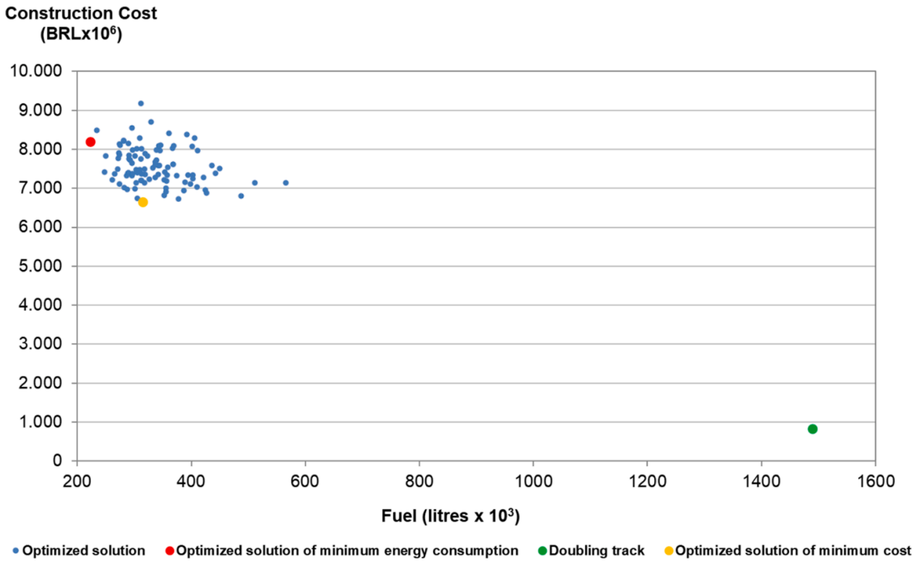


Fig. 6. Construction costs and fuel consumption.

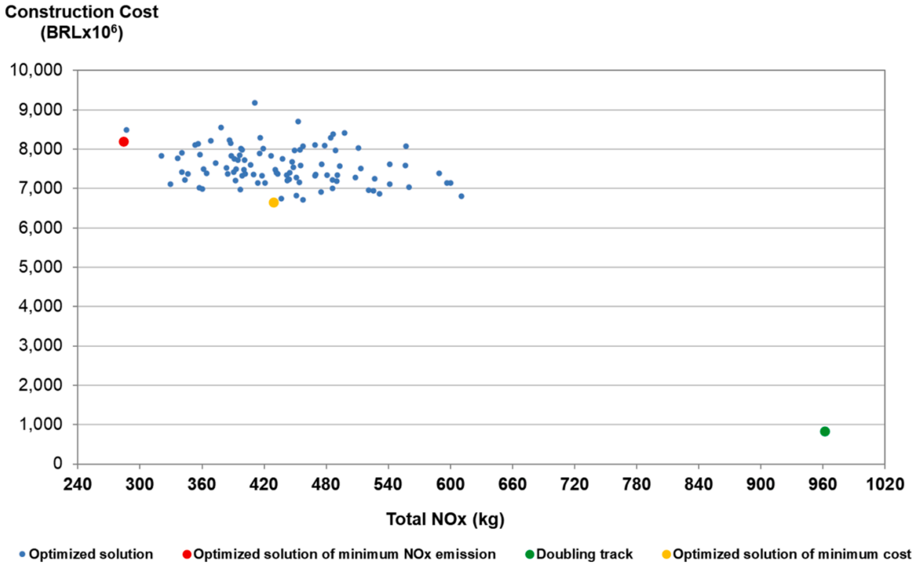


Fig. 7. Construction costs and NOx emission.

potential reduction of 77.1% compared in costs and 84.1% in fuel consumption with optimized alignments.

The same relationship is observed regarding pollutant emissions. Fig. 7 depicts the emission of 961.7 kg of NOx when running the 20 services over doubled tracks on the existing alignment, 429.1 kg considering the cheapest alignment, and 283.7 kg in the alignment with the lowest emissions. This results in potential reductions of 55.4% and 70.5% respectively compared to the existing alignment. Regarding CO emissions, Fig. 8 shows that the total emission of those services in the alignment of minimum cost is 98.9 kg, and 53.1 kg in the alignment with the lowest CO emissions. These values represent reductions of 58.3% and 77.6% when respectively compared to the total emission of 237.7 kg considering the operation in the existing alignment.

