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TNO report
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Emissions of air pollutants from civil aviation in the Netherlands

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Summary

Air pollutant emissions from civil aviation in the Netherlands are estimated using the CLEO model developed by TNO. The methodology is derived from the almost universally used method of the US Environmental Protection Agency (EPA), which was later applied by the International Civil Aircraft Organization (ICAO) in its measurement protocols for aircraft engines. The model estimates emissions from Landing and Take-Off cycles (LTO) of aircraft, from on-board Auxiliary Power Units (APU), fuelling and fuel handling, Ground Support Equipment (GSE) and wear of tyres and brakes. Aircraft cruise emissions (i.e. all emissions occurring above 3 000 ft.) are not part of the national totals and are therefore not estimated. The main data source used is an annual overview of all aircraft movements by aircraft type at airports in the Netherlands, compiled by Statistics Netherlands. Uncertainties in activity data and emission factors have been estimated and are reported.

The results show that NOx emissions from civil aviation have increased by approximately 140% over the period 1990 – 2015, to almost 3.4 kiloton in 2015. A similar increase can be seen in the fuel use, from 4.5 PJ in 1990 to 10.1 PJ in 2015. Over the same time period, PM_{10} emissions have increased by only 25% to 50 tonnes in 2015. Tyre are brake wear are important sources of PM emissions, having a share of 40% in 2015.
In the period 1990 – 2015, emissions of hydrocarbons (HC) have decreased by 14%, to 380 tonnes in 2015. About 25% of these are fugitive emissions caused by fuelling and fuel handling.
Carbon monoxide (CO) emissions decreased by 4% from 1990 to 2015, to 3.5 kiloton in 2015. It appears that modern aircraft engines emit less PM, HC and CO, but have hardly improved in terms of NOx emissions.

Smaller, piston-engine aircraft fuelled with aviation gasoline, have only a small share in total NOx emissions (<1%), but contribute more significantly to CO (~30%), HC and PM10 (~5%) emissions. Furthermore, aviation gasoline still contains lead in many cases, leading to an estimated 0.8 tonnes of lead emissions in 2015.

Contents

1 Introduction

Civil aviation in the Netherlands comprises both national and international civil aviation, including scheduled and charter flights, passenger and freight transport, helicopter flights, air taxiing and general aviation. Air pollutant emissions from civil aviation result in large part from the combustion of jet fuel (Jet-A) and aviation gasoline (AvGas). Additionally, emissions from auxiliary power units (APU), emissions from ground support equipment (GSE) including ground power units (GPU), particulate matter emissions from tyre wear and brakes, and fugitive emissions from aircraft fuelling and fuel handling are relevant for this sector. Most civil aviation in the Netherlands stems from Amsterdam Airport Schiphol, which is by far the largest airport in the country.

In 2016 TNO revised and merged the EMASA and Vloot2000 emission models, which were used to calculate the emissions of air pollutants for Amsterdam Airport Schiphol and the other Dutch airports respectively. The resulting model, called CLEO (Calculus Luchtvaart Emissies Onder 1000 meter; Calculus Aviation Emissions Below 1000 metres), is described in this report. The emission calculation is also described in the methodology report of the Taskforce on Transportation for the Dutch emission inventory (Klein et al., 2017).

The CLEO model is derived from the almost universally used method of the US Environmental Protection Agency (EPA), which was later applied by the International Civil Aircraft Organization (ICAO) in its measurement protocols for aircraft engines. The model is based on the four flight modes of the Landing and Take-Off (LTO) cycle, which include all aircraft activities below the altitude of 3 000 feet (914 metres). Cruise emissions of air pollutants of domestic and international aviation (i.e. all emissions occurring above 3 000 ft.) are not part of the national totals and are therefore not estimated.

At the time of writing, the CLEO model calculates annual air pollutant emissions for 1990 to present for 18 Dutch airfields and airports, two of which are currently no longer in use. An overview of airports included can be found in Table 2 in the Appendix. Emissions for military airfields or aircraft are not included. Emission results of greenhouse gases such as CO_2 are only indicative and are not used for national reporting purposes. Instead, reported aviation greenhouse gas emissions are calculated using a different methodology based on amounts of fuel delivered to the civil aviation sector.

2 Model and data description

2.1 Annual aircraft movements

The calculation of aircraft LTO emissions is based on the number of annual aircraft take-offs and landings by aircraft type and airport from 1990 onwards. Each LTO cycle consists of 2 aircraft movements (landing and take-off). Data on aircraft movements are gathered from 4 main data sources described below.

The first data source consists of annual statistical data on the number of movements per aircraft type at every civil airport in the Netherlands, compiled by Statistics Netherlands (CBS). This data is available for the years 1995, 2000, 2005 and all subsequent years (CBS, 2016b). Aircraft types are distinguished using their ICAO designator. The model contains a linking table between the ICAO designators and the aircraft types contained in the model (~400 types). This is typically a many-to-one relationship, where the most appropriate aircraft type is linked to a specific ICAO designator. When no appropriate aircraft type exists, it is added to the model.

Unfortunately, in some cases the designator used does not appear on the lists compiled by the ICAO (ICAO, 2016a), in which case it can be uncertain what type of aircraft is referenced to. When a recognizable type designator is used which is not on the ICAO lists (e.g. AG5B likely refers to the American General AG-5B Tiger, although the official designator for this aircraft is AA5), the link can be made manually. When it is not possible to identify the correct aircraft type a default aircraft type is used instead, chosen based on the size of the related airport and type of runway available. When an unknown designator has a very limited amount of flight movements (equal to or smaller than 10 per year), it is not linked to an aircraft type, but instead a correction is applied to the final emissions as explained in section 2.9.

The second source of data are the Schiphol airport annual statistical reports for the years 1990 and 1995 to 2004 (Amsterdam Airport Schiphol, 1990, 1995 - 2004). Since the CBS data is missing most years between 1990 and 2005, additional data on movements per aircraft type is gathered for Schiphol airport, which is the largest airport in the Netherlands. From 2005 onwards, CBS data is used also for Schiphol airport, while the emissions in the years 1991 to 1994 are, at the time of writing, estimated by using the interpolation method explained in section 2.8.

The CBS data holds no information on aircraft movements at Den Helder airport since it is also used as a military airfield. The airport website, however, lists the total annual number of civil aircraft movements (Den Helder Airport, 2016). Since the airport is mainly used for offshore helicopter flights, these movements were divided equally among 4 helicopter types in use with the companies operating from this airport.

The final data source consists of an overview, compiled every year by CBS, on the total annual number of aircraft movements at Dutch civil airports (CBS, 2016a). Although it does not specify aircraft types, it is a complete list for all years from 1990 onwards, and can thus be used for estimating emissions and fuel use for the years missing from the first CBS dataset based on the total number of movements at every Dutch airport. This calculation is explained in section 2.8.

