Title: Emissions from auxiliary power units and ground power units during intraday aircraft turnarounds at European airports

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Abstract: It is widely known that emissions from aircraft engines, Auxiliary Power Units (APU) and ground handling equipment contribute to air pollution at airports. During the aircraft turnaround process, the main source of emissions is the APU. The use of the APU can be significantly reduced if the aircraft stand is equipped to supply external electrical power and pre-conditioned air to the cabin. This paper analyses the actual duration of APU and external power usage during intraday aircraft turnarounds at 125 airports during June 2015. The data is derived from flight data recording units of more than 200 short-haul, narrow-body jet aircraft, conducting some 25,195 aircraft turnarounds and thus provides the most detailed assessment of aircraft power usage available. A common practice is for the APU to be running for a short period on arrival at the stand (arrival-cycle) and then again for a short period prior to departure (departure-cycle). It is identified in this study that departure-cycle emissions are three times greater than arrival-cycle emissions. These emissions could be reduced if more accurate forecasts of departure times are available to flight crew. The provision of external ground power is found to reduce emissions by up to 47.6%. However, the study also highlights that when the source of external power is a diesel-fuelled mobile Ground Power Unit (GPU), there is a net doubling in emissions of hydrocarbons. APU usage is also observed to vary with outside air temperature (OAT) leading to possible increases in emissions of up to 6%.

Keywords: Aircraft Turnaround, Auxiliary Power Units, Airport Emissions

1. Introduction

The operation of aircraft at airports is known to be a significant source of air pollution. The primary source of emissions is that produced by the main engines during the take-off, landing and taxi phase of flight. There are a number of studies that have quantified airport emissions from the main engines (e.g. Mazaheri et al. (2011), Herndon et al. (2008), Kesgin (2006)). However, very few studies have considered emissions during the turnaround phase when the main engines are operated for a very short time period or even switched off completely. The turnaround process generates emissions from a variety of sources including the aircraft’s auxiliary power unit (APU), mobile ground power units (GPU) and service vehicles. Pollutant emission levels are dependent on the type of equipment, fuel type and power output. For comparative purposes, it is often quoted in terms of an Emission Index (EI) value, defined as the mass of a pollutant emitted, in grams, per kilogram of fuel combusted. The predominant role of the APU on the ground is to provide electrical power to the aircraft and supply bleed air to the air conditioning packs. Due to the relatively high fuel consumption rate and usage duration, the APU is a significant source of emissions. Schafer et al. (2003) took direct measurements of APU emissions at airports. They concluded that these emissions could not be neglected compared to main engine emissions due to similar EI values and the longer operating duration of APUs compared to the main engines. In addition to emissions, the environmental impact of APUs includes elevated noise levels and as a result some airports have restricted APU usage to 5 minutes after arrival at stand and 5 minutes before departure. Detailed operational usage of the APU, including the duration of use and the mode of operation is difficult to obtain and very few airlines collect and analyse such data. The lack of transparency of APU usage prevents identification of operational inefficiencies and evidence of good practice. Furthermore, emission studies make use of likely estimates of usage parameters leading to inaccurate emission estimates. For example, Wade (2002) quantified the emission index for APUs for both military and commercial aircraft and then used the estimated operating time and number of cycles to determine emission values. Winther et al. (2015) quantified emissions from various sources including the APU and ground handling equipment at Copenhagen Airport, though used ICAO recommended Time-In modes for the APU. Stettler et al. (2011) estimated APU emissions for one mode of operation and assumed nominal run times of between 15 to 30 minutes. In recent years, many airports have provided ground power sources and pre-conditioned air that supply aircraft with electrical power and temperature-controlled cabin air, respectively. The change in the use of APU due to such provision is not known other than the generally accepted notion that APU usage is likely to be reduced.

In this study, detailed operational usage data of the APU and external power is analysed for 25,195 intraday aircraft turnarounds at 125 Airports in Europe. The data is gathered from 203 aircraft and includes arrival and departure times at stands, timestamps of APU and external power usage, the mode of operation of the APU and the fuel consumption at each mode. Such detailed observational data enables activities during the turnaround to be mapped, providing more accurate values of airport emissions and opportunities for efficiency improvements.