Fig. 9 illustrates PM emissions against construction costs and shows that the emissions of the services running parallel to the existing track equals 13.9 kg, and 6.6 kg over the tracks in the alignment with the lowest cost (i.e., 52.7% less than the existing alignment), and 5.0 kg when the services are operated in the alignment with the lowest PM emission, i.e., a reduction of 63.9% compared to the services running parallel to the existing alignment. Finally, Fig. 10 depicts the total emission of HC over the alignments with lowest cost and lowest emissions of the pollutant, equivalent to 12.0 kg and 8.4 kg respectively. These values are 60.4% and 72.6% lower than the 30.3 kg obtained when considering the operation of the services parallel to the existing tracks, respectively.

Table 3 describes the total values obtained in the simulations per service over the existing alignment, and the average values observed among the 100 replications of new railway alignments obtained from the GA algorithm. The values in parenthesis represent difference (in %) of these average values of the new alignments compared to the existing duplicated track.

Assessment of construction costs, fuel consumption and emissions

Following the results of the method to assess the life cycle of infrastructure improvement policies proposed in this paper, Fig. 11 represents the expected fuel cost and monetary values of CO_2-equivalent emissions in the first year of operation of the trains described in Table 1

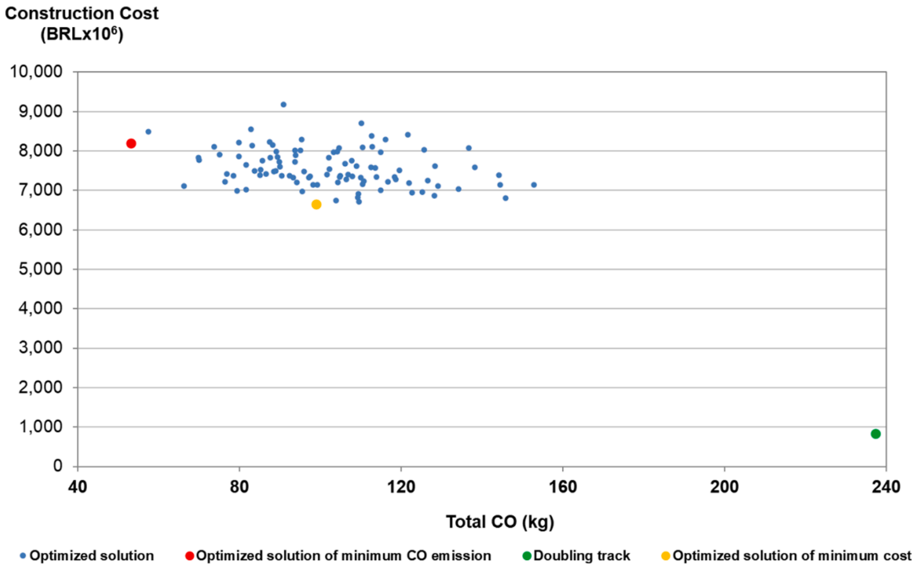


Fig. 8. Construction costs and CO emission.

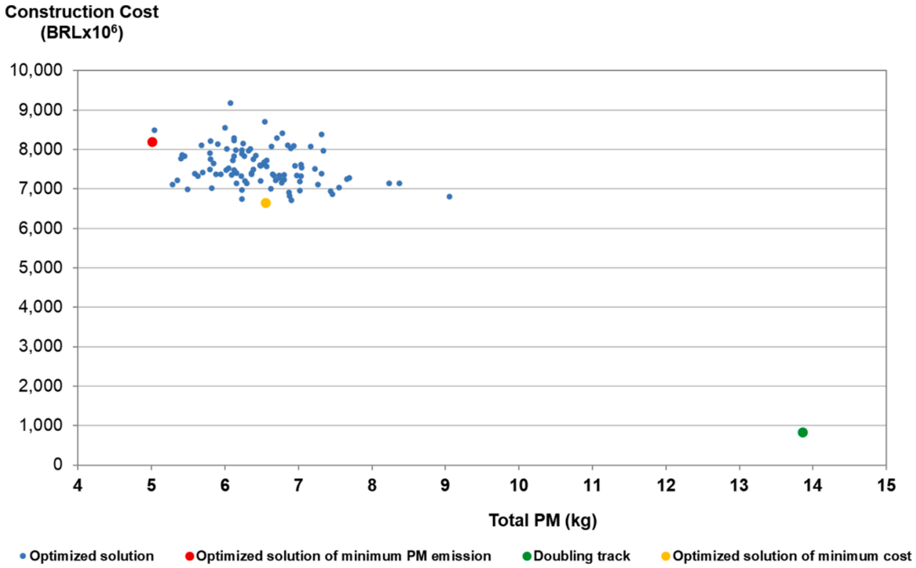


Fig. 9. Construction costs and PM emission.

