Evaluation of Railway versus Highway Emissions using LCA approach between the two cities of Middle Anatolia

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Conflict of Interest Declaration

The authors declare no conflict of interest

Abstract

Transfer of people and transportation of goods is an indispensable part of our daily lives. Choosing the most environmentally friendly alternative will have the least impact on human health, ecosystem, and the materials. This study aims to carry out a comparative assessment of various emission scenarios from highway and railway transportation between Kırşehir and Niğde-Ulukışla in the middle Anatolian Peninsula, in Turkey, to allow making an optimum decision from an environmental viewpoint. Currently, the transportation is sustained through highway, which has 232.6 km length between the cities used as a case study. High-speed railway construction is projected on the same route. We formed different capacity alternatives as alternative scenarios and life cycle assessment approach was applied to these scenarios. Environmental damage ratio decreased with the increasing utilization ratio of the railway. The greatest change was seen in ecosystem quality. We also assessed emissions during the construction activities of both railway and highway. A social cost-benefit analysis suggested that damage cost in the current situation was €562,000. The scenario with100% replacement of highway with railway transportation showed the lowest damage cost (€157,000) while the highest damage cost was due to NO_x emissions.

Keywords: Life cycle assessment, Sustainability, Social cost-benefit analysis, Transportation, Emissions

Research highlights

- Very first LCA comparison for railway and highway construction is carried out
- Railway utilization have the highest improvement on ecosystem quality
- Railway construction leads to resource preservation
- Increasing railway utilization decreases greenhouse gas emissions
- The lowest social cost is €157,000 per year for 100% railway utilization scenario

1. Introduction

The whole transportation sector, including road, rail, aviation, and navigation means, is responsible for approximately 28% of the total energy demand worldwide according to 2016 statistics (IEA, 2019). Oil, natural gas, and electricity meet the energy demand for transportation and their ratio are 95, 4, and 1%, respectively. Road transportation consumes 76% of the oil in the transportation sector, whereas rail transportation only consumes 1%. Urban transportation is responsible for 23% of greenhouse gas emissionsin the EU (European Commission, 2016). Road transportation emitted 72.8% of greenhouse gasses, while rail only contributed to 0.6% (European Commission, 2019). Among the greenhouse gasses, CO_2 emission is the major contributor from the transport sector. Its global share is 95% (Atabani et al., 2011; Singh et al., 2019). With an increase in the number of automobiles, emissions from the spare parts of these vehicles, together with the exhaust emissions, negatively impact the environment (Lombardi et al., 2017). In order to reduce the impact on the climate change and the dependence on petroleum fuels, researchers and policymakers are exploring low-cost transportation alternatives that are less harmful and capable of using limited resources at higher efficiency (Chang et al., 2011).

Rail transportation is one of those travel modes that releases the lowest CO_2 emissions and consumes less energy (Lombardi et al., 2017). Turkey's railway transportation system has made significant progress in recent years. For example, currently, Turkey has a total of 12,000 km railway line. The total length of High-Speed Rail (HSR) is 888 km and the remaining is Conventional Railway (CR) (Banar et al., 2015). In addition, according to the National Climate Change Action Plan, which aims to reduce greenhouse gas emissions, an increase in railway passenger transport rates is expected in all modes of transport through Turkish State Railways (TSR) by 2023 (TRS,2013). Dalkic et al (2017) showed the potential of reducing CO_2 emissions through a shift from road transportation to HSR transportation. The shift to railway transportation will meet the requirements of low carbon city concept (Azizalrahman and Hasyimi, 2018). Moreover, motor vehicles produce air pollutants in an urban area which the adversely impact the air quality of the cities (Mahesh et al., 2018; Kumar et al., 2018) and affect human health (Gabbe, 2018; Heal et al., 2012). In particular, nitrogen oxides (NO_x) and particulate matter ≤10µm (PM_{10}) and ≤2.5µm ($PM_{2.5}$) is a serious problem in cities (Kumar et al., 2015, 2016; Kuzu, article in press). Road transport accounted for 39% and 13% of NO_x and PM_{10} emissions in the EU in 2015, respectively (EEA, 2017). The alteration of transportation means stands inevitable for sustainable management of air pollutant emissions. This requires a comprehensive evaluation of different transportation methods.

Life cycle assessment (LCA) is identified as a method to determine the total environmental and social impacts of a product or service during its life cycle (SAIC, 2006). LCA approach is a combination of the following six philosophy: (i) rethink (the product and its function is analyzed in detail); (ii) reduce (minimizing the consumption of raw material and energy); (iii) replace(preferring less harmful raw materials and energy-efficient production methods instead of traditional ones); (iv) recycle (preferring recyclable materials); (v) reuse (designing the product as reusable); and (vi) repair (designing the product appropriate for periodical repairs) (UNEP, 2006). An LCA process can be sub-divided into four phases, which are closely related to each other: (i) goal and scope (analyses must be determined and identified in detail); (ii) Life Cycle Inventory (a comprehensive and complete inventory of the product or system must be formed); (iii) impact assessment (calculations should be realized to estimate the environmental, social and economic impacts of different stages); and (iv) interpretation (provides contact among other three stages) (Sharma et al., 2011).

Energy consumption of road vehicles is one of the most important driving forces of greenhouse gas emissions (Moretti et al., 2018; Huang et al., 2018). Huang et al. (2018)

compared the terrestrial transport modalities in China in terms of monetary, energy, and environmental costs. They found out that the cost percentage of the private car, regular trains, long-distance bus, and trucks were 40.87%, 5.48%, 10.41%, and 37.28%, respectively. The ratios of these transport modes in total cumulative energy demand were 35.38%, 15.41%, 10.89%, and 30.53%, respectively. Merchan et al. (2019) investigated the inland freight transport in terms of LCA and external costs. The authors indicated that the share of road and railway transport of total greenhouse gas emissions were 17% and 0.09%, respectively. According to other results of the study, the reference value of road transport is accepted as 100% for damage to the human health damage to the ecosystem diversity, damage to the resource availability and climate change, while this value was approximately 55% for rail transportation. Stephan and Crawford (2016) studied the total water requirement of petrol cars, diesel trains, and electric trains. They concluded that the need for water during the operation stage were 3.8, 3.4 and 1.6 L/passenger-km, respectively. Skrucany et al. (2017) compared rail and road transport in terms of greenhouse gas emissions. They reported that the energy intensity of gasoline and diesel cars were 70% and 50% higher than the railway vehicle, respectively, and in case of full occupancy of the vehicles. The authors also indicated that the difference between road and rail vehicles is increasing with the decrease in occupancy of the vehicles.