1. Method

Many commercial aircraft are fitted with a flight data recording unit which records key flight parameters received from numerous sensors on board the aircraft. Examples of parameters recorded include speed, altitude, fuel consumption, engine parameters etc. The stored data is later extracted and analysed for operational and safety reasons. While the primary purpose is to record and store data in-flight, the data recording unit can also be used to record and store data while the aircraft is on the ground, for example during an aircraft turnaround. During a relatively short intraday turnaround, electrical power and air conditioning is required so that the crew and support staff can prepare the aircraft for the next flight. The industry definition of the start of the turnaround is defined as the point when the aircraft arrives at a stand and is stationary with the parking brake applied. The end of the turnaround process is defined as the point when the aircraft departs the stand and begins to move with the parking brake released. A very good review of the processes involved in a typical turnaround are detailed by Schmidt (2017). Figure 1 shows the typical sequence of events during a turnaround which ensures that the aircraft is continually powered either from the main engines, the APU and/or an external power source. The data extracted and analysed from the flight recording unit includes a time-stamp of all these events. During departure from the stand, it is common practice for the main engines to remain switched off until the aircraft has pushed back. Upon arrival, aircraft often arrive at the stand with the main engines running, or more commonly, with at least one main engine switched off. As part of the data analysed for this study, the timestamps of operation for the main engines was unavailable and as a result fuel burn and emissions associated with the main engines is not analysed. The data is supplied by two major airlines operating a fleet of Airbus A320 family aircraft, operating to primary and secondary airports across Europe. Data for a total of 25,195 turnaround events was analysed for a period of one month from 1st June 2015 to 30th June 2015. The business model of the airlines can be described as low-cost/hybrid and as such the scheduled intraday turnaround time is short. The average turnaround time observed was 45 minutes with a standard deviation (SD) of ± 15 minutes. For 87% of turnarounds, the duration was less than 60 minutes. The study only considers intraday turnaround with time durations of between 25 minutes and 120 minutes. The analysis excludes, ground activities during overnight turnarounds when the aircraft is parked at an airport for a longer duration and usually undergoing routine maintenance. Any timestamp data for activities before the first flight of the day and after the last flight of the day is also excluded from the analysis.

2.1 Auxiliary Power Unit (APU) Operations

In almost all cases, the aircraft arrives and leaves the stand with the APU running. If external power is available, the APU is switched off to reduce the fuel and maintenance cost of the unit and to reduce harmful emissions around the airport. Depending on the cabin temperature, a source of conditioned air may be required to heat or cool the cabin for crew and passenger comfort. If external cabin air conditioning (AC) is not available, the crew may leave the APU running throughout the turnaround. For turnarounds where the APU is not switched off midway during a turnaround is, hereinafter described as a single-cycle APU event. The conventional method of operation is for the APU to be on for a short period upon arrival at a stand. Once the aircraft is accepting external power the APU is switched off. Later in the turnaround, close to departure from the stand, the APU is switched on again, in preparation for external power being disconnected. Hereinafter, these events are described as the arrival-cycle and departure-cycle of the APU and collectively as a double-cycle APU event. When the APU is switched on it can be operated in one of four modes appropriate to the power and air-conditioning requirements of the aircraft. The least energy intensive mode is the ‘Idle’ mode where the APU is on but does not provide any electrical power or bleed air for the cabin air conditioning (AC) packs. Above ‘Idle’ mode, the APU can be operated to provide only electrical power to the aircraft, only bleed air for the AC packs or a combination of both electrical power and bleed air for the AC Packs. The dataset available includes the timestamps of each mode of operation and the associated APU fuel flow rates. The total fuel consumption,, in kg, during an APU cycle is calculated using the formula:

 (Eq. 1)

where is the mass fuel flow rate, in kg/hr, and  is the time duration, in hours, of each *ith*  mode of operation of the APU.

Thus, the total fuel consumption is dependent on the mass fuel flow rate, which is strongly related to the mode of operation of the APU. Figure 2 shows the difference in mass fuel flow rate for different modes of operation. The diamond markers in the figure show the average fuel flow rate values, as measured by 196 aircraft of the same type. The lower and upper bars show the minimum and maximum time-averaged values, for the collective group of aircraft. The relatively large variance in fuel flow range at each mode is related to differences between individual aircraft. In general, older aircraft which have clocked up longer APU usage hours have higher fuel flow rates due to performance deterioration over time. The greater the power output of the APU, the greater the fuel consumption per unit time. The increase in average fuel flow rate above idle for electrical power output only is 5%, for bleed air output only above idle is 18% and a combined output above idle is 25%. Thus, using the APU for bleed air output for cabin air conditioning is the most fuel-intensive APU mode.

