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Research Article

Determination of Environmental Impacts of Commercial Flights During the Landing and Take-off Cycle

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Abstract

The aim of this study is to determine the hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO_x) emissions caused by commercial flights and the global warming potential of these emissions. Environmental effects were calculated for the landing and take-off (LTO) cycles of aircraft and their effects on global warming potential were determined. The environmental impacts of 22 different models of aircraft in the LTO cycle and their impact on global warming potential were calculated. Fuel consumption, HC and CO emissions reached the highest value in the taxi phase. It was determined that NOx emissions reached the highest value in the climb-out phase. It is concluded that HC and CO emissions can be reduced approximately 7% by shortening the taxi time by 2 minutes. It has been calculated that the effect of the climb-out phase on the global warming potential in the LTO cycle is the highest with 40%.

Keywords: Aircraft emission, Global warming potential, Environment effect.

Ticari Uçuşların İniş ve Kalkış Döngüsü Sırasında Çevresel Etkilerinin Belirlenmesi

Öz

Bu çalışmanın amacı ticari uçuşların neden olduğu hidrokarbon (HC), karbonmonoksit (CO), karbondioksit (CO_2), nitrojen oksit (NO_x) emisyonlarının ve bu emisyonların küresel ısınma potansiyelinin belirlenmesidir. Çevresel etkiler hava araçlarının iniş ve kalkış döngüsü için hesaplanmış ve küresel ısınma potansiyeli üzerine etkileri belirlenmiştir. 22 farklı model hava aracının LTO döngüsündeki çevresel etkileri ve küresel ısınma potansiyeline etkisi hesaplanmıştır. Yakıt tüketimi, HC ve CO emisyonlarının taksi fazında en yüksek değere ulaştığı görülmüştür. NO_x emisyonlarının ise tırmanma fazında en yüksek değere ulaştığı belirlenmiştir. Taksi süresinin 2 dakika kısalması ile HC ve CO emisyonlarının yaklaşık %7 azaltılabileceği sonucuna varılmıştır. LTO döngüsünde tırmanma fazının küresel ısınma potansiyeli üzerine etkisi %40 ile en yüksektir.

Anahtar Kelimeler: Hava aracı emisyonları, Küresel ısınma potansiyeli, Çevresel etki.

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1. Introduction

The rapid growth of aviation activities in recent years has led to increase in aircraft operations. Aircraft releases large amounts of exhaust gases into the atmosphere due to fossil fuel consumption during their operations. Aircraft emissions seriously affect local air quality during the landing-takeoff (LTO) cycle. Emissions resulting from the combustion of fossil fuels in the propulsion systems of aircraft throughout their operations are basically; nitrogen oxide (NO2), sulfur oxide (SOx), carbon dioxide (CO_2), carbon monoxide (CO) and hydrocarbons (HCx) [1]. Aviation activities are responsible for 2% of total CO_2 emissions. It is estimated that this rate will increase to 3% by 2050 [2]. Air quality and noise are important environmental problems in living areas close to the airport. It is known that exhaust gases have serious effects on human health and ecosystem. However, it has been proven that these gases contribute to serious environmental problems such as global warming [1,5].

Aircraft operations consist of two modes. The taxi-out, take-off, climb, approach, and taxi-in phases that occur below 3000 feet (914 m) are called the LTO cycle. The climb, cruise, and descent (CCD) phases occur above 3000 feet [3,4]. Emissions released to the atmosphere in the LTO cycle are defined as ground-based emissions. These emissions significantly affect the local air quality around the airport [6,7]. The calculation and reduction of emissions caused by aircraft in the LTO cycle at airports has become an important topic.

The determination and reduction of emissions from aviation in the LTO cycle have attracted the attention of many researchers. Schurmann et al. [8] carried out NO, NO_2, CO and CO_2 measurements at Zurich airport to examine the effects of aircraft on local air quality during idling. Tokuslu [9] calculated NO_x, CO, and HC emissions from aircraft operations at Tbilisi International Airport in 2018. In the calculations for the LTO cycle, NO_x emissions are responsible for 27% and 37% of the total NO_x emissions in take-off and climb mode, respectively. 77% and 70% of CO and HC emissions are produced in taxi mode. One of the most important results of the study is that the reduction in the 2-minute taxi time provides approximately 5% reduction in the emissions released into the atmosphere in the LTO cycle. Orhan [10] determined the pollutant emissions during the LTO cycle at airports. NO_x, CO, and HC emissions were calculated in the LTO cycle and it was determined that HC and CO emissions were higher in the taxi phase. The amount of NO_x released into the atmosphere is higher in the take-off and climb-out phase. Ekici and Sevinc [11] calculated CO, CO_2, HC, and NO_x emissions for the Turkish Airlines fleet with 2018 flight data. In addition, they also determined the total environmental impacts and environmental damage costs in their studies. Kafalı and Altuntas [12] calculated the NO_x, CO, and HC emissions at Dalaman airport using flight data for the years 2016-2018. The emissions per passenger in the study were determined on monthly basis. Ekici and Şöhret [13] investigated the effect of commercial flights on air pollution during the Covid-19 pandemic in Turkey. They determined that CO, CO_2, HC, and NO_x emissions in the LTO cycle decreased significantly during the pandemic.