In Turkey, HSR constructions are being expedited in recent years. Currently, road transportation is in service and HSR is in construction plans as an alternative to current road transportation in coming years. The first objective of this study is to evaluate the transportation emissions between the two cities (Kırşehir and Niğde-Ulukışla) in Turkey via road and railway trasnportation modes from an LCA perspective. To best of our knowledge, this is from one of the first studies to discuss LCA of construction activities contrasting between railway and road transportation (highway). The overall goal is to guide decision makers for implementing emission reduction strategies through a holistic viewpoint including construction and operation phases.

2. Materials and methods

2.1. Definition of the Study Area

The highway and railway connect Kırşehir and Niğde-Ulukışla passing through Aksaray province. These neighbour cities are located at the centre of Turkey, as shown in Figure 1. Ulukışla is a district of Niğde province, where is located approximately 56 km to the South of Niğde city centre. The terminal railway and highway location for Niğde is hereafter referred to as Ulukışla within the text. The total length of the highway is approximately 232.6 km, whose first part (94.6 km) is for Kırşehir-Aksaray and the other part (138 km) is for Aksaray-Ulukışla. The total length of the railway will be 209 km. The route on the map is given along with the corresponding populations for each city. The sum of the population of the cities is slightly over one million according to 2018 census.

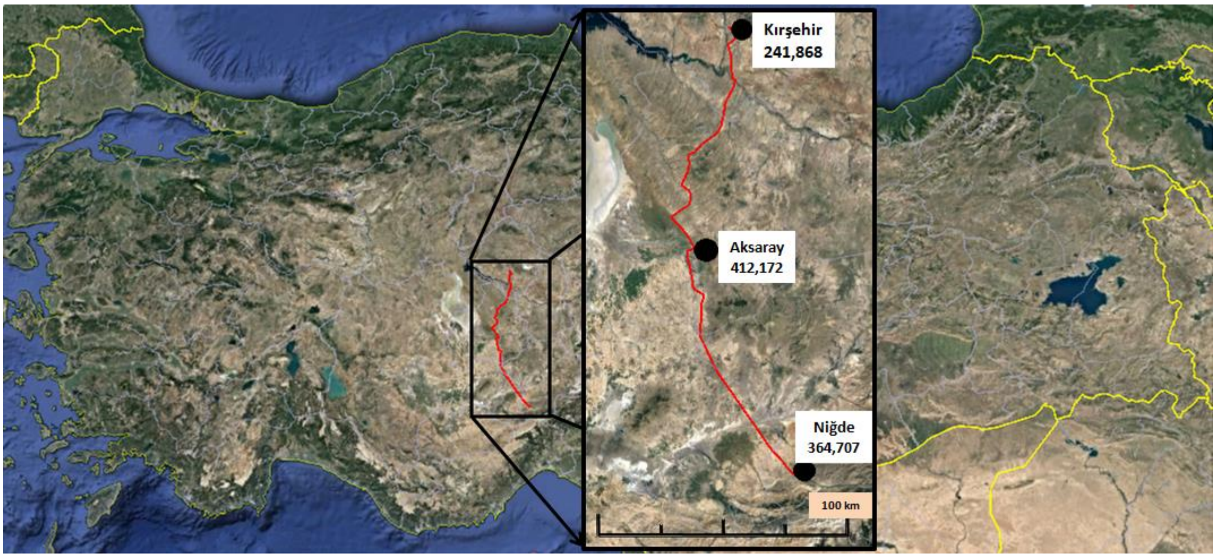

Figure 1. The route of railway and highway, shown by a red line on the map

2.2. Definition of the Scenarios and LCA

We used SimaPro 8.2.3.0 in order to compare the environmental impacts (characterization, damage assessment, and inventory) of railway and highway. Automobiles, buses, pick-up trucks, and trucks are considered as the main components of the road traffic in Kırşehir-Ulukışla highway.

Transport scenarios have begun to turn to more environmentally sensitive features with increasing concern about the environmental constraints of the planet. In order to realize the accurate results, we divided the highway into two parts: Kırşehir-Aksaray and Aksaray-Ulukışla. The highway density calculations were made based upon the data obtained from traffic volume maps of General Directorate of Highways. Table 1 presents the total number of automobiles, buses, pick-up, and trucks, which operate in Kırşehir-Ulukışla highway. The vehicles were also classified with their emission standards (Euro 4, Euro 5, and Euro 6).

Table 1. Annual vehicle count for 2017 on Kırşehir-Ulukışla highway

Location	**Vehicle Type**	**Euro 4**	**Euro 5**	**Euro 6**
Kırşehir-Aksaray	**Automobile**	4,561	1,401	500
	Bus	177	55	19
	Pick-up	435	134	48
	Truck	1,040	319	114
Aksaray-Kırşehir	**Automobile**	4,753	1,460	521
	Bus	207	64	23
	Pick-up	455	140	50
	Truck	1,027	316	113
Aksaray-Ulukışla	**Automobile**	2,713	833	297
	Bus	237	73	26
	Pick-up	165	51	18
	Truck	1,628	500	178
Ulukışla-Aksaray	**Automobile**	2,814	864	308
	Bus	193	59	21
	Pick-up	153	47	17
	Truck	1,511	464	166

According to the Environmental Impact Assessment Report of Kırşehir-Aksaray-Ulukışla Railway Project, on average, an automobile and a bus carry 2.5 and 28.3 people, respectively. Besides, a pick-up and a truck carry approximately 3.5 and 10 tones freight, respectively

(EIA, 2013). Walpole et al. (2012) expressed that the average body weight of a person is approximately 62 kg. SimaPro calculations are based on ton×km unit, the total weight of the vehicles was multiplied with the length of the road, as shown in Table 2.

