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Research Article

Life cycle comparison of passenger air and rail transportation

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ABSTRACT

Air transportation has an undisputed speed advantage among all other modes. On the other hand, it is known that the environmental metrics of aviation is quite unsatisfactory compared to other transportation types due to its fuel characteristics and the amount of consumed fuel. However, it would be a wrong choice to rely solely on operational processes to make a true comparison. For this reason, a Life Cycle Assessment (LCA) model should be generated by taking into account processes such as production except the operation process and the calculations should be performed with a comprehensive and holistic perspective. In this study, the environmental impacts of air and rail transport types are compared from the life cycle perspective. For this purpose, first, the emissions in the case of one passenger per one km (pkm) transportation by air and rail were calculated. Then, taking into account the production and disposal processes of the aircraft and passenger trains, the LCA cycle was completed and total emissions were calculated. SimaPro version 9.0.0.49 package program and 1.09 version of ReCiPe 2008 method were used for LCA calculations. With the help of the program, emissions generated during both production and one pkm transportation processes of an aircraft, high-speed and normal train were estimated. Accordingly, the greenhouse gas produced one pkm in air transport was 126.8 g in terms of carbon dioxide equivalent (CO_{2eq}), while CO_{2eq} was 0.3 and 0.31 g for high-speed trains and regular trains, respectively. Considering the production processes, 2072.1, 28.72, and 19.07 t of greenhouse gases are produced, respectively for these three transportation modes.

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INTRODUCTION

In today's society, environmental aspects are important in the transportation sector. The society will presumably change their choice in the transport sector due to changes in the energy/environmental situation in the future [1]. Strategic decisions concerning the development of the transport sector must be based on solid facts concerning both the transport infrastructure and the operation. With the increase in CO_2 emissions, the effects of global warming and climate change, which have accelerated in recent years, have become more evident [2–4]. Understanding the importance of CO_2 provides a new perspective on the discussion of air and rail transport uses [5]. The two transportation modes differ among themselves in terms of supply chain, costs, and energy use. In the literature, each trans-

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portation mode was examined individually and has not been compared to any other transportation mode [6–8]. It is important to examine the passenger air and the rail transportation and to compare them with each other.

The LCA method is used to identify, report, and manage environmental impacts at different stages of the life cycle, starting with the acquisition of raw materials that are used in the production of a product or service, including all relevant production, shipment, use by the consumer and disposal as waste [9–12]. LCA evaluates the entire life cycle of a product or service and their connections with each other. As a result, any environmental impact that may arise in all processes from "cradle to grave" of the product or service being evaluated [13, 14]. The railway system represents one of the most resource-efficient answer to the ever-growing demand for transport service. Development trends for the following years project a substantial increase in this sector. Environmental effects caused by railway transport services have been rarely inspected systematically and existing studies focus on single typologies of environmental aspects, like energy consumption and air emissions [15, 16]. A wide summary of LCA based studies showing the transportation sector was provided by Andreoni et al. [17].

In today's world, the aviation industry is becoming more and more important. While it is important in terms of the benefits it creates, it also contributes especially to air pollution and global warming, a problem that the whole world needs to find a solution [18]. Significant contribution to atmospheric pollution was determined in Istanbul Atatürk Airport in Turkey [19]. Some parameters such as NO_X exceeded the air quality threshold value within airport area. The resources used in aviation sector activities directly affect the lives of living things, cause climate change, and create global externalities. The aircraft industry continues to grow as predicted, so reducing emissions is critical. Aviation is responsible for almost 12% of transport related global CO_2 emissions, having approximately 500 Mt annual CO_2 emission [20]. Global passenger and freight air transportation is expected to grow annually at 3–5% per year rate over the next decades [20].

Therefore, this study evaluates the environmental impacts of the railway and the airline transportation through a life cycle analysis, considering CO_2 emissions from both operations and infrastructure construction. A full LCA was conducted to compare modes of transport in terms of their environmental impact.

MATERIALS AND METHODS

LCA is a method that started to be developed about 50 years ago and is now widely used by many industries. LCA examines the environmental impact of a product or service (or, with widespread use, product system) in a holistic way.