The total fuel consumption determines the level of emissions of gases and particulate matter. In addition to the mode of operation, fuel consumption is also related to the make and model of the APU unit. Airbus A320 family aircraft are in almost all cases fitted with one of two different APUs manufactured by Honeywell Aerospace and include either the 131-9 series or the GTCP 36-300 series models. The Emission Index (EI) values of these units for carbon monoxide (CO), oxides of nitrogen (NOx) and total hydrocarbons (THC) have been measured and published in several studies. Table 1 lists several published EI values for the two different APU models. The values presented are relatively similar for each APU model and variations are most likely due to measurements at slightly different power outputs, the measurement location relative to the APU exhaust and potential discrepancies in the measurement process. The mode of operation of the APU at which the measurements were taken is not known for any of the studies.

Using EI values presented in Table 1 and the average fuel flow rates determined in this study (Figure 2), the total emissions, in grams, can be calculated using the formula:

 (Eq. 2)

where is the emission Index value of each pollutant gas, in g/kg, is the APU mass fuel flow rate, in kg/hr and  is the time duration, in hours, of each *ith*  mode of operation of the APU.

2.2 External Ground Power Operations

The provision of external ground power available to aircraft comes from one of two sources. The provision is usually in the form of a mobile GPU which generates on-site electrical power at the stand by combustion of diesel fuel. This results in exhaust emissions on the apron but has the benefit of being available at all stands due to its mobility. Alternatively, a fixed electrical ground power system (FEGP) is permanently fixed at a stand and enables a lead to be connected to the aircraft which draws power from the main electricity supply to the airport terminal. FEGP systems have the benefit of zero emissions on the apron though are expensive to fit, particularly at remote stands located away from the terminal building. In either case, ground staff are required to connect a power lead to the aircraft which in itself can pose a safety risk. Upon arrival at a stand, the risk of collision with the aircraft or ingestion into the main engines poses a significant safety concern. As a result, ground staff are advised not to approach the aircraft until the flight crew have switched off the main engines and applied the parking brake. The flight crew signal that the aircraft can be safely approached by switching off red flashing anti-collision lights located above and below the fuselage. Once safety is assured, the ground crew place chocks around the wheels and connect the external power lead. The electrical power supplied to commercial jet aircraft is 115V, three-phase alternating current at 400Hz. The aircraft only accepts external power if the voltage and frequency are within certain tolerances. The dataset available for this study includes a timestamp of when electrical power is accepted by the aircraft. It is important to note that this is not necessarily the time the external power lead is connected, as there may be a time lag between power connection and acceptance. In some cases where the external power supply is poorly maintained, or intermittent, external power maybe physically connected to the aircraft, but the aircraft may reject the supply of power and therefore a timestamp is not generated. In such cases, the data is filtered out for analysis in this study. When the voltage and frequency of the external power is acceptable, a visual and audible alert is provided to the flight crew in the flight deck. The flight crew must then actively transfer power from the APU to the external power source by pressing a switch in the overhead panel. The available dataset includes a timestamp for the point at which the flight crew transfer the power. Close to departure, the flight crew switch on the APU and carry out a power transfer using the switch in the overhead panel. A visual hand signal or voice instruction over a headset device is given to the ground crew to request that external power be disconnected. The available dataset includes a timestamp of the disconnection of the external power. The dataset does not differentiate between a mobile GPU and an FEGP system as the sensors on board the aircraft cannot differentiate between different sources of external power. The availability of external pre-conditioned air into the cabin is less common than the provision of external power and the dataset only includes turnarounds where external air-conditioning is unavailable. The dataset does not include any turnarounds where external power is not available.

When the source of external power is a mobile GPU, emissions are released on the apron due to the combustion of diesel fuel by the unit. The most comprehensive study of mobile GPU emissions measurements is presented by Fleuti (2006) for Zurich airport. Exhaust emissions were measured for a total of 6 units at two different power output levels. The EI values measured are presented in Table 1. The average EI value for each pollutant listed in the last row of Table 1 are those recommended for use by Fleuti (2006) and are the values used in this study. The data from Fleuti (2006) shows that the average mobile GPU diesel fuel consumption at Zurich Airport in 2004 was 7.74kg/hr. This mass fuel flow rate value together with the GPU EI values presented in Table 1 and the operating time duration of a mobile GPU can be used to calculate the emissions released from a mobile GPU. These parameters were inserted into Equation 2, presented in section 2.1 to produce the emission values.