Table 2. The ton×km data for the road vehicles

		Euro 4	Euro 5	Euro 6
Kırşehir-Aksaray	**Automobile**	66,879	20,540	7,327
	Bus	29,456	9,047	3,227
	Pick-up	144,032	44,236	15,780
	Truck	983,742	302,132	107,781
Aksaray-Kırşehir	**Automobile**	69,691	21,404	7,636
	Bus	34,385	10,561	3,767
	Pick-up	150,785	46,310	16,520
	Truck	971,808	298,467	106,474
Aksaray-Ulukışla	**Automobile**	58,024	17,821	6,357
	Bus	57,343	17,612	6,283
	Pick-up	79,793	24,506	8,742
	Truck	2,247,105	690,144	246,198
Ulukışla-Aksaray	**Automobile**	60,191	18,486	6,595
	Bus	46,630	14,321	5,109
	Pick-up	73,937	22,708	8,101
	Truck	2,085,265	640,439	228,466

The total ton×km data is also accepted for the railway in order to achieve meaningful calculations. After classifying the traffic data, five scenarios were determined:

- Scenario-1: 100% Highway (hereafter referred to as 100% H)
- Scenario-2: 75% Highway-25% Railway (75% H -25% R)
- Scenario-3: 50% Highway-50% Railway (50% H - 50% R)
- Scenario-4: 25% Highway-75% Railway (25% H - 75% R)
- Scenario-5: 100% Railway (100% R)

Since the Euro 6 emission data in the inventory of SimaPro 8.2.3.0 is unavailable, the vehicles with Euro 6 emission standard were assumed to be Euro5. The length of the highway and railway were assumed to be the same. In order to obtain the results, SimaPro was run and Ecoinvent-3 library and IMPACT 2002+ (Impact Assessment of Chemical Toxics) method were used.

IMPACT 2002+ was initially developed by Swiss Federal Institute of Technology (Fig. 2). IMPACT 2002+ is used in order to provide a link between 14 mid-point categories to 4 damage categories (i.e. endpoint categories), as seen in Fig. 2. Midpoint categories are used to identify traditional impact assessment methods, which have constraints on quantitative modeling. Besides midpoint categories are also used to restrict uncertainties, which occur due to the cause-effect chain. Endpoint categories are also identified as damage categories and they are used by damage oriented methods. The results sometimes have a high degree of uncertainty. Midpoint categories present some information about the causes of damage categories and they are located between Life Cycle Inventory (LCI) results and endpoints. On the other hand, damage categories express a quality change on certain issues. IMPACT 2002+ answers three questions: (i) How to adopt conventional risk assessment methods to calculate cumulative chronic toxicological risks and potential impacts? (ii) How to account in a generic but accurate way for nonlinear functions? and (iii) How to structure fate, exposure, and effect of chemicals in a consistent way? (Jolliet et al., 2003).

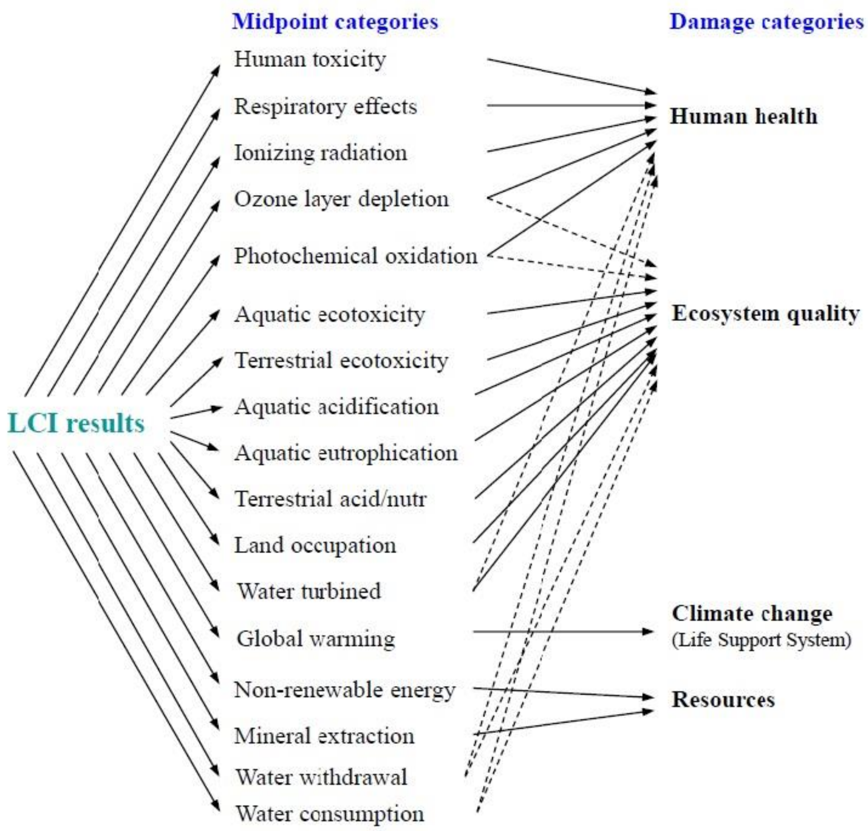

Figure 2. The overall scheme of IMPACT 2002+ (Jolliet et al., 2003)

Different midpoint categories affect different damage categories. For example, human health is directly affected by human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, and photochemical oxidation. Water turbine, water withdrawal, and water consumption have indirect or partial effects on human health. Ecosystem quality contains aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acidification, land occupation, and water turbine. Besides, water consumption has a partial effect on ecosystem quality. Global warming is the only category that has an effect on climate change. Resources have been affected by non-renewable energy and mineral extraction. The uncertainties for fate, exposure, and effect are low for resources, moderate for human health, and high for both ecosystem quality and climate change (Humbert et al., 2012).

The components of damage categories are identified with different units: DALY (disability-adjusted life years) for human health; PDF (potentially disappeared fraction) × m^2× yr for ecosystem quality; CO_2equivalent for climate change; MJ (megajoule) for resources.