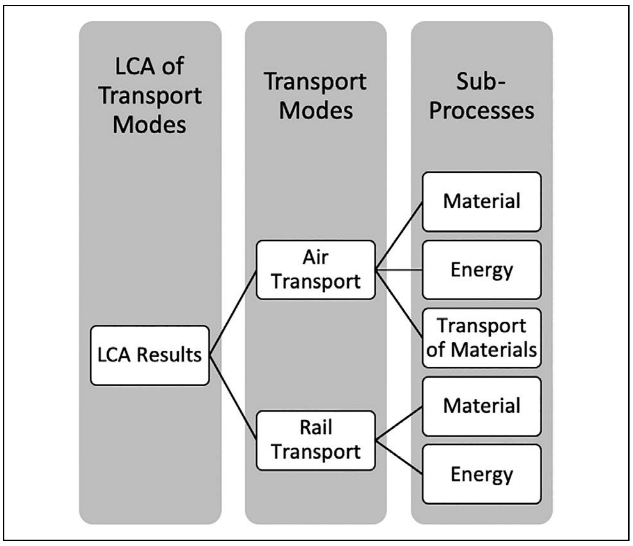


Figure 1. System boundaries.

Unlike traditional methods, the production, transportation, operation, maintenance, and disposal processes of a product system are simultaneously analysed and the results are correlated and then evaluated. This allows a comparison to be made as to which process has a better or worse environmental impact. In addition, thanks to the LCA, a wide variety of previously defined environmental impact categories can be calculated. LCA can also be used to estimate environmental costs [21]. There are many package programs available to make LCA calculations. There are also various methods in these programs. In this study, 9.0.0.49 version of SimaPro package program and 1.09 version of ReCiPe 2008 method were utilised.

In this study, LCA was chosen to make a comparison between product systems and has a holistic perspective on the environmental effects of the product system. The reason for choosing the ReCiPe 2008 method is that it offers up-to-date and comprehensive results. The emissions produced by air transport and regular and high-speed rail transport per 1 pkm, which means the transport of 1 passenger for 1 km, are calculated in this study.

In the calculations of the air transport, the production and operation data of 1 aircraft were used. In the production data; the material consumed during the production, energy and water, and the transportation of the materials by land and rail were considered. In the production data of high-speed and regular train; the production material, the amount of electrical energy and light oil used in production, and the disposal processes of the high-speed train were evaluated. Figure 1 presents the system boundaries for the upstream (manufacturing) processes.

Carbon dioxide (CO_2-biogenic and fossil), carbon monoxide (CO-biogenic and fossil), dinitrogen monoxide (N_2O), waste heat, methane (CH_4-biogenic and fossil), nitrogen

Table 1. Social cost factors (€/kg pollutant)

Pollutant type	Cost factor
CO_2	0.0566
CO	0.0958
N_2O	15
CH_4	1.75
NO_x	34.7
NMVOC	2.1
$PM_{2.5}$	79.5
SO_2	24.9

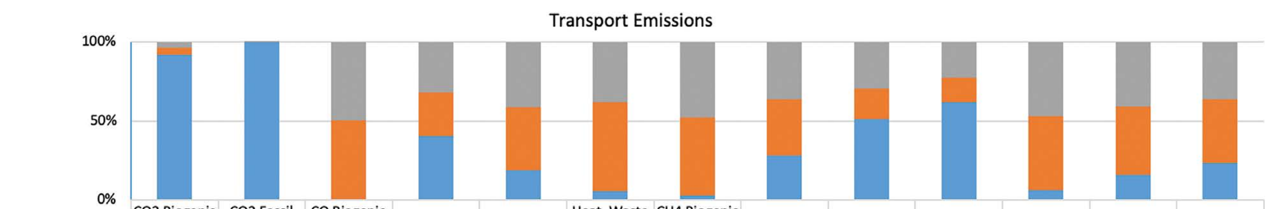
oxides (NO_x), non-methane volatile organic compounds (NMVOC), particulate matter ($PM_{2.5}$), sulphur dioxide (SO_2) and water vapour (H_2O) were calculated in the LCA. Of these gases, CO_2, N_2O, CH_4, and H_2O are the main contributors of global warming [22]. There are findings that waste heat and $PM_{2.5}$ may contribute to global warming [23–27]. In addition, NO_x, $PM_{2.5}$ and CO have adverse effects on human health and the environment [28]. Unlike the others, CO_2, CO, and CH_4 emissions were examined under both biogenic and fossil emission headings. Biogenic emissions are defined as part of the carbon cycle. Therefore, the net value of biogenic emissions is zero, i.e. the amount of emissions produced and used by nature through photosynthesis is equal [29].