1. Results and Discussion

For turnarounds involving single-cycle APU events, the average turnaround duration determined from the dataset is 43 minutes ± 13 minutes (SD) and for double-cycle APU events is 46 minutes ± 16 minutes (SD). Double-cycle APU events accounted for 74% (18,645) of all turnarounds and therefore it is common for the APU to be shut down during the turnaround when external power is available. In the remaining 26% of turnarounds, the flight crew opted to keep the APU running during a single-cycle APU event, even though external power was available. There are various operational and economic reasons for doing so. At many airports, GPUs are owned by the airport or a ground handling company. At some airports, the cost to the airline for using the GPU may be higher than using the APU. At such airports, the airline policy may be to keep the APU running throughout the turnaround, leading to a single-cycle APU event. During some turnarounds, the cabin temperature maybe outside the range of comfortability for passengers and crew and therefore APU bleed air is required to cool or heat the cabin for the duration of the turnaround. For some turnarounds, the provision of electrical power from the GPU maybe unreliable due to poor maintenance of the units, making it necessary to keep the APU running throughout the turnaround. Of the 6,611 single-cycle APU turnarounds analysed, 1019 involved an intermittent source of external power. Whilst the proportion of turnarounds with unreliable power represents just 4% of the total, it highlights an opportunity for airports and ground handling companies to regularly maintain ground power equipment to reduce APU usage. Since the APU is operated for longer during single-cycle APU events, the average fuel consumption per turnaround is also higher at 67kg ± 23kg (SD) compared to 40kg ± 20kg (SD) for double-cycle APU events. The average use of external power per turnaround was found to be 30 minutes + 7 minutes (SD).

* 1. Turnaround Efficiency during the APU arrival-cycle

The usage duration of the APU and external power is interrelated and dependant on the efficiency of processes involving the flight crew and ground crew. Upon arrival at the stand, the initial process is for the ground crew to connect the aircraft to an external power source. This activity requires the flight crew to switch off the anti-collision lights. Figure 3(a) shows that this process is relatively quick with reliable external power available to 70% of aircraft within 3 minutes of arriving at the stand. According to Fleuti (2013), the procedure at Zurich Airport is for the ground crew to position the wheel chocks and connect external power to aircraft at the same time. This process is the same at other airports and is convenient because most aircraft have the external power connection point located close to the nose wheel. Figure 3(a) also shows that in 12% of turnarounds the external power is not available for at least 5 minutes after arrival at the stand. This could be due to a number of reasons. For example, the flight crew may be delayed in switching off the anti-collision lights until they are satisfied that the engines are completely off; It could be due to the late arrival of the ground crew to service the aircraft; It could also be due to the time lag associated with the aircraft assessing the voltage and frequency of the external power supply. While this is usually an instantaneous process, poorly maintained external power units could make the process longer. Further work is required here to identify the cause in delay and could be achieved through observations and further interrogation of avionics data. Nevertheless, it represents some opportunity for improvement though cannot be at the expense of safety. As discussed earlier, following acceptance of external power by the aircraft the flight crew transfer power to the external power source. Figure 3(b) shows that this process is relatively quick with flight crew responding within 90 seconds in 75% of turnarounds. The workload for the flight crew is relatively high upon arrival at a stand with flight preparation activities for the next flight taking priority. Upon arrival at a stand the number of flight crew in the cockpit may also be reduced due to the need for comfort breaks and walk around checks. Alternatively, there may be ground staff (dispatchers, engineers) in the cockpit which may hamper activities. Whilst there is some opportunity for improvements in efficiency activating external power, figure 3(b) also highlights that for half of all turnarounds the flight crew activate the external power within 25 seconds of it being available.