2.2 Aircraft LTO emissions and fuel use

Aircraft LTO emissions are calculated for all 4 stages of the LTO cycle, which together include all aircraft activities near the airport that take place below the altitude of 3000 ft.; taxiing (Idling), starting (Take-off), climbing to 3000 ft. (Climb-out) and descending from 3000 ft. (Approach). Each LTO stage corresponds with specific engine settings (power settings) of the aircraft (Idle: 7%, Take-off: 100%, Climb-out 85%, Approach 30%). These settings have been standardised in a measurement protocol prescribed by the ICAO for measuring aircraft engine emissions, primarily within the framework of certification of larger aircraft engines (ICAO, several years). The power settings result in a specific fuel consumption per unit of time. For each engine type, the fuel consumption results in a specific emission (emission factor per weight unit of fuel). Engine emission factors and fuel use parameters are typically measured and reported for all four LTO phases and may differ significantly between these phases. Cruise emissions of air pollutants of domestic and international aviation (i.e. all emissions occurring above 3000 ft.) are not part of the national totals and are not estimated.

The CLEO model includes data on approximately 400 aircraft types, specifying the engine type, the number of engines, the aircraft maximum take-off weight (MTOW) and, where applicable, the type of APU. Data on the engine type, number of engines and MTOW are widely available on the internet and are gathered through regular internet searches. Data on the APU type is gathered from (Netcen, 2004).

The model contains data on ~530 engine types, including the type (e.g. piston, turbofan, turbojet, turboprop or turboshaft engine), fuel type used (aviation gasoline or Jet-A) and related emission factors and fuel use parameters for every LTO phase. Data on the engine type and fuel type are widely available on the internet. However, since specific aircraft models may be fitted with different types of engines, for larger aircraft the allocation of the aircraft engines to the types of aircraft is based primarily on the aircraft-engine combinations in use by the “home carriers” at Schiphol such as KLM. For smaller (piston-engine) aircraft, the Dutch aircraft register was used to see which type of engine was most often equipped by a certain aircraft type in the Netherlands (Ministerie van Infrastructuur en Milieu, 2016).

Measurement data on engine fuel use and emission factors for NOx, CO and HC are mostly gathered from the ICAO engine emissions databank (ICAO, 2016b), which contains measurements for ~520 engine types. Piston engine emission factors are based on measurement reports by the US EPA and the Swiss Federal Office for Civil Aviation (Rindlisbacher et al., 2007; US EPA, 1985). The emission factors for turboprop engines are taken from a database of the Swedish FFA (FFA, 1996). Emission factors for helicopter engines are based on (Rindlisbacher, 2009) which provides emission factors specified by flight phase for most commercial helicopters that are in use nowadays.

Per group of aircraft engines the PM_{10} emission factors are calculated from ‘Smoke Numbers’ according to the method described in a Eurocontrol report (EEC/SEE/2005/0014, eq. 8, p.69) (Kugele, Jelinek, & Gaffal, 2005). Afterwards the values have been doubled because of the OC-fraction in aircraft-PM (Agrawal et al., 2008).

The emissions of $PM_{2.5}$ and $EC_{2.5}$ are estimated by applying a fraction to the calculated PM_{10} emissions. The fractions used are taken from (Visschedijk, Appelman, Hulskotte, & Coenen, 2007) and are shown in Table 6 in the Appendix.

Emissions of CO_2, lead and SO_2 are directly related to the characteristics of the fuel type used. For jet fuel, emission factors of SO_2 are based on the EMEP/EEA guidebook (EMEP/EEA, 2016). For AvGas, the SO_2 emission factors are based on the Dutch SO_2 emission factors for petrol (Klein et al., 2017). The emission factor for lead is estimated based on the lead content of AvGas 100LL, which is the most commonly used fuel type for piston engines. Note that in recent years unleaded types of AvGas have been introduced which potentially reduce the lead emissions of AvGas fuelled aircraft. However, since there are no statistics available on the use of these unleaded fuels, their inclusion in the model remains a point of improvement. The SO_2 and lead emission factors used can be found in Table 4 in the Appendix.

The time in mode (TIM), i.e. the time spent in the 4 different LTO phases, is dependent on the aircraft type and the airport size. For example, time spent in the idle phase is typically longer for large turbofan aircraft than for helicopters, and is also longer at larger airports, where the taxi distance to the runway is larger.
The duration of the flight modes (except the Idle mode) were derived from the EPA (US EPA, 1985). The average taxi/idle time (Idle) was calculated based on measurements conducted by the airport Schiphol (Nollet, 1993) and the National Air Transport Service (RLD) for taxi times per individual runway combined with the usage percentages per runway. For heavier aircraft (JUMBO class) a separate TIM category was introduced with somewhat longer times for the flight modes Take-off and Climb-out, based on information obtained from the RLD. Estimates on the time spent in every LTO phase are included in the model and can be found in Table 5 in the Appendix.

A simplified structure of this part of the model is visualized in Figure 1.

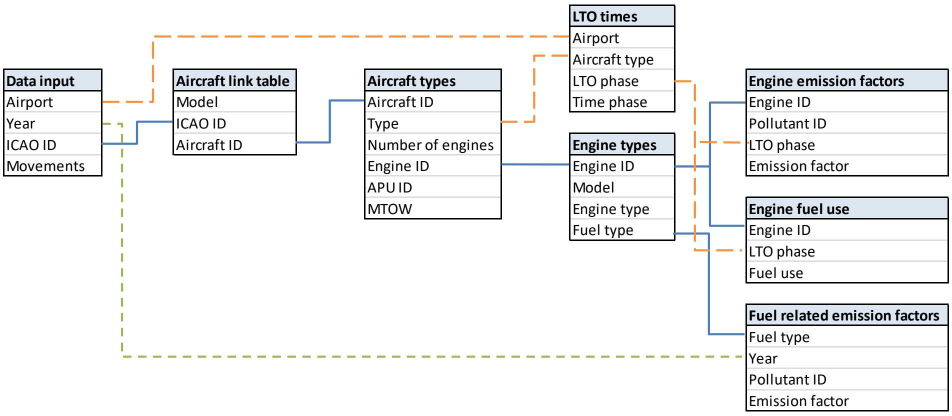

Figure 1: Aircraft LTO emissions and fuel use in the model

Table 3 in the Appendix shows which compounds are calculated for each civil aviation activity.