There are many studies on the reduction of fuel consumption and related pollutant emissions. Optimizing aircraft taxi times directly reduces engine operating time, thus reducing emissions. In the study conducted with 3510 flight data records at London Heathrow airport, the effect of single engine taxiing on emissions was investigated. Fuel consumption and pollutant emissions are significantly reduced by single-engine ground motions. Taxiing with a single engine at airports should be considered by aviation authorities [14]. Analyzes using 3336 flight data showed that reducing take-off thrust reduces fuel consumption by 1% to 23.2%, NO_x emissions by 10.7% to 47.7% and black carbon emissions by 49% to 71.7% [15]. The effects of alternative aviation fuels on pollutant emissions and particulate matter were experimentally investigated by NASA on a CFM56-2C1 engine of a DC-8 aircraft. Although synthetic fuels have a very small effect on engine performance, they significantly reduce emissions [16]. It has been determined with experimental tests that the use of alternative jet fuels with low aromatic content in aircraft engines significantly reduces black carbon emissions [17]. The use of kerosene and liquid hydrogen fuels in aircraft was compared in terms of greenhouse gas emissions. In the comparison made by considering NO_x, HC, and CO emissions, However, there are some difficulties in the use of hydrogen as a fuel in aircraft. Liquid hydrogen requires 4 times larger fuel tanks than conventional jet fuel. The use of hydrogen as aircraft fuel is promising for sustainable aviation [18].

In this study, fuel consumption and pollutant emissions were calculated for 8845 different flights in August, the month with the highest number of flights at Izmir Adnan Menderes airport. In calculations made for 22 different aircraft, fuel consumption, NO_x, CO, HC and CO_2 emissions were calculated for each phase of the LTO cycle. In addition, the global warming potential (GWP) caused by pollutant emissions was also calculated.

2. Material and Method

2.1. Study Area

Adnan Menderes Airport is in Turkey's Izmir province and is among the top five airports in the country in terms of flight traffic and number of passengers. Table 1 presents statistics for the top five airports in Turkey in terms of air traffic and number of passengers in 2019 and 2020. As can be seen from Table 1, it served 76,577 aircraft and 12,365,256 passengers in 2019. The main reason for the decrease in air traffic in 2020 is the restrictions due to the Covid-19 pandemic. The geographical location of Adnan Menderes airport can be seen in Figure 1.

2.2. Methodology

In order to calculate the environmental emissions caused by aircraft in the LTO cycle, the information given below determined respectively.

Type and model of aircrafts

Aircraft/engine configuration

Number of engines

LTO count

The duration of each phase in the LTO cycle

Fuel consumption and emission index (EI) data in the LTO cycle were obtained from the ICAO exhaust emission data bank (EEDB). The emissions caused by aircraft in the LTO cycle can be calculated by equation 1 [19]. The examined aircraft, engine types and LTO count are given in Table 4.

Table 1. Number of flights and passengers in 2019 and 2020

	2019		2020	
Airport	**Commercial Flight**	**Passenger**	**Commercial Flight**	**Passenger**
İstanbul	326,407	52,009,220	178,918	23,410,380
İstanbul Sabiha Gökçen	229,918	35,560,610	122,436	16,951,190
Ankara Esenboğa	90,101	13,740,595	39,774	5,162,569
İzmir Adnan Menderes	76,577	12,365,256	39,838	5,464,858
Antalya	197,379	35,679,421	59,456	9,711,195