* 1. Turnaround efficiency during the APU departure-cycle

During the second cycle of a double-cycle APU turnaround event, the flight crew switch on the APU in preparation for the departure. To limit APU noise and emissions, some airports restrict the use of the APU. According to Scholz (2015), 21% of airports surveyed by Boeing had some kind of APU restriction. It is common for many airports to limit APU usage to a 5-minute period following arrival and before departure from the stand. Winther et al. (2015) and Fleuti (2013) describe the 5-minute rule for Copenhagen and Zurich Airports respectively. Figure 3(c) shows that of the turnarounds analysed, just 6% have the APU switched on for less than 5 minutes before departure from the stand. The median time is 16 minutes ± 10.5 minutes (SD). Personal communication with flight crew suggests that the APU is switched on with the anticipation that departure from the stand will occur within 5 minutes. However, Air Traffic Control (ATC) restrictions and the occasional operational issue before push-back often leads to a delay at the stand. As is discussed later, starting the APU too early prior to departure is a significant source of emissions as often the flight crew will configure the APU to a more power intensive mode (supply of both electrical power and bleed air for air-conditioning), resulting in an elevated fuel flow rate.

Once the APU has been switched on, the external power remains on unless the ground staff physically disconnect the supply. When a mobile GPU is being used additional emissions occur as the electrical power is generated by the combustion of diesel. The data from Fleuti (2006) suggests that a typical mobile GPU burns 7.74kg of diesel per hour. In 2005, the use of mobile GPUs released 7.6 tonnes of Nitrogen Oxides (NOX) at Zurich Airport alone. Figure 3(d) shows that the process of flight crew requesting the disconnection of the external power and ground staff complying is relatively efficient. In 50% of turnarounds the external power was disconnected within 70 seconds of the APU being switched on prior to departure. Nevertheless, some improvements in efficiency are possible since Figure 3(d) also shows that in 20% of turnarounds external power is not disconnected for up to 6 minutes after the APU is switched on. This is likely due to a delay in communication between the flight crew and ground crew or the ground staff being occupied in carrying out other turnaround activities.

3.3 APU Mode of Operation and Fuel Burn

Figure 4 shows the average percentage time duration of each APU mode of operation for the three different APU cycles. When the APU is used as a single-cycle, in 83% of events it is used to supply bleed air for air conditioning. The average fuel consumption for single-cycle APU events is 67kg per turnaround and represents the most inefficient method of operation. The high proportion of bleed air output, during single-cycle APU events suggests that the provision of pre-conditioned air from an external source would reduce fuel consumption significantly. For double-cycle APU events, the departure cycle is on average more than 11 minutes longer than the arrival cycle. While this difference in duration is partly because of the efficient processes of flight crew and ground staff on arrival, it is largely due to the early start of the APU during the departure cycle by the flight crew (see Figure 3d). In addition, Figure 4 shows that, on average, 87% of the departure-cycle duration uses the more fuel intensive mode of APU operation involving the supply of bleed air for air conditioning. For the arrival cycle the average duration of APU bleed air supply is 62% and for a shorter duration. The higher power output of the APU during the departure cycle combined with the longer duration of operation results in an average APU fuel consumption of 30.2kg ± 18.4kg (SD) compared to just 10.2kg ± 6.5kg (SD) for the arrival cycle. The average APU fuel flow rate weighted according to the duration of usage of the APU mode is 99.6kg/hr, 104.4kg/hr and 103.2kg/hr for the arrival cycle, departure cycle and single-cycle events respectively. Thus, the most inefficient process occurs during the departure cycle and the greatest efficiency can be gained during this time by delaying the start of the APU to a time closer to the actual departure time from the stand. There could be a number of reasons why the flight crew switch on the APU too early. At some airports, a policy to restrict APU usage to 5 minutes prior to departure from stand may not exist. At airports where a policy does exist, it may not be well communicated to airlines and/or flight crew. Where a policy does exist, and flight crew are aware, departure delays at the stand may occur due to congestion, technical issues etc. During normal operations, when the flight crew are ready to depart, they request an air traffic control (ATC) clearance via voice communication over the radio. If there is sufficient taxiway and take-off runway capacity, ATC will issue a departure clearance relatively quickly. However, if the airfield is congested and capacity is reduced, the aircraft maybe instructed to remain on stand and await a departure clearance. It is far more efficient to wait at the stand with the APU running than wait on a taxiway with the main engines running. In such cases, better exchange of information regarding departure delays between ATC and the flight crew could enable better planning of APU usage and thus reduce APU usage prior to departure. At many European airports such a system of information exchange and operational planning already exists in the form of the Airport Collaborative Decision Making (A-CDM) system. The system implemented at 17 major European airports requires the flight crew and ground handling team to issue, in advance, an accurate estimate of the departure time from the stand, the so called target off-block time (TOBT). It also requires air traffic controllers to issue, in advance, an accurate estimate of the departure time, the so called target start-up approval time (TSAT). The correct forecast of TOBT and TSAT should in theory reduce delays at the stand and there is some evidence of this outlined by the Eurocontrol (2016) document. The document reports that departure delays at the stand have reduced by 36 seconds at Oslo Gardermoen Airport and by 60 seconds at both Helsinki and Madrid Barajas Airports. Benefits at other airports is not reported and the general consensus is that a collaborative approach should result in reduced delays.