To calculate the emissions for all LTO stages for every aircraft type and airport, the following equation is used:

$$Emission_y = \sum_{p,m,f} \mathrm{LTO}_{p,m} * N_p * FUEL_{m,f} * TIM_{p,f} * EF_{m,f}$$

Where:

- $Emission_y$ = Emission of a specific substance in a specific year; (kg/year)
- $LTO_{p,m}$ = Number of LTO cycles per aircraft type (p) with engine type (m) per year; (1/year)
- N_p = Number of engines per aircraft (p)
- $FUEL_{m,f}$ = Fuel consumption of engine (m) in flight mode (f); (kg/s)
- $TIM_{p,f}$ = Duration of flight mode (f) for aircraft (p); (s)
- $EF_{m,f}$ = Emission factor of engine (m) per quantity of fuel in flight mode (f); (kg/kg)

2.3 Aircraft APU emissions and fuel use

Larger aircraft with a significant amount of on-board electronics and air conditioning equipment typically have an auxiliary power unit installed to provide electricity when the aircraft is on the ground. An APU consists of a small gas turbine, often mounted in the tail of the aircraft, and is fuelled by Jet-A. APU emissions may be considerable since aircraft often spend a significant time on the ground between flights. Data on the type of APU installed on different aircraft types is taken from (Netcen, 2004), while emission factors and fuel use for these APU types were taken from (Netcen, 2004) and (KLM, 2016). APU emissions are only calculated for the large airports.

The APU running time between landing and take-off may differ per aircraft type and airport. To limit APU emissions, several airports limit the allowed running time of APU's and require aircraft to use fixed electricity connections (gate power) and preconditioned air instead. For the large airports except Schiphol, a default running time of 45 minutes per LTO cycle is assumed based on the value for short-haul aircraft operation in the ICAO airport air quality manual (ICAO, 2011). Especially Schiphol airport has introduced gate power equipment and stricter rules concerning APU use. Since this is also the largest airport, the model includes year dependent APU running times for Schiphol Airport. The estimated running time is 45 minutes for years until 2010 and is then assumed to reduce linearly to 20 minutes in 2015, which is slightly higher than the 15 minute estimate for aircrafts with gate power in (ICAO, 2011) to account for the fact that not all gates at Schiphol airport have been equipped with gate power.

APU emissions for the applicable aircraft types are calculated using the following equation:

$$Emission_y = \sum_{apu} \mathrm{LTO}_{apu} * FUEL_{apu} * TIME_{airport} * EF_{apu}$$

Where:

- $Emission_y$ = Emission of a specific substance in a specific year; (kg/year)
- LTO_{apu} = Number of LTO cycles per APU type per year; (1/year)
- $FUEL_{apu}$ = Fuel consumption of APU; (kg/s)

- $TIME_{airport}$ = Duration of APU use per LTO at airport; (s)
- EF_{apu} = Emission factor of APU per quantity of fuel; (kg/kg)

A simplified structure of this part of the model is visualized in Figure 2.

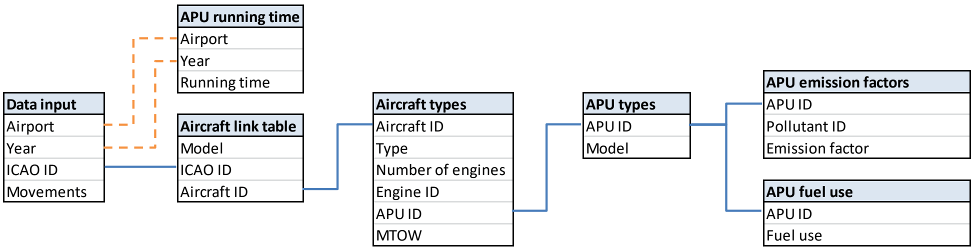

Figure 2: APU emissions and fuel use in the model

2.4 GSE emissions and fuel use

Airport ground support equipment exists mainly of GPU's, but also includes aircraft tractors, de-icing equipment, stairs and belts, loaders and transporters, water and service trucks, cars, vans and busses. GSE typically runs on diesel fuel. Data on the fuel use and emission from the GSE at Schiphol Airport is received annually from KLM Equipment Services for years 1996 onwards (Feldbrugge, 2014). For earlier years, the 1996 emission factors are used and fuel use is scaled to the total MTOW of aircraft taking-off and landing at the airport.
For the other large airports (Eindhoven, Rotterdam, Lelystad, Groningen and Maastricht), the GSE fuel use is estimated based on the total MTOW. Since GSE is mostly needed for larger aircraft, only aircraft with an MTOW larger than or equal to 6 tonnes are counted towards the total MTOW. A factor of 0.41 litre diesel per tonne MTOW is assumed, which is an average calculated based on Schiphol airport. GSE emission factors are estimated by dividing the emissions reported by KLM equipment services through the diesel use reported. The implied emission factors (IEF) for GSE are given in Table 7.

GSE emissions are calculated using the following equation:

$$\boxed{Emission_y = MTOW_{total} * Fuel_{GSE} * Density_{diesel} * IEF_{GSE}}$$

Where:

- $Emission_y$ = Emission of a specific substance in a specific year; (kg/year)
- $MTOW_{total}$ = Total summed MTOW per airport; (tonne/year)
- $FUEL_{GSE}$ = Fuel consumption of GSE; (l/tonne MTOW)
- $Density_{diesel}$ = Density of diesel (0.84); (kg/l)
- IEF_{GSE} = Implied emission factor of GSE per quantity of fuel; (kg/kg)

2.5 Fuelling and fuel handling emissions

A small amount of fuel may escape as fugitive hydrocarbon emissions when fuelling aircraft or handling aircraft fuels. These emissions are calculated only for Schiphol airport.

Data on fuel handling and related emissions was received in the past from AFS B.V., the company that handles aircraft fuelling at Schiphol airport (AFS, 2013). Based on this data, annual emission factors per cubic meter (m^3) of fuel handled have been calculated. The total amount of fuel handled is extrapolated based on the annual number of aircraft movements at Schiphol airport.

2.6 Tyre wear emissions

Landing aircraft causes wear of the aircraft tyres, resulting in both coarse and fine particulate matter emissions. The amount of wear and emission is mostly related to the weight of the aircraft and is therefore calculated through the aircraft MTOW. The emission factors per MTOW are gathered from (Morris, 2007) and are listed in Table 8. Tyre wear emissions are not calculated for helicopters since they land vertically.

The particulate matter emissions from tyre wear per aircraft are calculated using the following equation:

$$\boxed{Emissions_y = MTOW_y * EF_{tyre}}$$

2.7 Brake wear emissions

In addition to tyre wear, landing aircraft also requires strong braking, associated with wear of the brakes and related PM emissions. Similar to tyre wear emissions, brake wear is mostly dependent on the weight of the aircraft and is thus also calculated through the aircraft MTOW. Brake wear emissions are not calculated for helicopters since they do not use wheel brakes during landing. The emission factors per MTOW are gathered from (Morris, 2007) and are listed in Table 8.