in the doubling track, and the average values estimated for the optimized alignments, considering the CO_2-equivalent monetary values (USD/tonneCO_2) equal to USD42/tonneCO_2 [20], USD83.7 and USD156.6 [31], and USD21.9 and USD944.5 [33] with a fixed discount rate of 3%. Consider 1 USD equals 4.25 BRL.

Fig. 11 shows that the sum of fuel cost and monetary value of CO_2-equivalent increases for both the doubling track and average value of the optimized alignments as the CO_2-equivalent cost per tonne increases. The difference in the sum of fuel cost and monetary value of CO_2-equivalent increases around 188.3% in the considered range of CO_2-equivalent cost per tonne, from BRL31.26 x10^6 for USD21.9/tonne CO_2-equivalent to BRL90.12 x10^6 for USD944.7/tonne CO_2-equivalent.

As result of Eq. (5) solved in the variable number of years (*t*) to different monetary values of CO2-equivalent and interest rates (*r*), Fig. 12 represents the average number of years required to the fuel costs and monetary value of CO_2-equivalent savings in the optimized alignments discount by the equivalent values in the alignment parallel to the current alignment pay the difference of construction costs of these alignments compared to improving the infrastructure parallel to the existing tracks.

According to Fig. 12, the maximum number of years in which savings in fuel and emissions compensate for the greater construction costs of the optimized alignments is 111 years in the conservative scenario of average 1.2% GDP growth over the years, CO_2-equivalent value of USD21.9/tonCO_2 and fixed discount rate of 3.0%. On the other hand, the shortest timespan for this compensation is 16 years, on average, in the optimistic scenario of GDP growth of 4.6% per year given the more stringent CO_2-equivalent value of USD944.5/tonCO_2 and the same fixed discount rate.

When considering the conservative scenarios of 1.2% GDP growth, an average of 69 years is required for the operational savings to compensate for the greater construction costs, with a minimum of 37 years considering USD944.5/ton of CO_2-equivalent. Meanwhile, in the realistic scenario of 2.3% GDP growth, the maximum number of years to the compensation is 74 and the minimum is 17 years, and 51 years on average. Finally, given the optimistic scenario of GDP growing 4.6% per year, the maximum number of years to the operation compensate the construction costs is 49 with average estimated value of 37 years.

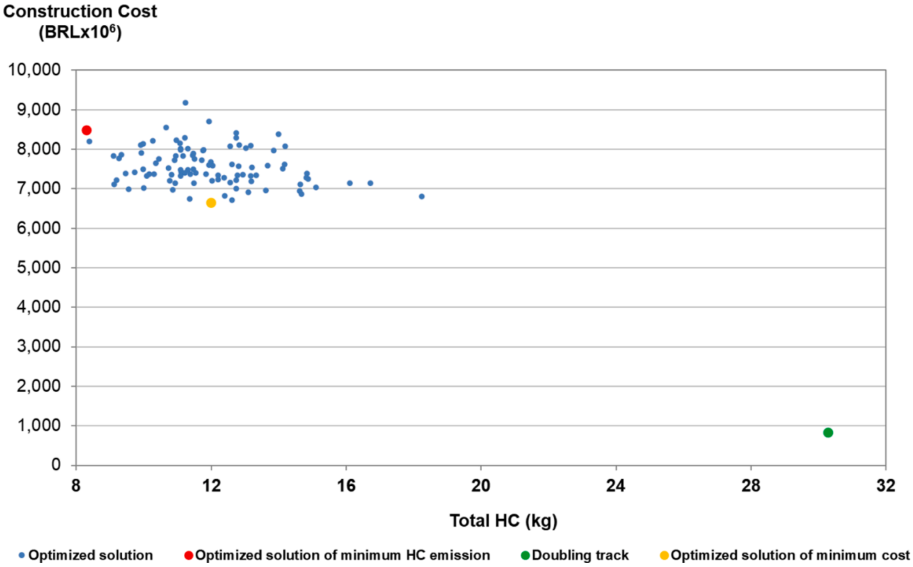


Fig. 10. Construction costs and HC emission.