Figure 1. Geographical location of İzmir Adnan Menderes Airport

$$E_{i,m} = \sum_a \sum_e n_a I_{a,e} F_{a,e,m} E_{e,m,i} t_{m,a} \quad (1)$$

Where:
n_a: number of engines
a: type of aircraft
i: emission
e: engine type
m: taxi-out phase
F: fuel consumption
t: time in phase
$I_{a,e}$: monthly number of LTO cycles for aircraft a equipped with engine e
$F_{a,e,m}$: fuel consumption for aircraft type a with engine type e in mode m,
$E_{i,m}$: monthly emissions i for phase m
$t_{m,a}$: time in mode m for aircraft type a

The take-off, climb out, approach and taxi (taxi-in/out) times in the LTO cycle are as in Table 2 in ICAO standards. The phases of the LTO cycle are given in Figure 2. In this study, the duration of each phase in the LTO cycle is taken from ICAO standards. In addition, calculations were made by considering the thrust levels accepted by ICAO in each phase.

Table 2. ICAO standards for LTO phases [20]

Operation Mode	Thrust Setting (%)	Time in Mode (min)
Take-off	100	0.7
Climb-out	85	2.2
Approach	30	4
Taxi	7	26

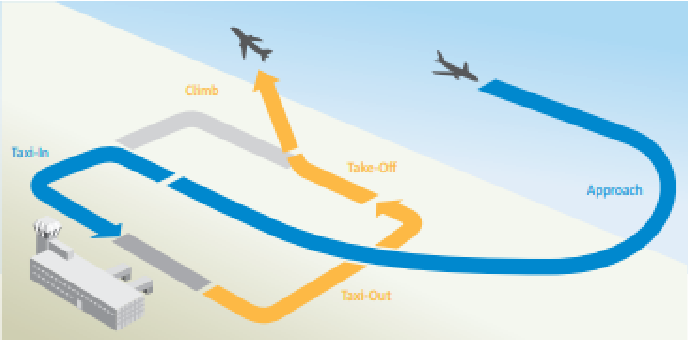

Figure 2. Landing and Take-Off (LTO) cycle [23]

The global warming potential (GWP) caused by emissions in the LTO cycle is calculated by equation 2 [21]. GWP values of pollutant emissions are given in Table 4 [5,22].

$$GWP_{total} = \sum_{i=1}^{i=n} \dot{m}_i GWP_i \qquad (2)$$

GWP total, m_i, GWP_i and i represent the total value of the total GWP, the amount of each pollutant emission, the GWP of each emission and the type of emission, respectively. The CO_2 equivalent (CO_2eq) of each pollutant emission is given in Table 3.

Table.3 CO_2 equivalent of exhaust emissions

Pollutant	**CO_2 equivalent**
HC	21
CO	1
CO_2	1
NO_x	310

Table 4. Aircrafts with engine type and LTO count

Family	**Aircraft**	**Engine type**	**Engine count**	**LTO cycle**
Airbus	A-300-600	CF6-80C2A5	2	43
Airbus	A-310	CF6-80C2A2	2	27
Airbus	A318	CFM56-5B8	2	1
Airbus	A319	IAE V2524-A5	2	126
Airbus	A320	IAE V2527-A5	2	917
Airbus	A321	IAE V2533-A5	2	223
Airbus	A330-200	CF6-80E1A3	2	3
Airbus	A330-300	Trent 772B-60	2	2
Airbus	A340-300	CFM56-5C4	4	1
Boeing	B737-300	CFM56-3B2	2	24
Boeing	B737-400	CFM56-3C-1	2	58
Boeing	B737-500	CFM56-3B1	2	2
Boeing	B737-600	CFM56-7B18	2	2
Boeing	B737-700	CFM56-7B24	2	503
Boeing	B737-800	CFM56-7B26	2	6656
Boeing	B747-400	PW 4056	4	21
Boeing	B747-8	GEnx-2B67	4	1
Boeing	B757-200	PW2040	2	9
Boeing	B767-300	PW4062	2	3
EMBRAER	ERJ-135	AE-3007A3	2	7
EMBRAER	E170	CF34-8E	2	11
EMBRAER	E190	CF34-10E	2	205

3. Results and Discussion

In this study, the environmental effects of the LTO cycle were calculated for 8845 flights of 22 different models of aircraft. CO, CO_2, NO_x, and HC emissions were determined for the taxi, take-off, climb-out and approach phases. In addition, the GWP caused by all these emissions calculated and expressed as CO_2eq. Fuel consumption (FC) related HC, CO and NO_x emissions were calculated for 22 different aircraft in the LTO cycle and presented in Table 5.