3.4 APU and Mobile GPU Emissions

Figure 5 shows the emissions of CO, NOX and THC, in grams, for the departure and arrival cycle, during a double-cycle APU event and a single-cycle APU event. The emissions of CO and THC occur due to the incomplete combustion of fuel and as such emissions index values are higher at lower APU power output levels. The diamond markers represent the emission values, based on average fuel flow rates and APU EI values taken from Table 1. The upper bars and lower bars represent emission values based on maximum and minimum fuel flow rates, respectively. All emission values are based on average fuel consumption for the duration events presented in Figure 4. As expected, average emissions during a single-cycle event are greatest and occur due to the higher absolute APU fuel consumption. For each cycle, the emissions of nitrogen oxide and carbon monoxide are a factor of 10 greater than emissions of hydrocarbons. For the departure cycle, absolute emission values are approximately three times greater than during the arrival cycle. The higher weighted fuel flow rate and longer duration of the operation of the APU results in significantly higher emissions at departure. As APUs accumulate an increasing number of usage cycles and hours, higher fuel flow rate values are required to maintain similar power output levels. This trend in performance deterioration of APUs is documented by Gorinevsky et al. (2002). The maximum emission values in Figure 5 are representative of older APUs with higher usage cycles and hours.

Double-cycle APU turnaround events are only possible because aircraft have access to an external power source. For double-cycle APU events the average shutdown duration of the APU in between the arrival and departure cycle is 22 minutes 28 seconds. Thus, the equivalent amount of APU emissions is saved due to the provision of the GPU. By quantifying GPU diesel fuel consumption and emissions for the same time period as the APU shutdown, the net release of emissions can be quantified as shown in Figure 6. The provision of the GPU has a significant benefit in reducing CO and NOX emissions by 90g and 203g respectively. Of matter of interest is that the EI value for THC from the GPU is significantly higher than that of a typical APU. Thus, even though the total consumption of fuel by the GPU is significantly less than the APU, Figure 6 shows that there is a net increase in THC emissions of 8.7g, if the GPU is used in place of an APU. If an FEGP system is used as a source of external power, the average emissions savings would be that of the APU alone in Figure 6.

Since the APU is active in different modes at various stages of a turnaround, the emission rate of pollutants will also vary throughout the turnaround. A typical timeline of the APU mode of operation can be determined by calculating median timestamps of each active APU mode of operation. Once the activity times and duration of the APU are determined, these can be combined with the emission index values and average mass fuel flow rates at the relevant modes of operation to determine the emission rate. The timeline and duration of a mobile GPU can be similarly determined by calculating the median timestamps of operation. Corresponding emission rates from a mobile GPU can then be determined assuming that exhaust gas emissions are released at a constant rate throughout the period that acceptable electrical power is being generated for the aircraft. For double-cycle APU events, the dataset shows that the median turnaround time is 42 minutes. Using this as the duration of a hypothetical turnaround, Figure 7 shows a timeline of emission rates of CO, NOX and THC, for a double-cycle APU turnaround with external power being supplied by a mobile GPU. The figure shows that there is an elevated emissions rate for all pollutants approximately 2 minutes after arrival on stand and then again approximately 10 minutes before departure. These elevated rates of emission occur due to the simultaneous operation of the mobile GPU and APU with the latter being used to provide electrical power and bleed air for cabin air-conditioning. The low emission rates for the middle portion of the turnaround is when the APU is switched off and the mobile GPU is generating electrical power and therefore is the only source of emissions. The mode of operation of the APU differs at arrival and departure. The APU only provides electrical power upon arrival at stand. However, on departure, bleed air is also being supplied by the APU and therefore APU emission rates are slightly higher on departure compared to arrival.