Table 3
Fuel consumption and pollutant emissions (NOx, CO, PM and HC) by service running parallel to the existing infrastructure compared with the average values of the optimized alignments.

	Existing alignment						New alignment (100 runs)					
Service	Fuel (litresx10^3)	Time (hour)	NOx (kg)	CO (kg)	PM (kg)	HC (kg)	Energy (litresx10^3-%)	Time (hour-%)	NOx (kg-%)	CO (kg-%)	PM (kg-%)	HC (kg-%)
1	3.5	1.9	59.1	15.9	1.3	2.5	0.4 (−90.3)	1.5 (−20.8)	14.7 (−75.1)	2.9 (−82.4)	0.3 (−82.5)	0.4 (−85.2)
2	5.4	1.5	45.4	10.6	0.5	1.2	0.2 (−97.4)	1.5 (−6.1)	6.2 (−86.4)	0.6 (−94.6)	0.2 (−66)	0.2 (−83.9)
3	9.6	2.0	50.6	12.6	0.8	1.7	0.3 (−97.4)	1.6 (−23.6)	10.5 (−79.3)	1.6 (−87.3)	0.2 (−75.0)	0.3 (−83.3)
4	6.7	2.5	41.8	9.2	0.3	0.9	0.2 (−97.5)	1.8 (−31.6)	5.9 (−86.0)	0.6 (−94.5)	0.2 (−48.5)	0.2 (−78.9)
5	5.7	1.5	46.0	10.8	0.5	1.3	0.2 (−97.4)	1.5 (−7.2)	6.5 (−85.8)	0.7 (−94.1)	0.2 (−67.7)	0.3 (−84.0)
6	6.8	1.6	47.7	11.5	0.6	1.4	0.2 (−97.4)	1.5 (−11.9)	7.8 (−83.7)	1.0 (−92)	0.2 (−71.5)	0.3 (−84.0)
7	31.1	5.6	53.3	13.7	0.9	1.9	1.3 (−95.9)	2.5 (−56.8)	33.7 (−36.9)	8.5 (−38.1)	0.4 (−65.3)	0.8 (−62.2)
8	33.4	5.9	53.8	13.8	1.0	2.0	1.4 (−95.8)	2.5 (−58.6)	35.6 (−33.8)	8.8 (−36.6)	0.4 (−64.7)	0.8 (−60.0)
9	22.4	5.9	46.5	11.0	0.6	1.3	1.0 (−95.7)	2.5 (−58.9)	26.6 (−42.9)	7.1 (−36.2)	0.3 (−47.6)	0.6 (−58.0)
10	15.2	7.5	34.2	8.8	0.3	0.7	0.8 (−95.3)	2.6 (−66.2)	18.8 (−45.1)	4.6 (−48.6)	0.3 (−21.3)	0.5 (−43.2)
11	12.6	1.8	59.0	15.9	1.3	2.5	1.9 (−84.9)	1.6 (−15.6)	50.9 (−13.9)	12.7 (−20.1)	0.9 (−36.6)	1.8 (−30.5)
12	8.1	2.9	42.5	9.4	0.3	0.9	1.1 (−87.5)	2.4 (−18.9)	28.8 (−32.2)	8 (−15.4)	0.4 (−6.8)	0.6 (−38.1)
13	20.1	4.1	50.9	12.7	0.8	1.7	3.4 (−83.4)	2.5 (−40.3)	52.4 (2.8)	13.3 (4.4)	0.9 (10.0)	1.9 (7.6)
14	19.2	3.9	50.7	12.6	0.8	1.7	3.1 (−83.8)	2.5 (−38.3)	51.1 (0.6)	12.8 (1.0)	0.9 (2.4)	1.8 (1.8)
15	10.9	1.6	58.3	15.6	1.2	2.4	0.8 (−93.4)	2.4 (50.2)	20 (−65.7)	4.9 (−68.5)	0.3 (−79.5)	0.5 (−81.7)
16	13.8	4.5	43.7	9.9	0.4	1.1	0.6 (−95.7)	2.4 (−46.8)	16.9 (−61.5)	3.7 (−63.1)	0.3 (−40.7)	0.4 (−63.1)
17	14.2	4.5	43.8	10.0	0.4	1.1	0.7 (−95.6)	2.4 (−47.2)	17.4 (−60.5)	3.9 (−61.2)	0.3 (−41.2)	0.4 (−62.9)
18	16.5	4.9	44.8	10.3	0.5	1.2	0.8 (−95.4)	2.5 (−50.5)	21.1 (−52.9)	5.4 (−48.5)	0.3 (−43.0)	0.5 (−61.2)
19	7.4	1.3	54.4	14.1	1.0	2.0	0.4 (−95.6)	2.4 (85.4)	9.1 (−83.4)	1.4 (−90.5)	0.2 (−81.3)	0.3 (−87.4)
20	3.1	1.5	35.2	8.9	0.3	0.7	0.1 (−97.2)	1.5 (−2.4)	3.7 (−89.7)	0.3 (−97.5)	0.2 (−52.2)	0.2 (−81.4)