Table 5. FC, HC, CO, and NO_x emissions during LTO cycle

Aircraft	FC LTO (ton)	HC LTO (kg)	CO LTO (kg)	NO_x LTO (kg)
A-300-600	74.91	255.04	1201.17	1062.32
A-310	40.68	174.92	775.33	525.37
A318	0.67	1.09	12.85	5.89
A319	108.09	7.72	682.35	1329.96
A320	800.77	59.08	5069.70	9871.02
A321	230.69	15.81	999.52	3855.68
A330-200	5.86	20.63	80.84	115.53
A330-300	4.34	4.19	42.38	70.64
A340-300	2.02	3.90	25.23	34.81
B737-300	20.22	16.20	287.43	202.21
B737-400	52.02	33.27	648.57	558.01
B737-500	1.57	1.67	26.07	14.38
B737-600	1.38	2.20	18.26	13.89
B737-700	414.80	434.92	4022.32	5179.56
B737-800	5864.60	4810.41	47034.40	81849.68
B747-400	68.28	24.20	301.28	1095.63
B747-8	3.49	0.84	14.67	44.32
B757-200	11.25	10.33	115.41	180.44
B767-300	5.37	21.61	87.01	87.33
ERJ-135	2.10	5.05	27.45	18.42
E170	4.97	0.46	47.73	42.67
E190	124.24	349.78	2787.56	1164.48

As seen in Table 5, the aircraft with the highest share in environmental emissions is B738. Table 6 shows the HC, CO and NO_x emissions caused by the aircraft family in the LTO cycle.

Table 6. Total emissions of aircraft families.

Family	FC LTO (ton)	HC LTO (kg)	CO LTO (kg)	NO_x LTO (kg)
Airbus	1268.03	542.37	8889.38	16871.23
Boeing	6442.99	5355.65	5355.65	89225.45
Embraer	131.31	355.28	355.28	1225.57

Fuel consumptions (FC) and related HC, CO, NO_x, and CO_2 emissions for each flight phase in the LTO cycle were calculated in this study. The total fuel consumption of Airbus, Boeing and Embraer family aircraft is 1,268.03, 6,442.99 and 131.31 tons, respectively. The share of each flight phase in the total fuel consumption in the LTO cycle is given in Figure 3. Taxi, climb-out, approach and take-off phases account for 41%, 30%, 18% and 11% of total fuel consumption, respectively.

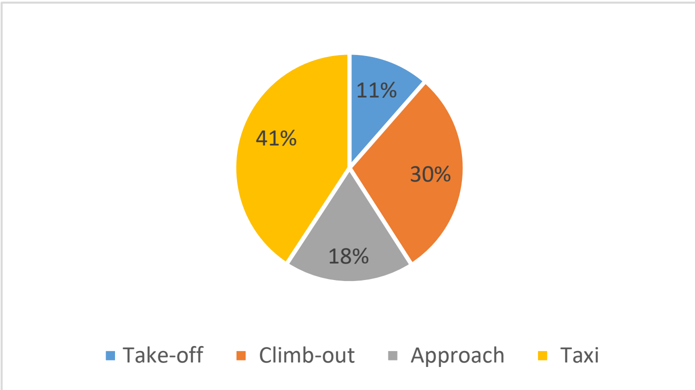

Figure 3. Fuel consumption of phases in LTO cycle

Figures 4 and 5 show the contribution of each phase to the total HC and CO emissions in the LTO cycle. Long taxi-in and taxi-out times cause high environmental emissions along with high fuel consumption. 93% and 94% of the total HC and CO emissions were released into the atmosphere during the taxi phase. The effects of other flight phases on HC and CO emissions are given in Figures 4 and 5. Total shares of take-off, climb-out and approach phases in HC and CO emissions are 7% and 6.38%, respectively.

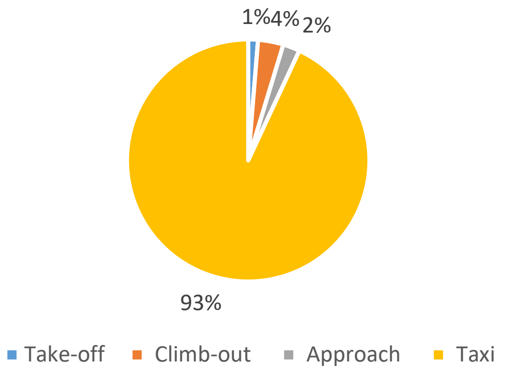

Figure 4. The distribution of HC emissions in LTO

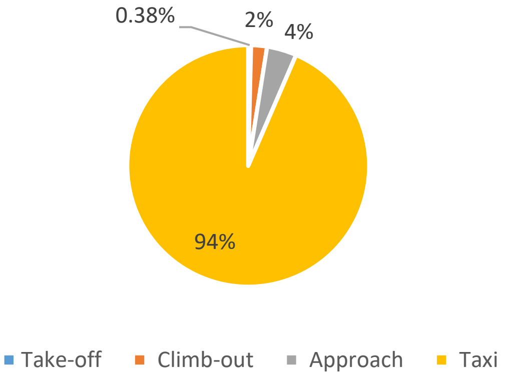

Figure 5. The distribution of CO emissions in LTO

As seen in Figure 6, the share of NO_x emissions in the climb-out phase is the highest with 48%.