DALY is widely used to quantify the burden of diseases on public health. It is identified as years of healthy life lost. According to DALY measurement methods, every person is born with certain life years lived in optimal health. However, people may lose these healthy life years due to various factors. Briefly, DALY is a measure for the total losses in accepted healthy life years (Devleesschauweret al., 2014). For instance, if the DALY score of a product or a process is 3, it implies the loss of 3 years of life over the human population. PDF × m^2× yr represents to potentially disappeared fraction of species in an m^2 area of the earth during one year. For example, if the PDF × m^2× yr score is 0.2, it implies the loss of 20% of the species on 1 m^2 of the earth during 1 year. Kilogram equivalent of a reference substance expresses the amount of a reference substance that equals the impact of the considered pollutant. CO_2 is the reference substance in this study. For instance, a product or a process having a climate change score of 27.75 kg $CO_{2(eq)}$ implies 27.75 times higher than CO_2. MJ measures the amount of energy extracted or needed to extract the resource (Humbert et al., 2012).

3. Results

3.1 LCA Assessment of operational phase

We have compared the environmental impacts of the projected railway and the existing highway, which are planned to be used in different ratios. Figure 3 presents the damage assessment data obtained from LCA modeling for different scenarios.

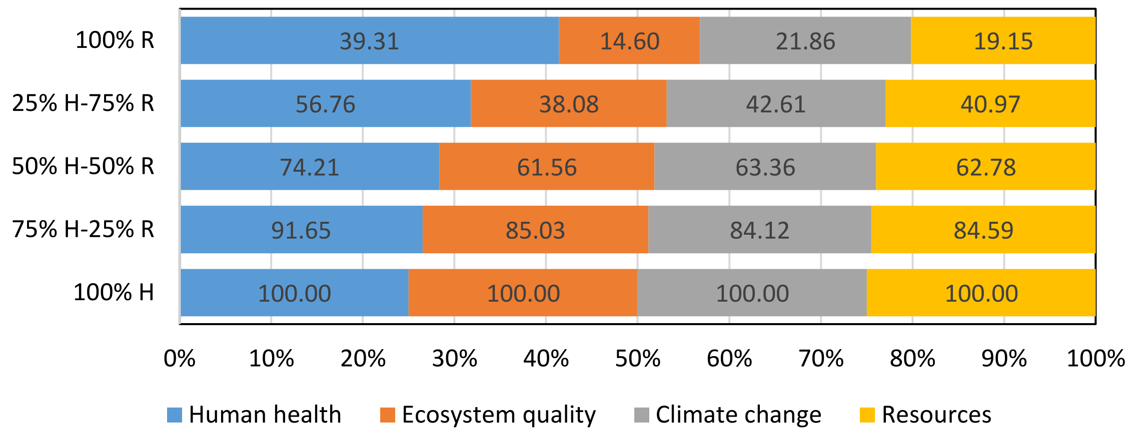

Figure 3. Damage assessment according to scenarios

Due to the highest impacts to the environment occurred in the highway, Scenario-1, in which all the passengers are considered to use the highway for transportation, was accepted as 100%. It can be clearly seen in Figure 3 that the damage ratio decreased with the increasing utilization ratio of the railway. The greatest change was seen in ecosystem quality, in which the reference value of 100% in Scenario-1 decreased to 14.6% in Scenario-5. Although the least change occurred in human health, there was still a major decrease from 100% in Scenario-1 to 39.31% in Scenario-5. Thus, Figure 3 clearly demonstrates that utilization of the railway had significant benefits for human health and the environment.

3.2 LCA assessment of Construction Phase

We also examined the environmental impacts caused by the materials used in the construction of highway and railway, as shown in Figure 4. While the length of the road is 232.6 km, according to the project documents of General Directorate of Highways, the average width of the road is 26 m. Besides, the average thickness of the asphalt is 0.2 m (Maser et al., 2003). The average density of the asphalt is accepted as 2.235 kg/m^3 (Hassani et al., 2005). Thus, according to these values it has been estimated that approximately 2,703,277.2 t of asphalt was consumed for 232.6 km highway construction.

According to the Environmental Case Study datasheet of World Steel Association, a total of 102,000 t steel is consumed for 600 km railway, which means the steel utilization for one km railway is 170 t (WSA, 2015). Besides, concrete sleepers are placed with 60 cm intervals under the railway and one sleeper is approximately 290 kg (Shahraki et al., 2014). Thus, it has been estimated that approximately 1,124,223.3 t of concrete was used for the sleepers and approximately 39,542 t of steel was used for the rails between Kırşehir-Ulukışla.

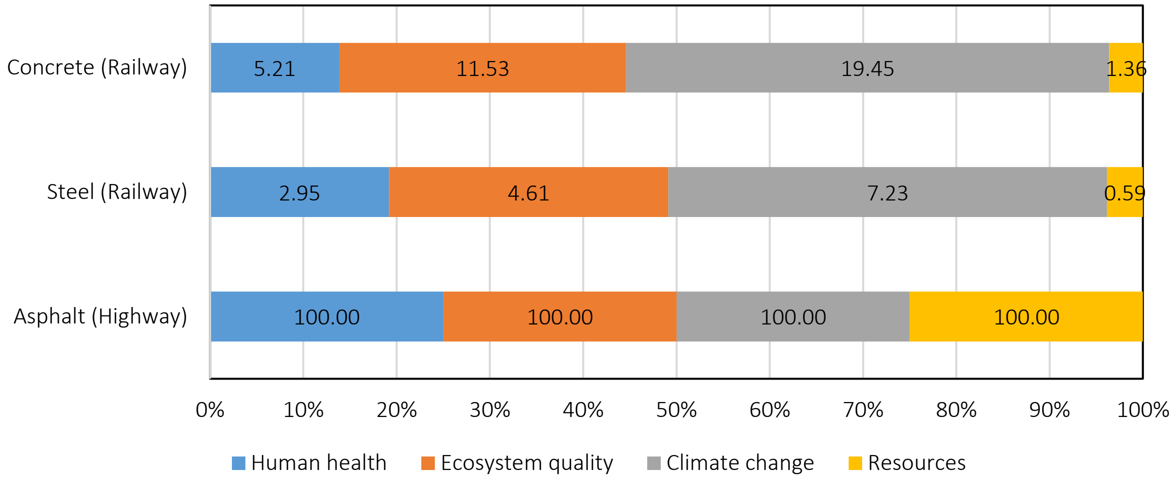

Figure 4. Damage assessment of highway and railway construction materials

A sharp damage reduction was observed construction phase in railway compared to the highway. Damage to resources had the highest damage reduction. The sum of the railway infrastructure made up less than 2% of asphalt damage to resources. The second highest damage decrease was observed for human health and the change was slightly more than 10%. The least reduction was observed for climate change. The reduction of railway infrastructure was approximately one-fourth of the highway infrastructure.