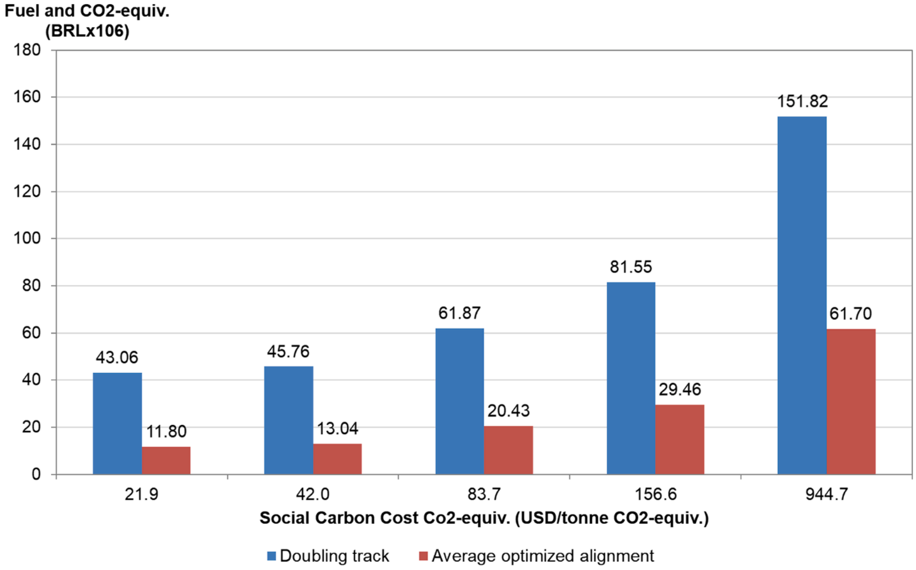


Fig. 11. Fuel and CO_2-equivalent in the first year of operation of trains per type of alignment given multiple SCC values.

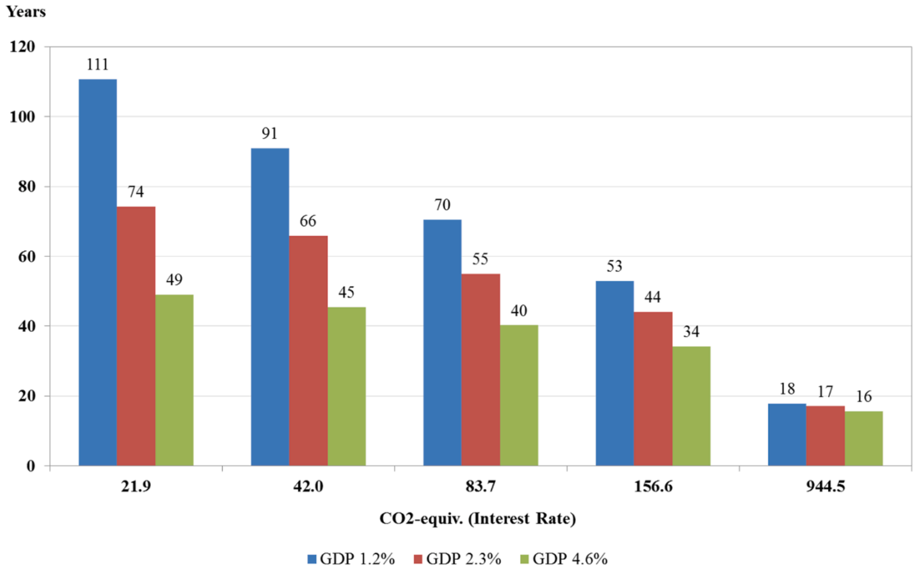


Fig. 12. Average number of years to compensate the construction of optimized alignments per monetary CO_2-equivalent values and interest rates.