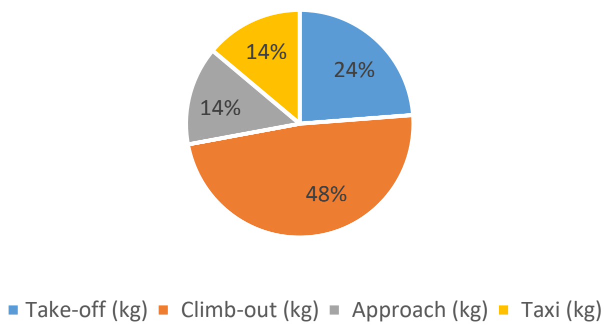

Figure 6. The distribution of NOx emissions in LTO

Table 7. CO_2 emission and GWP during LTO cycle

Aircraft	CO_2 (ton)	CO_2 eq (ton)
A-300-600	*236.71*	*572.59*
A-310	128.54	295.85
A318	2.13	3.99
A319	341.57	754.70
A320	2530.44	5596.77
A321	728.98	1925.58
A330-200	18.50	54.83
A330-300	13.70	35.73
A340-300	6.38	17.28
B737-300	63.89	127.21
B737-400	164.39	338.72
B737-500	4.95	9.47
B737-600	4.35	8.72
B737-700	1310.77	2929.59
B737-800	18532.14	44053.59
B747-400	215.78	556.23
B747-8	11.04	24.82
B757-200	35.56	91.83
B767-300	16.97	44.58
ERJ-135	6.65	12.49
E170	15.70	28.99
E190	392.59	763.71

The share of the take-off phase in NO_x emissions is 24%, while the share of the approach and taxi phases is 14%.

Table 7 shows the amount of CO_2 emissions caused by each aircraft in the LTO cycle and the CO_2eq, which is the measure of the GWP. The Boeing 737-800 LTO caused 18,532.14 tons of CO_2 emissions in LTO cycle. In addition, B737-800 caused 44,053.59 tons of CO_2 equivalent greenhouse gas.

In Figure 7, the contribution of the phases in the LTO cycle to the global warming potential is presented. The phase with the highest GWP is climb-out with 23,382.54 tons of CO_2eq. The phase with the lowest GWP is the approach phase with 9,04.46 tons of CO_2eq.

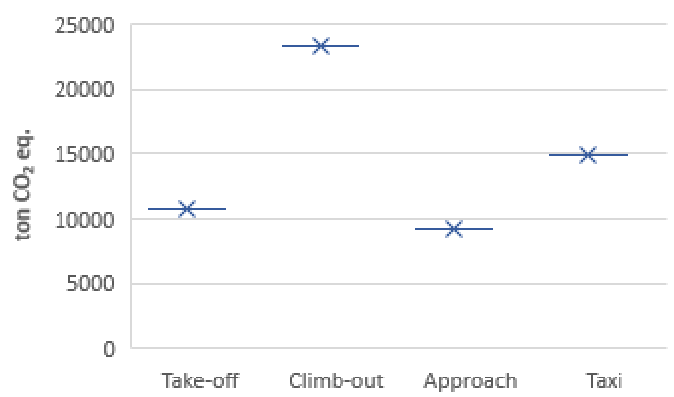

Figure 7. GWP in LTO cycle

In Figure 8, the effects of phases on GWP in LTO cycle are given. The Climb-out phase has the highest GWP of 40%. In the take off phase, this rate is 18%. Take-off and climb out times are much shorter than the other phases, but the higher GWP in these phases is due to NO_x emissions released into the atmosphere at high thrust force.