4. Discussion

4.1 Summary of the overall assessment

Table 3 presents the amounts of major and most harmful emissions to air, soil, and water. It clearly shows that the presence of the railroad provided a significant reduction in emissions to air. The increase in the use of the railway line resulted in a reduction in emissions, except for Cr^{+6} and CH_4; however, the use of mixed transport lead to an increase in heavy metal emissions to soil and water. Nevertheless, all emissions, except Hg emissions, to water were decreasing due to the increase of the share of the railway in total transportation and it is minimized in case of 100 % rail use.

Table 3. Emission inventory for air, soil and water under different scenarios.

Air	**100 % H**	**75 % H-25 %R**	**50 % H-50 % R**	**25 % H-75 % R**	**100 % R**	**Unit**
N_2O	106.34	86.58	63.55	40.52	17.49	kg
CO_2	2,092.93	1,977.03	1,306.58	653.29	444.66	t
Cr^{+6}	17.68	41	27.33	13.67	31.58	g
CH_4	2.79	3.12	2.08	1.05	1.07	t
NO_x	9.60	8.73	5.82	2.93	1.59	t
NMVOC	2.11	2.02	1.36	0.68	0.26	t
$PM_{2.5}$	439.24	642.83	428.56	214.28	347.18	kg
SO_2	2.36	3.44	2.31	1.15	1.85	t
Soil						**Unit**
As	0.30	3.90	2.60	1.30	0.87	g
Cd	0.97	2.76	1.84	0.92	0.17	g
Cr	6.89	34.60	23.07	11.53	2.64	g
Pb	38.27	90.46	60.31	30.15	1.57	g
Hg	14.36	41.42	27.61	13.81	0.45	mg
Water						**Unit**
As	0.22	2.55	1.70	0.85	0.49	kg
Cd	0.10	1.04	0.69	0.35	0.16	kg
Cr	45.76	195.42	130.28	65.14	20.76	g
Pb	0.36	2.83	1.88	0.94	0.32	kg
Hg	4.72	64.68	43.12	21.56	16.48	g

Table 3 indicates an encouraging use of railway through a significant reduction in overall emissions. A remarkable decrease is observed in all air emissions, except for Cr^{+6}, with the increasing utilization of railway. The most significant decrease (87.67%) occurred in NMVOC emissions when transportation mode is shifted from 100% H to 100% R. While Pb and Hg emissions to soil reduced drastically by 95.89% and 96.96%, respectively. Likewise, emissions to soil and water increase in case of switching all transportation from highway to railway. The emissions, except for As and Hg, to water tend to decrease in case of the utilization of railway completely. Conversely, the emissions to soil and water increase when the two modes are used together (Table 3). CO_2 emissions were 2,092.93 and 444.66 tons for 100% H and 100% R, respetively. CO_2 emissions from Aksaray landfill in 2017 was 8674 tons (Çetinkaya et al., 2018). The CO_2 emission reduction due to a shift from complete highway utilization to complete railway utilization is eqivalent to 19% of CO_2 emissions relesed from Aksaray landfill.

Our results resemble with those reported by Merchan et al. (2019). In Belgium, road transport was considered as a reference value of 100 % and the railway transportation lead to a 55% performance in damage to the human health damage to the ecosystem diversity, damage to the resource availability and climate change. These rates were calculated as 39.31%, 14.6%, 19.15% and 21.86% in Kırşehir-Ulukışla railway project, respectively. Although the results obtained from both studies are numerically different, it is clear that the railway is more environmentally friendly than the highway.

4.2. Comparison of Construction Phase

Table 4 presents the amounts of major and most harmful emissions occurred during the construction to air, soil, and water. The construction phase is independent of the scenarios. Therefore, the same construction phase emissions occur in each scenario. A number of studies have conducted highway and railway construction from the LCA perspective. However, there are no directly comparable studies for comparison of highway and railway construction. Most studies have evaluated and compared the highway and railway, separately. This is a first study in the best knowledge of the authors in which the construction of highways and railways is investigated in the LCA perspective.

Table 4. Emission inventory for air, soil, and water

Air	Asphalt (Highway)	Steel (Railway)	Concrete (Railway)	Unit

N_2O	7.37	1.29	4.01	t
CO_2	1.08	0.08	0.24	Mton
Cr^{+6}	5.41	0.54	5.97	kg
CH_4	0.46	0.28	0.29	kton
NO_x	8.49	0.20	0.88	kton
NMVOC	5.78	0.14	0.13	kton
$PM_{2.5}$	0	70.72	69.34	ton
SO_2	0	5.80	43.64	kg
Soil				**Unit**
As	0	66.97	287.14	g
Cd	0	24.60	128.81	g
Cr	0	0.38	2.00	kg
Pb	0	0.47	2.90	kg
Hg	0	0.29	1.72	g
Water				**Unit**
As	3.00	0.17	0.37	t
Cd	443.12	38.79	176.10	kg
Cr	24.96	0.002	0.012	t
Pb	6.31	0.27	0.30	t
Hg	10.40	6.44	7.32	kg

Considerably higher greenhouse gas emissions occur during highway construction than railway construction. Based on ICPP AR5 (2013) global warming potentials, highway construction released 1.1 Mton$CO_{2(eq)}$, whereas it is 0.34 Mton $CO_{2(eq)}$ for railway construction, considering both steel and concrete. NO_x and NMVOC emissions are also higher than those of railway construction. However, Cr^{+6} emissions at railway construction are slightly higher than highway construction. No $PM_{2.5}$ and SO_2 emission occur during highway construction. All emissions to soil occur from railway construction. Higher As, Cd, Cr, and Pb emissions are released to water body from highway construction. Only Hg emission is higher in railway construction.