The particulate matter emissions from brake wear per aircraft are calculated using the following equation:

$$\boxed{Emissions_y = MTOW_y * EF_{brake}}$$

2.8 Interpolation of emissions

As explained in section 2.1, CBS data does not list the number of movements per aircraft type for the years 1990 – 1994, 1996 – 1999 and 2001 – 2004. Therefore, the emissions in these years are interpolated through scaling with data on total number of aircraft movements. For Schiphol airport, this method is only used to calculate emissions for the years 1991 – 1994, since annual reports are used to complement CBS data. For Den Helder airport, a complete time series is available from their website, so no interpolation is applied.

The interpolation is performed by first calculating a scaling factor: the ratio of total aircraft movements between the target year and a reference year for each airport using data from CBS. This scaling factor is then multiplied by the emissions in the reference year to calculate the emissions for the target year.

$$\boxed{Interpolated\ emissions_{ty,a} = Emissions_{ry,a} * \frac{LTO_{ty,a}}{LTO_{ry,a}}}$$

2.9 Correction for aircraft movements with unlinked ICAO designators

As described in section 2.1, not all designators used could be successfully linked to an aircraft type in the model. This means that for a small number of aircraft movements, no emissions are calculated initially.
To correct for this, the ratio between total movements reported and the number of movements with linked aircraft types is calculated. This correction factor is then applied to the annual emissions at each airport.

$$\boxed{Corrected\ emissions_{y,a} = Emissions_{y,a} * \frac{LTO_{y,a,total}}{LTO_{y,a,linked}}}$$

2.10 Uncertainties and future improvements

Based on an expert session on transport emission uncertainties, the uncertainties that have been estimated for the civil aviation sector in the Netherlands are shown in Table 1. Some emissions are not relevant for a specific source and have not been quantified (n.q.).

Table 1: Uncertainties civil aviation (95% uncertainty range)

Type	Fuel	Uncertainty activity data	Uncertainty emission factor						
			NOx	SOx	NH_3	PM_{10}	$PM_{2.5}$	$EC_{2.5}$	NMVOC
LTO	Jet fuel	10%	35%	50%	n.q.	100%	100%	100%	200%
LTO	Aviation gasoline	20%	100%	50%	n.q.	100%	100%	100%	500%
APU	Jet fuel	50%	35%	50%	n.q.	100%	100%	100%	200%
Fuelling and fuel handling		10%	n.q.	n.q.	n.q.	n.q.	n.q.	n.q.	100%
GSE	Diesel	10%	50%	20%	200%	100%	100%	100%	n.q.
Tyre wear		10%	n.q.	n.q.	n.q.	n.q.	100%	n.q.	n.q.
Brake wear		10%	n.q.	n.q.	n.q.	n.q.	100%	n.q.	n.q.

The following points for future improvement have been identified:

- There is a lack of reliable data on the share of unleaded AvGas that is used annually at airports in the Netherlands. Data on the use of unleaded AvGas types could be used to improve the calculation of lead emissions.
- APU running time for all years and all airports has been estimated based on a number of literature values. Year and airport specific data on APU running time could be used to improve the APU emissions calculation.
- The values of time-in-modes for various aircraft types may have changed in years due to other configurations of the airport(s) or changed flight procedures (for instance Continuous Descent Approach (CDA) that has been introduced gradually and causes fewer emissions during Approach). Current time-in-mode values should be re-evaluated.
- In general more accurate data on engine load and time-in-mode could be taken from real flight data. Together with a more accurate calculation of fuel flow, like the Boeing method 2, more accurate emission data can be calculated.

3 Results

This chapter gives an overview of the emissions as calculated by the CLEO model for the different airports in the years 1990 – 2015. Table 9 in the Appendix shows the fuel consumption for the different aircraft activities.

Figure 3 shows the NOx emissions from Amsterdam Schiphol Airport by source. The combustion of jet fuel during the LTO cycle is the dominant source of NOx emissions with almost 3 000 tonnes in 2015. While NOx emissions from GSE and APU's are slowly declining, emissions from LTOs are still rising.

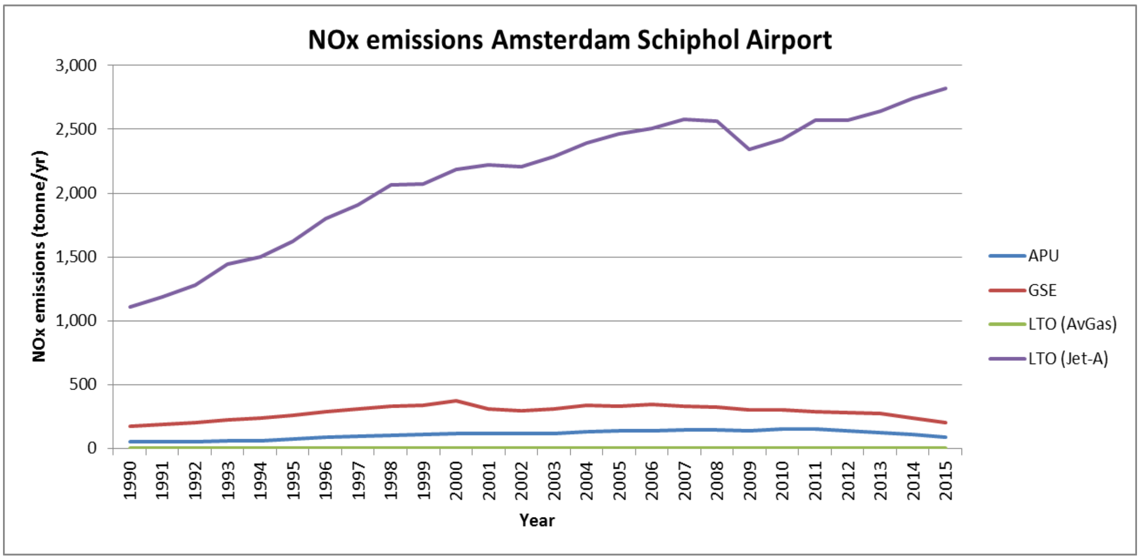

Figure 3: NOx emissions at Amsterdam Schiphol Airport by source

Figure 4 shows the emissions of PM_{10} at Amsterdam Schiphol Airport. The most important sources are the GSE and LTO cycles of jet fuel aircraft. Despite increasing flight movements, PM_{10} emissions from LTOs have remained relatively stable over time. Apparently, aircraft engine manufactures have succeeded in limiting PM_{10} emissions but have had fewer success in limiting NOx emissions from aircraft engines.