In addition to the emission amounts, the social (or environmental) cost, which expresses the cost spent to reduce the environmental damage caused by the emissions, is also included in the calculations. In this way, the economic, as well as environmental, burden of the emissions can be calculated. Social cost factors are taken from Zevenhoven and Beyene [23] and presented in Table 1.

RESULTS AND DISCUSSIONS

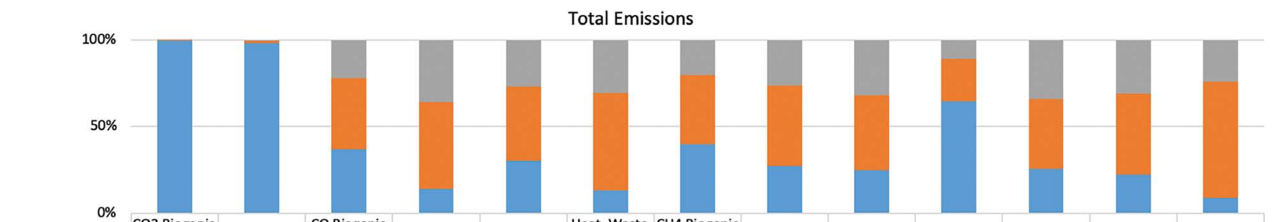
Results obtained as a result of LCA calculations are presented in Figure 2. While Figure 2 includes only the emissions released during the transport process, Figure 3 presents the values obtained as a result of taking the production process into account.

Emissions and waste heat generated during the transport process are quite low for 1 pkm. Figure 2 shows that air transport has higher fossil CO_2 emissions than rail transport. Air transport generates 126.54 g of fossil CO_2 per 1 pkm, while this value is calculated as 0.11 g for rail transport. N_2O and fossil CH_4 production per 1 pkm is higher in railway transportation. Similarly, water vapour production is higher for the rail transportation. However, due to the abundance of CO_2 production, air transport is more unfavourable than the rail transport in terms of greenhouse gas (GHGs) production potential and contribution to global warming. When other emissions are analysed, it



	CO2 Biogenic (g)	CO2 Fossil (g)	CO Biogenic (g)	CO Fossil (g)	N2O (mg)	Heat, Waste (J)	CH4 Biogenic (mg)	CH4 Fossil (g)	Nox (g)	NMVOC (g)	PM2,5 (g)	SO2 (g)	H2O (cm3)
Rail	0,0053	0,12	5,27	0,12	3,01	231,51	5,85	0,18	0,31	0,038	0,06	0,33	108,25
Rail-High Speed	0,0053	0,10	5,34	0,10	2,90	341,53	5,95	0,18	0,20	0,026	0,06	0,35	120,39
Air	0,12	126,54	0,0003	0,15	1,39	34,39	0,37	0,14	0,54	0,11	0,01	0,13	71,11

Figure 2. Transport emissions of air and rail modes.



	CO2 Biogenic (t)	CO2 Fossil (t)	CO Biogenic (t)	CO Fossil (t)	N2O (t)	Heat, Waste (GJ)	CH4 Biogenic (t)	CH4 Fossil (t)	Nox (t)	NMVOC (t)	PM2,5 (t)	SO2 (t)	H2O (m3)
Rail	0,07	13,73	0,07	13,73	0,07	3,10	0,06	5,15	6,50	1,12	2,49	15,08	6852,96
Rail-High Speed	0,12	19,31	0,12	19,31	0,11	5,75	0,11	9,06	8,75	2,57	2,95	22,86	18926,91
Air	30,68	2035,82	0,11	5,46	0,076	1,32	0,11	5,33	5,03	6,76	1,85	10,86	2457,25

Figure 3. Total emissions of air and rail modes.

is observed that there is a balanced distribution. For example, air transport is more dominant in the production of biogenic CO_2, fossil CO, NO_x, and NMVOC, while rail transport produces more biogenic CO, $PM_{2.5}$, and SO_2. The values for high-speed and regular train emissions are generally close to each other. Only waste heat is produced much more by high-speed train.