Liu et al. (2017) studied CO_2 emissions for the construction phases of highway projects in China and concluded that the utilization of asphalt in the highway cause 1.92 times more CO_2emissions compared with paved roads. The authors also reported that materials cause 55% of the total emissions, while off-road machinery has a contribution of 45%. Wang et al. (2015) compared the emissions produced during raw material production, material transportation and onsite construction of highways and concluded that 80% of the CO_2emissions were generated during raw material production. The road, bridge, and tunnel constructions were also compared and it was concluded that road construction yielded the least CO_2 production. Moretti et al. (2018) compared the trench and embankment phases of the road construction and identified six transportation scenarios, which consisted of different distances and motorization classifications (Euro 4 and Euro 6). It was concluded that engine classification had the greatest impact on global warming and human toxicity potential. Besides, the majority on the environmental and human health impacts were caused by raw materials and fuel supply and manufacturing phases. Shinde et al. (2018) applied a life cycle analysis on Mumbai Suburban Railway in India and concluded that the construction, coach manufacturing, operation, and maintenance phases were responsible for 218, 147, 5,532 and 270 mg $CO_{2(eq)}$ emissions. Besides, while steel rails were responsible for 53.67% of total CO_2 construction of 1 km track, sleepers were responsible for 33.40%. Banar and Ozdemir (2015) indicated that the construction of lines and operation of train vehicles had the greatest share in global warming and human toxicity category. Although there are no studies comparing the LCA of highway and railway construction phase, it can be concluded from the results that the railway construction is far more environmentally friendly.

3.3 Emission Valuation

When quantitative emissions are known, environmental prices can be used to calculate the environmental damage of the activity or the investment in concern. The quantitative emissions (in kg pollutant) are multiplied by the relevant environmental prices(in cost/kg pollutant) for the valuation process. Therefore, the environmental price for each pollutant can be determined. Environmental prices are indices, which determine the social marginal value of preventing emissions. In this study, the environmental prices of the emissions were gathered from (de Bruyn et al., 2018). Additionally, these costs are useful in explaining the degree of pollution to unprofessional people. Various studies have been implemented in cities that investigate the perception of air pollution in cities (Schmitz et al, 2018). We believe that emission costs stand as a self-explanatory indicator among various parameters. Figure 5 presents the sum of the prices based on various air pollutants under different scenarios.

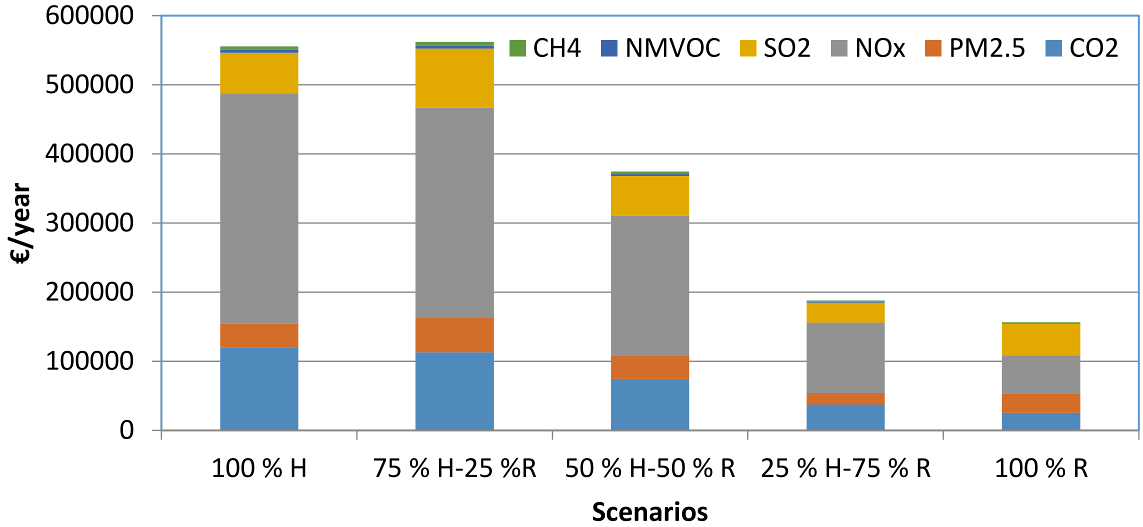

Figure 5. Social cost-benefit analysis of transportation scenarios

The second scenario with 75% H and 25% R had the highest environmental cost with €562,000. The lowest cost belonged to 100% R scenario with €157,000. The difference between the highest and lowest environmental cost scenario is €405,000. This value is considerably lower than the cost of emissions from Atatürk International Airport, Istanbul (Kuzu, 2018), which was €9,420,000.

Under all scenarios, NO_x emissions had the highest monetary contribution share. In the current situation (100% H), NO_x emission share was 60% as opposed to 35% for 100% R scenario. The second highest contribution was from CO_2 emissions for 100% H activities with a 21% share. The scenarios with the combination of highway and railway activities at different portions were very close (20%) to that of 100% H. For 100% R, the share of CO_2 cost was 16%, however, it was the third highest contributor as opposed to the rest of the scenarios. The second and the third highest emission costs were due to SO_2 (29%) and $PM_{2.5}$ (18%), respectively. SO_2 and $PM_{2.5}$ had the highest third and forth share for all scenarios expect 100 % R. 100% H scenario had lower shares for SO_2 (11%) and $PM_{2.5}$ (6%) than the combination of different scenarios for SO_2 (15%) and $PM_{2.5}$ (9%). Nevertheless, the total costs were higher for 100% H scenario (€34,900 for $PM_{2.5}$ and €58,800 for SO_2) than the others (€34,100 for $PM_{2.5}$ and €57,500 for SO_2).NMVOC and CH_4 had 1% share for each pollutant and for each scenario.