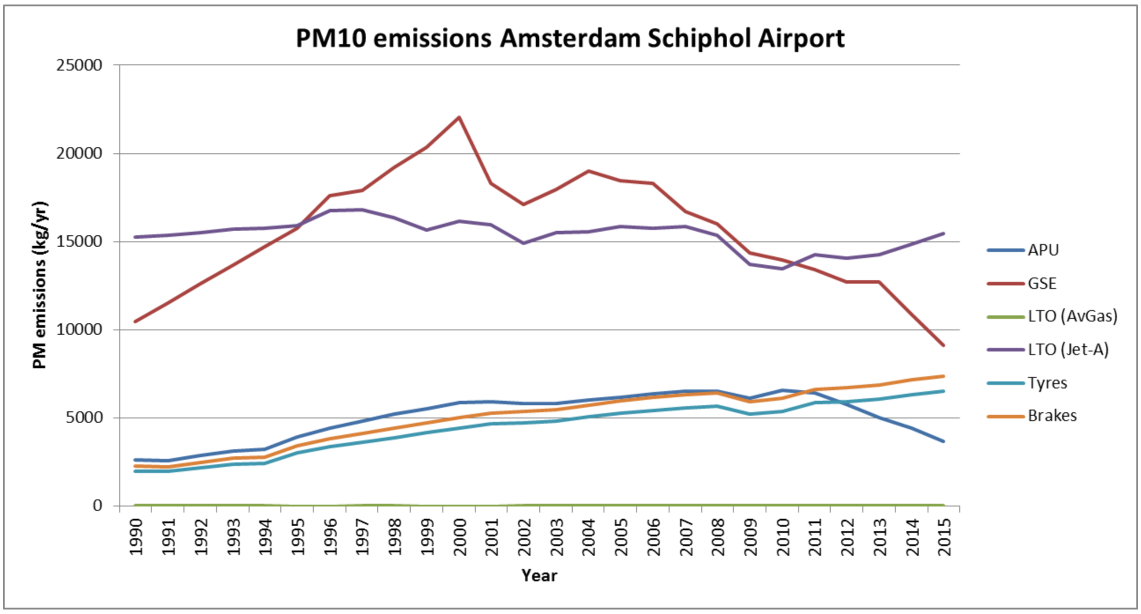

Figure 4: PM_{10} emissions at Amsterdam Schiphol Airport by source

Emissions of hydrocarbons at Schiphol Airport are shown in Figure 5, differentiated by source. The emissions from aircraft fuelling and fuel handling are significant, but have been reduced since 2012 when a kerosene vapour processing system was installed to limit emissions (AFS, 2013). The largest source of HC emissions stems from the idling/taxiing stage of the LTO cycle, when the aircraft engines run at low power load.