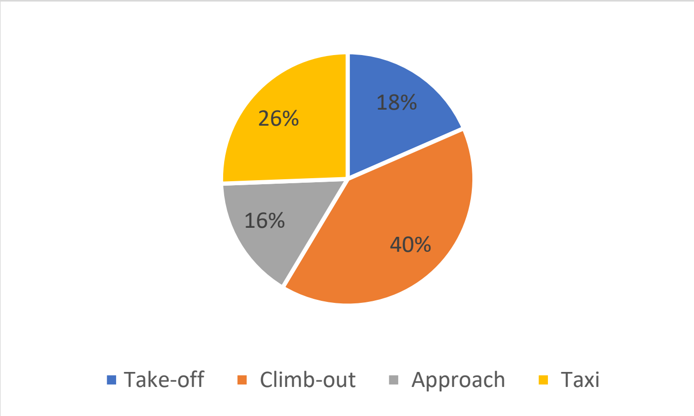

Figure 8. GWP rate in LTO cycle

Fuel consumption and emissions can be reduced by optimizing taxi times at airports. Figure 9 presents the relationship between taxi time and emissions. 2-minute reduction in taxi time contributes to a 7.13%, 7.22% and 1.04% reduction in HC, CO and NO_x emissions, respectively.

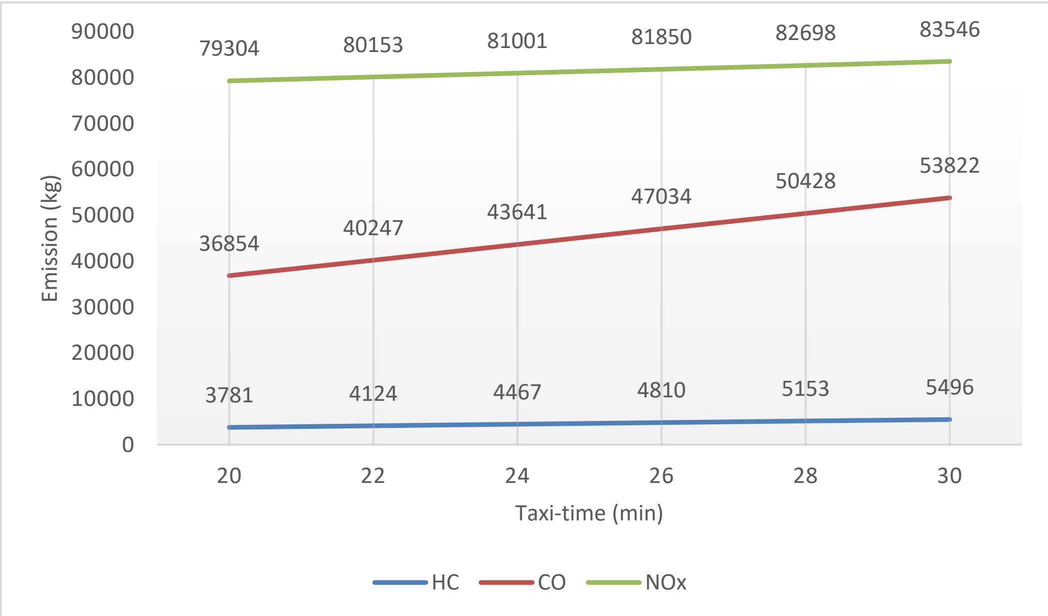

Figure 9. Effect of taxiing time on HC, CO, NOx

4. Conclusion

In the presented study, fuel consumption, pollutant emissions and GWP were calculated in the LTO cycle of aircraft. These parameters were calculated separately for each aircraft and their effects were determined. Total emission amounts is calculated as 6.25 tons for HC, 64.31 tons for CO and 107.32 tons for NO_x. CO_2 emissions due to fuel consumption is determined as 24,781.76 tons. The aircraft with the highest share in fuel consumption and environmental emissions is the B737-800.

The taxi phase is responsible for 93% and 94% of HC and CO emissions. The phase with the highest NO_x emissions is the climb out phase with a share of 48%. In the analyzes carried out on the GWP, the total impact of the emissions has been calculated as 58,247.28 tons CO_2eq. The biggest share in this effect belongs to the climb-out phase with 48%. The fact that the amount of NOx emissions released into the atmosphere is quite high in the climb-out phase causes the GWP to be high in this phase.

Taxi phase has a high share in both consumption and environmental emissions. Therefore, optimizing and shortening taxi times at airports reduces environmental impacts. Reducing the taxi time by 2 minutes provides approximately 7% reduction in HC and CO emissions. In addition, taxi movements with single engine are an important action to reduce environmental emissions. It is also an important parameter for reducing noise. In this respect, it is important for aviation authorities to make regulations on the taxi movements of aircraft with single engine.

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