The results herein suggest that it is possible to decide for a more environmentally friendly transportation alternative. Thus, low-cost environmental pollution abatement can be applied. These results will guide city planners and local authorities to take action within the context of sustainable cities.

5. Summary and Conclusions

Road transportation has a major fraction in energy demand; as its result in fuel consumption, as well as environmental emissions. Generating investment or operation alternatives create different routes for reaching the target with varying environmental impacts. For such cases, LCA is a useful tool in order to quantitatively analyze the life cycle of activities within an environmental impact perspective. Moreover, social cost-benefit analysis is self-explanatory to the people who are unprofessional to the environmental field. This value, alone, can show how much should be paid to revive the effect of a contaminant. This analysis is endpoint level impacts such as effects on human health, ecosystem, and materials.

We applied LCA and social cost-benefit analysis to an operating highway and a projected HRS through forming different scenarios. The environmental impact was evaluated for both construction and operation phase. The emissions were quantified and then they were expressed in terms of environmental costs. According to LCA results, the damage ratio decreased with the increasing utilization ratio of the railway. A sharp improvement was observed in ecosystem quality. The reference value of 100% decreased to 14.6% for complete highway utilization and complete railway utilization, respectively. Construction phase LCA results show that the highest improvement is expected in terms of resource usage. A significant amount of greenhouse gas reduction occurs in railway construction in comparison with highway construction. The scenario with 75% H and 25% R had the highest environmental cost with €562,000, whereas the lowest environmental damage costs €157,000, which is 100% R. NO_x emissions makes up the highest share for each of the scenarios.

There are 195 countries in the world. Only 27 of these countries boost HSR system. Although the HSR system is present in Turkey, it is in an emerging phase. LCA shows benefits of HRS over the highway from the environmental viewpoint for both construction and operation phase, separately. Although emissions from 100% of railway utilization have the least pollution in amount and environmental effect, and this is already evident from the literature, it is not alone enough to answer the following questions. Does environmental cost reduction of 100% railway option compensate construction costs? If this is the case, in how many years environmental benefit will amortize construction and operating costs? Which option is feasible for both environmental and economic viewpoint? As certain methods are used in the construction of railway and highway, the results of this study will be directly applicable not only for Turkey but also any country can benefit from the research results. Especially, the countries having a comparable population and high-speed railway length can readily benefit from emission values.

Air pollution control of mobile sources differs from stationary sources. Although pollution prevention at stationary can be applied through engineering interventions, the emission reduction of mobile sources is applied through mitigation strategies by policymakers. This study shows strategies of air pollution control towards sustainable cities, bringing benefits to the environment and socio-economic aspects through the use of different transportation methods. The results will also guide to authorities so that they can make the optimum decision for the utilization of sustainable transportation means. Moreover, reducing certain amounts of pollutant mass does not mean anything practical for society. Therefore, it is possible to raise environmental awareness by converting emissions to monetary benefits.

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6. References

Atabani, A.E.,Badruddin, I.A., Mekhilef, S., & Silitonga, A.S. (2011). A review on global fuel economy standards, labels and technologies in the transportation sector. *Renewable and Sustainable Energy Reviews*, 15, 4586-4610.

Azizalrahman, H., & Hasyimi, V. (2018). Towards a generic multi-criateria evaluation model for low carbon cities. *Sustainable Cities and Society*. 39, 275-282.

Banar, M., & Özdemir, A. (2015). An evaluation of railway passenger transport in Turkey using life cycle assessment and life cycle cost methods. *Transportation Research Part D: Transport and Environment*, 41, 88-105.

Chang, B., & Kendall, A. (2011). Life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system. *Transportation Research Part D: Transport and Environment*, 16:(6), 429-434.

Çetinkaya, A.Y., Bilgili, L., & Kuzu, S.L. (2018). Life cycle assessment and greenhouse gas emission evaluation from Aksaray solid waste disposal facility. *Air Quality Atmosphere and Health*, 11, 549-558.

Dalkic, G., Balaban, O., Tuydes-Yaman, H., & Celikkol-Kocak, T. (2017). An assessment of the CO_2 emissions reduction in high-speed rail lines: Two case studies from Turkey. *Journal of Cleaner Production*, 165, 746-761.

deBruyn, S., Ahdour, S, Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., & Vergeer, R. (2018). Environmental Prices Handbook 2017: Methods and numbers for valuation of environmental impacts, CE Delft, Delft, The Netherlands.

Devleesschauwer B.,Havelaar A.H.,Noordhout C.M.,Haagsma J.A.,Praet N.,Dorny P.,Duchateau L.,Torgerson P.R., Oyen H.,& Speybroeck N. (2014). Calculating Disability-Adjusted Life Years to Quantify Burden of Disease. *International Journal of Public Health,* 59:(3), 565-569.

EEA (2017). Air quality in Europe – 2017 report, EEA technical report http://dx.doi.org/10.2800/358908.

European Commission, (2016). A European Strategy for Low-Emission Mobility

European Commission, (2019). Transport Emissions, https://ec.europa.eu/clima/policies/transport_en/ Accessed 22 April 2019

Environmental Impact Assessment (EIA) Report for Kırşehir-Aksaray-Ulukışla Railway Project. Vol. 1. Final EIA Report. (2013). MGS Project Consultancy and Engineering Ltd. Ankara. Turkey.

Gabbe, C.J. (2018). Residential zoning and near-roadway air pollution: An analysis of Los Angeles. *Sustainable Cities and Society*, 42, 611-621.

Gronlund C.J., Humbert S., Shaked S., O'Neill M.S., & Jolliet O. (2015). Characterizing the burden of disease of particulate matter for life cycle impact assessment. *Air Quality, Atmosphere and Health*, 8, 29-46.

Hassani, A., Ganjidoust, H., & Maghanaki, A.A. (2005). Use of plastic waste (poly-ethylene terephthalate) in asphalt concrete mixture as aggregate replacement. *Waste Management & Research*, 23:(4), 322-327.

Heal, M.R., Kumar, P., & Harrison, R.M. (2012). Particles, air quality, policy and health. *Chemical Society Reviews*, 41, 6606-6630.