It must be highlighted that the values used for fuel consumption and pollutant emissions derive from the literature and not real locomotive data. As such, results in the calculation provide an aggregate understanding of life-cycle emissions and may not precisely reflect the real consumption that depends on the performance and condition of infrastructure and rolling stock. This has a certain impact on the accuracy of the simulations, but it is argued that the differences are of small magnitude comparing the long term planning horizon of those lines (70–100 years).

Furthermore, it is important to add that the paper focused on the reduction of emissions from diesel powered trains, where emerging technologies may become more prominent in that timespan. Emphasis was given to the relative comparison between options within the life-cycle of railway assets using existing data, which explains why electrification or alternative fuels were not included in the process. While their potential impact on the findings must not be overlooked, especially from the perspective of reduced or entirely cut emissions from operations, it is difficult to estimate them in the context of Brazilian railways at this point. The vast majority of rail traffic is of heavy haul trains, which puts in question the times and costs associated with the infrastructure required to deliver those specific capabilities. In addition, such research would require some level of speculation around additional construction costs for those alternatives.

Concluding remarks

In this paper, the life cycle costs of different railway improvement strategies were assessed. This issue has been raised extensively in the literature where policies must look at ways to curb fuel consumption and emissions from transport. Using a real case study from Brazil, a comparison was made of the construction costs of duplicating the existing alignment with optimized theoretical alignments. The analysis looked at the operating costs of 20 different services running on these tracks in terms of fuel consumption, and more importantly, the internalized monetary values of CO_2-equivalent emissions related to four pollutants (NOx, CO, PM and HC).

The most significant finding comes from internalizing the Social Costs of Carbon into the life cycle costs of railway lines. In times of growing concerns with the environmental impacts of transport activities, and considering the life span of railway assets, fuel consumption and emissions must be taken seriously. One challenge that arises is that there is no unanimity in monetizing the environmental externalities caused by railway operations. To overcome that, all optimized alignments through different scenarios that accounted for various GDP growth rates, and the monetary values of each ton of CO_2e emission were analyzed.

Using the literature on Social Carbon Costs, the average number of years required to compensate the greater construction costs of a new optimized alignment with the savings in fuel consumption and CO_2-equivalent emissions is 51 years over a scenario of 1.2% Brazilian GDP growth per year. In the worst case (conservative GDP growth of 1.2% and USD21.9/ton of CO_2-equivalent), the number of years is 111 which seems more financially challenging even when considering the long life span of railway assets. On the other hand, the best scenario occurs with optimistic GDP growth of 4.6% and monetary value to CO_2-equivalent equals USD944.5/ton, and requires only 16 years to compensate for the greater construction costs of a new optimized alignment.

Given a life span that can stretch up to 150 years, railway infrastructure improvements could potentially avoid significant impacts from fuel consumption costs and monetized values of pollutant emissions. Moreover, considering that the greater construction costs can be fully compensated within the lifespan of optimized alignments, policies to internalize externalities in project appraisal can be seen more positively. Finally, building new optimal alignments would bring benefits as economic development to underdeveloped regions by promoting new train operations for passenger transport or use of urban space for cultural and economic activities.

It is concluded that promoting new optimized alignments could bring economic benefits in terms of lower fuel consumption to the companies operating the trains and to society as saving in pollutant emissions in terms of CO_2 equivalent. Railway lines are likely to need improvements to serve the necessary volumes that can reduce overall transport emissions. In times where the costs of emissions must be computed, it is anticipated that this research can provide a more comprehensive framework to appraise projects to improve railway infrastructure.

CRediT authorship contribution statement

Cassiano Augusto Isler: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Marcelo Blumenfeld:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Clive Roberts:** Conceptualization, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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