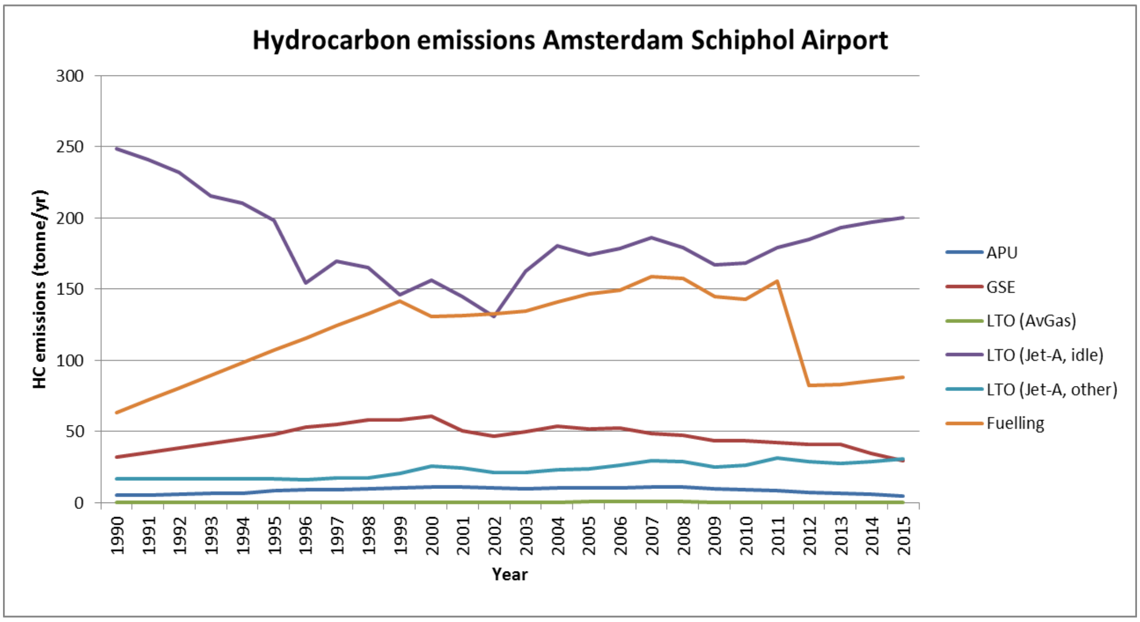

Figure 5: Hydrocarbon emissions at Amsterdam Schiphol Airport by source

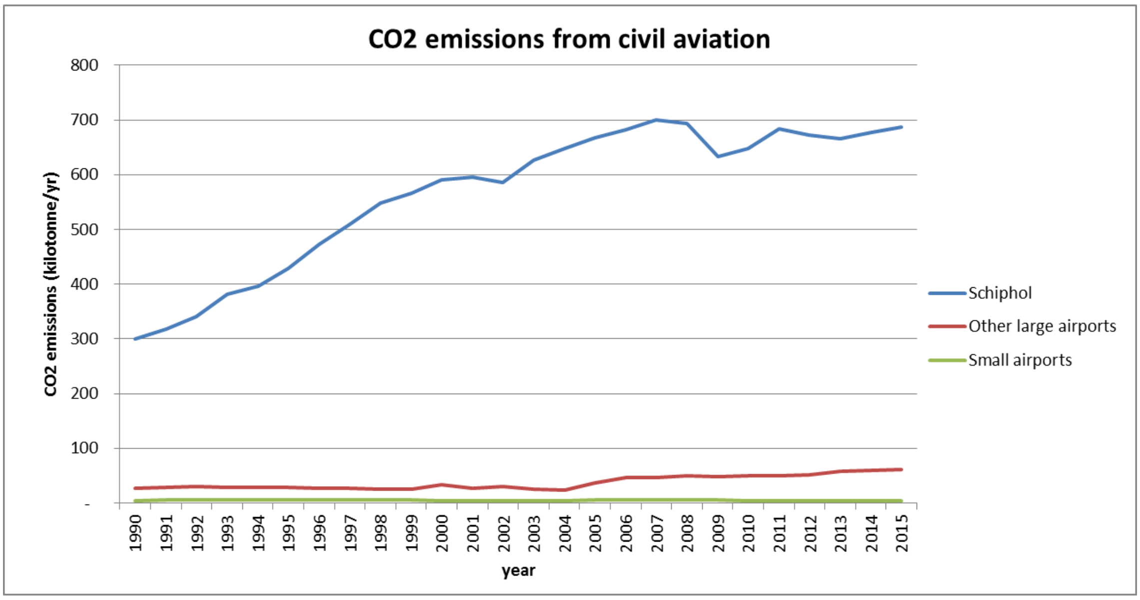

Figure 6: CO_2 emissions from civil aviation

Figure 6 shows the CO_2 emissions of Schiphol and the other large and small airports combined. Eindhoven airport is responsible for the largest share of the CO_2 emissions and increase among the other large airports. Note that these results are not used in the national reporting since the greenhouse gas emissions of aviation are calculated using a different methodology.

Many types of aviation gasoline are still leaded, making civil aviation one of the largest sources of air emissions of lead since leaded car fuels have been phased out. Lead emission at the larger and smaller airports are shown in Figure 7. Since jet fuel does not contain lead, the emissions at small airports are at times higher than those at larger airports where the use of AvGas is limited.

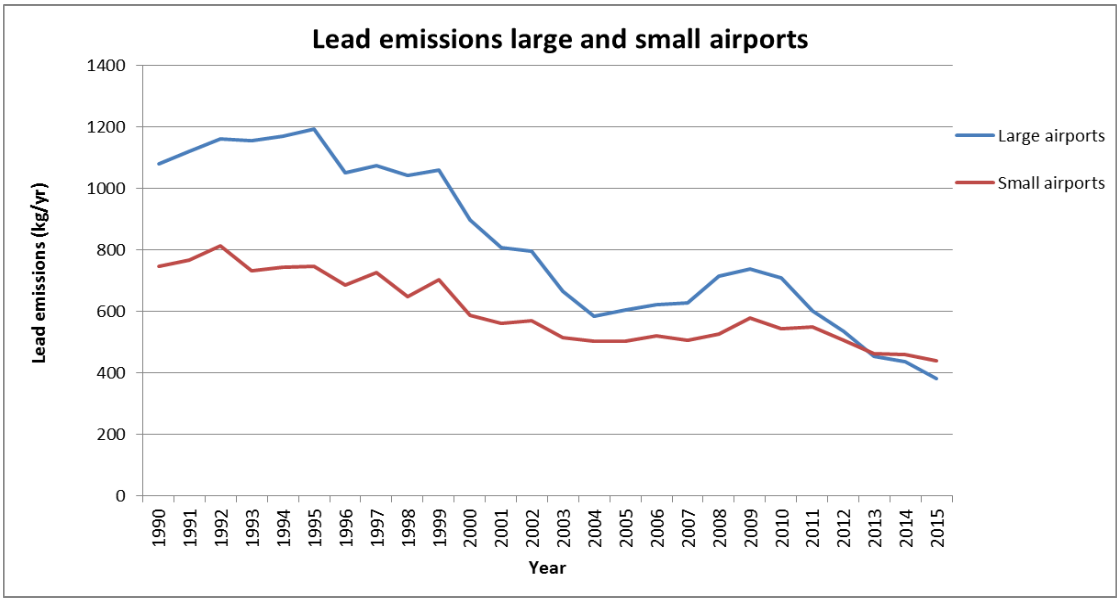

Figure 7: Lead emissions at large and small airports

From Figure 8 it becomes clear that Schiphol airport is by far the most important in terms of NOx emissions. However, note that while Schiphol and Rotterdam airport increased their emission by more than a factor 2 over the period 1990 – 2015, Eindhoven airport has seen a remarkable growth resulting in NOx emissions that are almost 20 times higher in 2015 than in 1990.

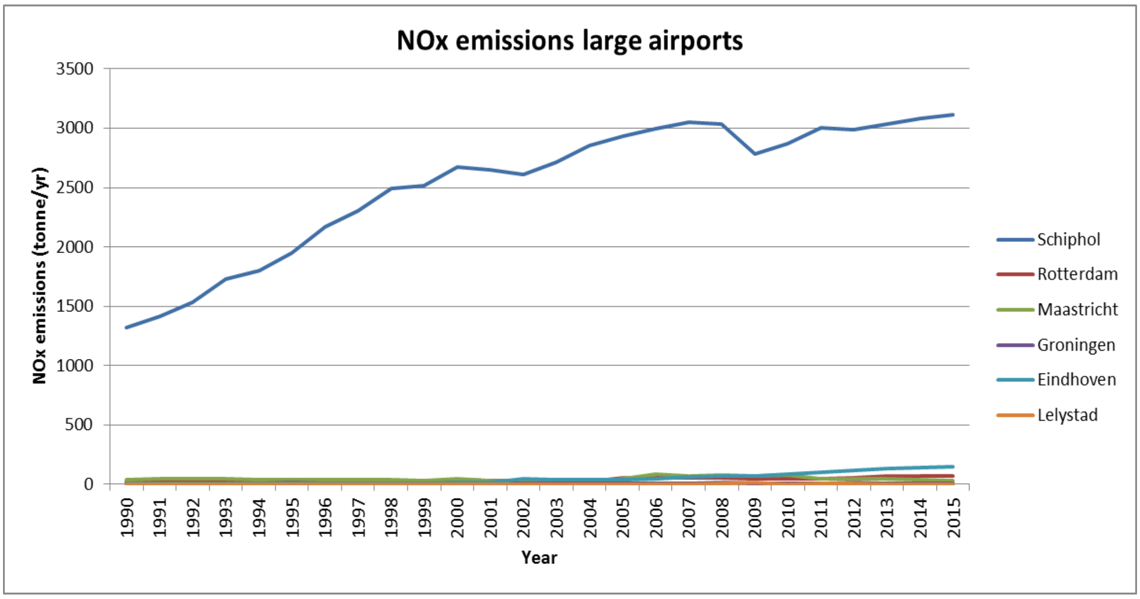

Figure 8: NOx emissions at large airports

Figure 9 shows the emissions of NOx, PM_{10}, CO and HC from all airports and civil aviation activities as calculated by the CLEO model. Emissions of NOx and PM have increased over time and continue to rise.