Huang S., An H., Viglia S., Fiorentino G., Corcelli F., Fang W., & Ulgiati S. (2018). Terrestrial transport modalities in China concerning monetary, energy and environmental costs. *Energy Policy*, 122, 129-141.

Humbert. S., Schryver. A.D., Bengoa. X., Margni. M.,& Jolliet. O. (2012). IMPACT 2002+: User Guide. Draft for version Q2.21 (version adapted by Quantis).

IEA (2019) Key World Energy Statistics, Available at: https://www.iea.org/statistics/kwes/consumption/ Accessed 12 March 2019

IPCC AR5 (2013) Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jolliet. O., Margni. M., Charles. R., Humbert. S., Payet. J., Rebitzer. G., & Rosenbaum. R. (2003). IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. *The International Journal of Life Cycle Assessment*, 8, 324-330.

Kumar, P., Khare, M., Harrison, R.M., Bloss, W.J., Lewis, A., Coe, H., & Morawska, L. (2015). New directions: Air pollution challenges for developing megacities like Delhi. *Atmospheric Environment*, 122, 657-661.

Kumar, P., Andrade, M.F., Ynoue, R.Y., Fornaro, A., de Freitas, E.D., Martins, Martins, J.L.D., Albuquerque, T., Zhang, Y., & Morawska, L. (2016). New Directions: From biofuels to wood stoves: the modern and ancient air quality challenges in the megacity of São Paulo. *Atmospheric Environment*, 140, 364-369.

Kumar, P., Patton, A.P., Durant, J.L., & Frey, H.C. (2018). A review of factors impacting exposure to $PM_{2.5}$, ultrafine particles and black carbon in Asian transport microenvironments. *Atmospheric Environment*, 187, 301-316.

Kuzu, S.L. (2018). Estimation and dispersion modeling of landing and take-off (LTO) cycle emissions from Atatürk International Airport. *Air Quality, Atmosphere and Health*, 11, 153-161.

Kuzu S.L. (article in press). Source identification of combustion-related air pollution during an episode and afterwards in winter-time in Istanbul. *Environmental Science and Pollution Research*, doi: 10.1007/s11356-016-7831-6

Liu, Y., Wang, Y., & Li, D. (2017). Estimation and uncertainty analysis on carbon dioxide emissions from construction phase of real highway projects in China, *Journal of Cleaner Production*. 144:337-346.

Lombardi, L., Tribioli, L., Cozzolino, R., & Bella, G. (2017). Comparative environmental assessment of conventional, electric, hybrid, and fuel cell powertrains based on LCA. *The International Journal of Life Cycle Assessment*, 22(12), 1989-2006.

Mahesh, S., Ramadurai, G., Nagendra, S.M.S. (2018). Real-world emissions of gaseous pollutants from diesel passenger cars using portable emission measurement systems. *Sustainable Cities and Society*, 41, 104-113.

Maser, K.R., Holland, T.J., Roberts, R., Popovics, J., & Heinz, A. (2003). Technology for quality assurance of new pavement thickness. In 82nd Annual Meeting of the Transportation Research Board, Washington DC.

Merchan, A.L., Léonard, A., Limbourg, S., &Mostert, M. (2019). Life cycle externalities versus external costs: The case of inland freight transport in Belgium.*Transportation Research Part D*, 67:576-595.

Moretti, L., Mandrone, V., D'Andrea, A., & Caro, S. (2018). Evaluation of the environmental and human health impact of road construction activities. *Journal of Cleaner Production*, 172, 1004-1013.

SAIC (Scientific Applications International Corporation), (2006). Life cycle assessment: principles and practice. In: EPA/600/R-06/060

Schmitz, S., Weiand, L., Becker, S., Niehoff, N., Schwartzbach, F., & von Schneidemesser, E. (2018). An assessment of perceptions of air quality surrounding the implementation of a traffic-reduction measure in a local urban environment. *Sustainable Cities and Society*, 41, 525-537.

Shahraki, M., Sadaghiani, M.R.S., Witt, K.J., & Meier, T. (2014). 3D modelling of train induced moving loads on an embankment. *Plaxis Bulletin*, 36, 10-5.

Sharma, A., Saxena, A., Sethi, M., Shree, V, & Varun, (2011). Life cycle assessment of buildings: A review. *Renewable Sustainable Energy Reviews*, 15, 871–875.

Shinde, A.M., Dikshit, A.K., Singh, R.K., & Campana, P.E. (2018). Life cycle analysis based comprehensive environmental performance evaluation of Mumbai Suburban Railway, India. *Journal of Cleaner Production*, 188, 989-1003.

Singh, N., Mishra, T., & Banerjee, R. (2019). Greenhouse Gas Emissions in India's Road Transport Sector. In Climate Change Signals and Response (pp. 197-209). Springer, Singapore.

Skrucany, T., Kendra, M., Skorupa, M., Grencik, J., & Figlus, T. (2017). Comparison of chosen environmental aspects in individual road transport and railway passanger transport. *Procedia Engineering*, 192, 806-811.

Stephan, A., & Crawford, R.H. (2016). Total water requirements of passenger transport modes. *Transportation Research Part D: Transport and Environment*, 49, 94-109.

TSR, (2013). Turkish State Railways Annual Statistics 2008–2012. TCDD, Ankara (Originally in Turkish)

UNEP (United Nations Environment Programme). (2006). Background report for a UNEP guide to life cycle management-a bridge to sustainable products

Walpole, S., Prieto-Merino, D., Edwards, P., Cleland, J., Stevens, G.,& Roberts, I. (2012). The Weight of Nations: An Estimation of Adult Human Biomass. *BMC Public Health*, Vol. 12(1). p. 439.

Wang, X., Duan, Z., Wu, L., & Yang, D. (2015). Estimation of carbon dioxide emission in highway construction: A case study in southwest region of China. *Journal of Cleaner Production*, 103, 705-714.

WSA (2015). https://www.worldsteel.org/en/dam/jcr:3ecb07b6-ca04-469e-8f77-b3d27cbb8f7d/Rail%2520case%2520study_2015_vfinal.pdf Accessed 22 April 2019