Figure 3 includes the calculations results of production processes to the transportation emissions shown in Figure 2. Air transport is obviously ahead in fossil CO_2 production, when the production processes are also considered. Although rail transport (especially the high-speed train) produces most of other GHGs (N_2O, CH_4 and H_2O), it is possible to admit that the negative contribution of air transport to global warming is higher than that of rail transport. A relatively balanced distribution is observed in other gases. While rail transport is ahead of air transport in the production of fossil CO, waste heat, NO_x, $PM_{2.5}$, and SO_2, air transport surpassed the rail transport in NMVOC production. Since the data in Figure 3 includes the production values of one plane and train, the pkm unit is no more applicable. Since the production values are very high, the values in Figure 2 have decreased to a negligible level.

Social costs caused from emissions were also calculated by multiplying the social cost factors in Table 1 with the values in Figure 3. Accordingly, the total costs of air transport, high-speed train and regular train were calculated as € 355,109, € 288,059, and € 167,898, respectively. According to these values, air transport performed the worst for the environmental costs.

In one of the studies conducted in 2016, environmental performance comparison of airline and high-speed rail transportation was performed [30]. According to the findings of that study, although the general belief is that the high-speed train operations on the same route are more environmentally friendly than the airline operations, the environmentally friendliness of high-speed train operations generally depends on the source from which the energy is obtained, so a definite conclusion cannot be reached. Results of the present study show that the use of the railroad is clearly more environmentally friendly. On the other hand, if a more comprehensive LCA calculation based on country-based energy production studies is made, changes in results are very likely.

In another study conducted in the same year, a comparison was made between a high-speed train operating in Australia and short-distance air transport [26]. CO_2 production per 1 pkm in 2026 was estimated as 104.5 g and 30.3 g for air transport and high-speed rail transport, respectively. These values include the production, maintenance, and operation of the aircraft and the production, maintenance, operation, and disposal processes of the train. According to the results of the study, using high-speed trains instead of airways in short-distance travels in Australia will provide a great reduction in GHG production [26]. In our study, CO_2 values calculated per pkm for air transport and high-speed train are 126.54 g and 0.1 g, respectively. The common point of both studies is that the high-speed train is more environmentally friendly than the air transport.

CONCLUSIONS

Transportation is one of the principal needs of modern people. Different modes of transportation have been developed to meet different demands. These modes of transport have superior and weak characteristics in various areas. Especially in recent years, with the foundation of the concept of sustainability into daily life, the environmental performance of different transport modes has been questioned extensively. LCA is one of the most frequently used methods in these comparisons due to its holistic perspective.

In this study, air and rail modes for 1 pkm transportation were compared with LCA method in terms of environmental performance. Air transport seems to be ahead of the rail transport, especially in GHG production. Air transportation produces 126.54 g of fossil CO_2 per 1 pkm, while the high-speed train produces 0.1 g and the regular train produces 0.12 g of fossil CO_2. Similar results are obtained when the production process is also considered. When the production of one aircraft and the transportation per 1 pkm are examined together, it is seen that 2035.82 t CO_2 is produced. The same values are 19.31 t and 13.73 t for high-speed and regular train. In addition, it is seen that air transportation produces higher social costs compared to rail transport. On the other hand, while air transportation produces more CO, NO_x, and NMVOC during transportation phase, rail transportation modes cause more of them in terms of total emissions. Besides, rail transportation modes are generally responsible for more emissions.

According to these results, it is concluded that air transportation produced worse results for GHGs and thus, for climate change. However, rail transportation is not as environmentally friendly as it is thought when compared to air transport. On the other hand, despite the comparison of the modes of transportation made within the scope of the LCA, more detailed data on the production, operation, maintenance, and disposal processes are required in order to reach more precise conclusions and judgments. The question of 'which mode gives the best solution for the environment' is not easy to answer and because the results of the study provides a limited outcome for a certain comment, it is of great importance to support further studies with a more comprehensive database.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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