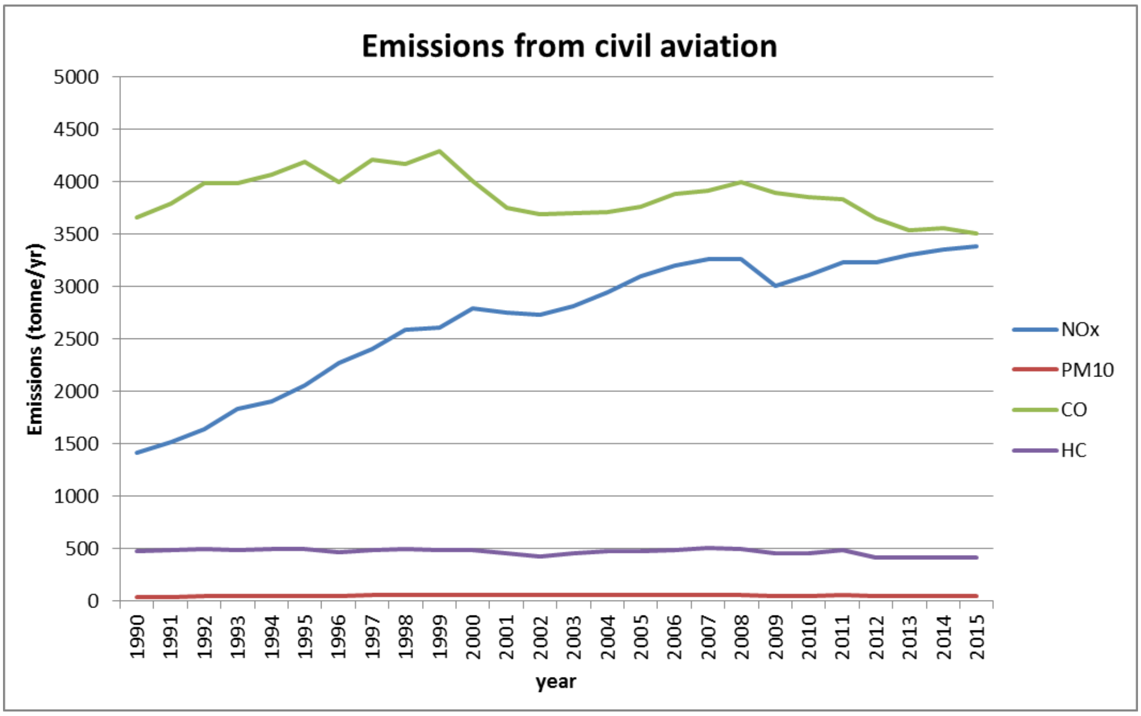

Figure 9: Emissions civil aviation

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5 Signature

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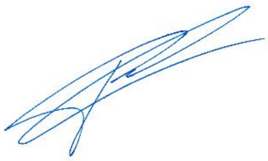

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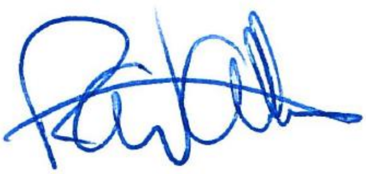

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Appendix

Table 2: Airports included in the model

Airport	Size category
Amsterdam Schiphol	Large
Rotterdam	Large
Maastricht	Large
Lelystad	Large
Eindhoven	Large
Groningen Eelde	Large
Hilversum	Small
Twente	Small
Budel	Small
Den Helder, De Kooy	Small
Hoogeveen	Small
Midden-Zeeland	Small
Noordoostpolder	Small
Seppe	Small
Teuge	Small
Texel	Small
Drachten	Small
Ameland	Small

Table 3: Selection of substances per activity and airport

Compound	Activity	Airports
CO_2, CO, NOx, SOx, N_2O, $EC_{2.5}$	LTO	All
	APU	Large
	GSE	Large
CxHy	LTO	All
	APU	Large
	GSE	Large
	Fuelling	Schiphol
Lead	LTO	All
NH_3	GSE	Large
$PM_{(10)}$, $PM_{2.5}$	LTO	All
	APU	Large
	GSE	Large
	Tyres	Large
	Brakes	Large
Coarse dust	Tyres	Large

Table 4: Emission factors SO_2 and lead (g/kg fuel)

	SO_2		***Lead***
Year	**AvGas**	**Jet-A**	**AvGas**
1990	0.48	1.00	0.777
1991	0.42	1.00	0.777
1992	0.38	1.00	0.777
1993	0.32	1.00	0.777
1994	0.26	1.00	0.777
1995	0.20	1.00	0.777
1996	0.14	1.00	0.777
1997	0.14	1.00	0.777
1998	0.14	1.00	0.777
1999	0.14	1.00	0.777
2000	0.14	1.00	0.777
2001	0.10	1.00	0.777
2002	0.12	1.00	0.777
2003	0.06	1.00	0.777
2004	0.06	1.00	0.777
2005	0.04	1.00	0.777
2006	0.04	1.00	0.777
2007	0.04	1.00	0.777
2008	0.02	1.00	0.777
2009	0.02	1.00	0.777
2010	0.02	1.00	0.777
2011	0.02	1.00	0.777
2012	0.02	1.00	0.777
2013	0.02	1.00	0.777
2014	0.02	1.00	0.777
2015	0.02	1.00	0.777

Table 5: TIM times during various LTO flight phases (seconds)

Schiphol	**JUMBO** [1)]	**TF** [2)]	**TP** [3)]	**TPBUS** [4)]	**TFBUS** [5)]	**HELI** [6)]	**PISTON** [7)]
Take-off	56	34	30	30	24	0	18
Climb-out	120	100	150	150	30	390	300
Approach	240	240	270	270	96	390	270
Idle (until 2002)	1015	1015	1015	1015	780	420	960
Idle (from 2003, 5th runway into operation)	1229	1229	1229	1229	780	420	960
Other airports	**JUMBO** [1)]	**TF** [2)]	**TP** [3)]	**TPBUS** [4)]	**TFBUS** [5)]	**HELI** [6)]	**PISTON** [7)]
Take-off	56	34	30	30	24	0	18
Climb-out	120	100	150	150	30	390	300
Approach	240	240	270	270	96	390	270
Idle	760	760	760	760	760	420	600

The TIMCODE's have been applied to the following aircraft types:
[1)] JUMBO = wide-body planes (Boeing 747, DC10, MD11 etc.)
[2)] TF = other commercial aircraft with turbofan engines
[3)] TP = commercial aircraft with turboprop engines
[4)] TPBUS = business planes with turboprop engines
[5)] TFBUS = business planes with turbofan engines
[6)] HELI = helicopters
[7)] PISTON = general aviation with piston engine

Sources:
The flight phase times (except for the Idle-phase) were derived from (US EPA, 1985).

The average taxi/idle time (Idle) has been determined on the basis of accurate measurements at the various airports (Nollet, 1993) and the Dutch Civil Aviation Authority concerning taxi times per separate runway combined with use figures (%) per runway.

Table 6: Particulate matter profiles for aircraft activities

	Share in PM_{10} (%wt)	
	$PM_{2.5}$	$EC_{2.5}$
Combustion of jet fuel	100	75.4
Combustion of aviation gasoline	100	75.4
Combustion of diesel	95	48.9
Brake wear	15	0
Tyre wear	20	0

Source: (Visschedijk, Appelman, Hulskotte, & Coenen, 2007)

Table 7: Implied emission factors for ground support equipment at Dutch airports (g/kg diesel)

Year	CO	NOx	PM_{10}	VOC	SO_2
1990	44.8	56.0	3.39	10.27	3.94
1991	44.8	56.0	3.39	10.27	3.94
1992	44.8	56.0	3.39	10.27	3.94
1993	44.8	56.0	3.39	10.27	3.94
1994	44.8	56.0	3.39	10.27	3.94
1995	44.8	56.0	3.39	10.27	3.94
1996	44.8	56.0	3.39	10.27	3.94
1997	43.8	54.8	3.21	9.90	3.88
1998	43.6	54.5	3.20	9.70	3.88
1999	39.7	53.3	3.20	9.17	3.04
2000	39.3	54.2	3.22	8.83	0.98
2001	29.8	43.6	2.65	6.68	0.34
2002	30.2	42.1	2.46	6.75	0.12
2003	29.4	42.4	2.44	6.78	0.12
2004	28.7	42.4	2.41	6.79	0.12
2005	26.8	40.9	2.26	6.36	0.07
2006	24.4	38.4	2.04	5.84	0.02
2007	22.6	37.3	1.91	5.55	0.02
2008	21.5	36.9	1.82	5.41	0.02
2009	20.2	35.8	1.69	5.12	0.02
2010	19.9	34.2	1.60	4.99	0.02
2011	19.7	33.3	1.55	4.85	0.02
2012	20.4	33.0	1.49	4.81	0.02
2013	20.2	32.4	1.50	4.83	0.02
2014	17.0	28.4	1.32	4.19	0.02
2015	15.4	24.9	1.12	3.65	0.02

Table 8: Dust emissions from tyre and brake wear (g/tonne MTOW)

Activity	Fine dust (PM_{10})	Coarse dust
Tyre wear	0.223	1.784
Brake wear	0.253	

Table 9: Air traffic fuel consumption

	Schiphol					Other airports	
	Take-off	Climb-out	Approach	Idle	APU	Jet fuel	Aviation Gasoline
	million kgs						
1990	11.7	23.9	19.4	29.7	8.6	7.8	2.3
1991	11.7	23.8	19.3	29.5	8.5	8.1	2.4
1992	12.9	26.3	21.3	32.6	9.4	8.6	2.5
1993	14.0	28.6	23.2	35.5	10.2	8.4	2.4
1994	14.4	29.4	23.8	36.5	10.5	8.3	2.5
1995	16.9	35.0	27.3	41.1	12.8	8.4	2.5
1996	18.7	38.5	29.9	45.3	14.3	8.1	2.2
1997	20.0	41.2	32.1	48.8	15.4	8.1	2.3
1998	21.3	44.1	34.5	53.3	16.7	7.8	2.2
1999	22.0	46.0	36.0	54.1	17.4	7.7	2.3
2000	22.8	47.8	37.4	56.5	18.3	10.2	1.9
2001	23.0	48.3	37.7	56.5	18.5	8.5	1.8
2002	22.7	47.8	37.2	55.3	18.1	9.3	1.8
2003	23.1	48.3	37.4	66.8	18.1	8.0	1.5
2004	23.9	50.0	38.6	68.7	18.8	7.6	1.4
2005	24.8	51.9	39.8	70.2	19.3	11.7	1.4
2006	25.1	52.6	40.3	72.1	19.9	14.3	1.4
2007	25.9	53.9	41.2	74.3	20.5	14.4	1.4
2008	25.7	53.5	40.8	73.6	20.4	15.2	1.6
2009	23.3	48.6	37.0	66.7	19.0	14.7	1.7
2010	24.1	49.9	37.7	67.2	20.3	15.2	1.6
2011	25.6	53.4	40.4	72.0	19.6	15.1	1.5
2012	25.4	53.0	40.1	71.3	17.5	16.0	1.3
2013	25.5	53.1	40.1	71.4	15.2	18.0	1.2
2014	26.3	54.8	41.3	73.2	13.3	18.7	1.1
2015	27.1	56.5	42.6	75.3	11.1	19.1	1.0
	PJ						
1990	0.51	1.04	0.84	1.29	0.37	0.34	0.10
1991	0.51	1.03	0.84	1.28	0.37	0.35	0.11
1992	0.56	1.14	0.93	1.42	0.41	0.37	0.11
1993	0.61	1.24	1.01	1.54	0.45	0.37	0.11
1994	0.63	1.28	1.04	1.59	0.46	0.36	0.11
1995	0.74	1.52	1.19	1.79	0.56	0.37	0.11
1996	0.82	1.67	1.30	1.97	0.62	0.35	0.10
1997	0.87	1.79	1.40	2.12	0.67	0.35	0.10
1998	0.93	1.92	1.50	2.32	0.73	0.34	0.10
1999	0.96	2.00	1.56	2.35	0.76	0.34	0.10
2000	0.99	2.08	1.63	2.46	0.80	0.44	0.08
2001	1.00	2.10	1.64	2.46	0.80	0.37	0.08
2002	0.99	2.08	1.62	2.41	0.79	0.40	0.08
2003	1.00	2.10	1.63	2.91	0.79	0.35	0.07
2004	1.04	2.18	1.68	2.99	0.82	0.33	0.06
2005	1.08	2.26	1.73	3.06	0.84	0.51	0.06
2006	1.09	2.29	1.75	3.14	0.87	0.62	0.06
2007	1.12	2.34	1.79	3.23	0.89	0.62	0.06
2008	1.12	2.33	1.78	3.20	0.89	0.66	0.07
2009	1.01	2.11	1.61	2.90	0.83	0.64	0.07
2010	1.05	2.17	1.64	2.92	0.88	0.66	0.07
2011	1.12	2.32	1.76	3.13	0.85	0.66	0.06
2012	1.10	2.30	1.75	3.10	0.76	0.70	0.06
2013	1.11	2.31	1.75	3.11	0.66	0.78	0.05
2014	1.14	2.38	1.80	3.19	0.58	0.81	0.05
2015	1.18	2.46	1.86	3.28	0.48	0.83	0.05