If a provision of external power is not available to the aircraft, the APU would be not be switched off and instead would be operated in a mode to provide electrical power. In this case the total emissions of CO, NOX and THC would be 202g, 544g and 14g respectively. The provision of an FEGP system for a period of 22 minutes 28 seconds would enable the APU to be switched off during the turnaround for that period of time and this would reduce all APU emissions by an average of 47.6%. Similarly, the provision of a mobile GPU would reduce net CO emissions by 40%, net NOX emissions by 30% and approximately double the net emissions of total hydrocarbons.

3.5 APU Emissions and Outside Air Temperature

One of the important functions of the APU on the ground is to power the on-board air conditioning packs to provide warm or cool air into the cabin for the comfort of passengers and crew. Cabin air temperature is strongly related to the outside air temperature (OAT) and the level of solar radiation coming through the cabin windows. The dataset analysed includes the average outside air temperature as measured by a temperature probe on the exterior of the aircraft during the turnaround. The greater the level of cabin heating or cooling required, the greater the power and fuel consumption of the APU as the mode of operation must include the provision of bleed air to supply the AC packs. The outside air temperature across 6,611 single-cycle turnarounds ranged from 7oC to 43oC. Figure 8a shows the duration of bleed air supply by the APU as a percentage of the total duration of the APU cycle for the turnaround. The line of best fit shows a minimum percentage of approximately 75% at an OAT of 15oC. As expected, the percentage duration of bleed air supply to the AC packs by the APU increases as the OAT gets warmer, tending towards 100% as temperatures rise above 40oC. For OAT values below 15oC the need to heat the cabin also causes the percentage duration of bleed air supply to increase. Figure 8b shows the corresponding variations in APU fuel flow rate with temperature. Across the OAT range studied, the fuel flow rate varies from approximately 100.5 kg/hr to 105.5kg/hr. When considered together with Figure 8a, it is highly likely that the increase in APU fuel flow rate is driven by the increase in the supply of bleed air by the APU. The corresponding impact on emissions of pollutants is shown in Figure 8c. Here the minimum pollutant emission values at approximately 15oC is used as the baseline to calculate relative percentage increases in emissions due to changes in OAT. For OAT values between 7.5oC and 25oC the relative percentage increase is within 1%. As the OAT increases from 15oC to 43oC, pollutant emissions increase by up to 6%. In the short-term, scheduling aircraft turnarounds at cooler times of the day would help to reduce APU emissions. While this may be possible at less congested airports it is unlikely to be the case at busier airports. In the long-term, APU emissions could trend upwards where daily temperatures are forecast to increase in the future as a result of climate change. Some airports in colder climates where temperatures are forecast to increase may benefit from a reduction in APU emissions. However, at airports where temperatures are forecast to increase to values above 15oC, APU emissions are likely to increase. An increase in the provision of pre-conditioned air at aircraft stands would help to mitigate future apron emissions levels and are likely to be most effective at airports situated in warmer climates.

1. Conclusions

The analysis of APU and external power usage from more than 25,000 intraday turnarounds has shown that there is some scope for improving the efficiency of the turnaround process that would lead to reduced emissions of CO, THC and NOX on the apron. In particular, streamlining activities close to departure from the stand provides the greatest opportunity for improvement. Minimising the use of the APU prior to departure would be most effective at reducing emissions. Although many airlines and airports have implemented a policy to restrict APU usage prior to departure to 5 minutes, the dataset analysed shows that compliance to the policy is only occurring on average in 6% of turnarounds. It is hypothesised that more accurate estimates of departure time, efficiently communicated between air traffic controllers and flight crew would enable APU fuel and emissions savings. Further reductions can be achieved by better coordination of activities between the ground crew and flight crew to ensure that mobile external power units are disconnected and switched off as soon as the aircraft begins to be powered by the APU. The provision of FEGP systems at stands is the most effective mechanism for reducing net emissions with average savings of 47.6%. While mobile GPU systems also help to reduce APU emissions, they also release emissions of their own through the combustion of diesel fuel. This study shows that while net emissions of CO and NOX are reduced by 40% and 30% respectively, the net emissions of hydrocarbons is doubled. The data analysed in this study also considers the relationship between APU emissions and outside air temperature during the turnaround process. It is shown that for OAT deviations above and below 15oC, APU emissions increase due to the requirement of the APU to supply more bleed air for the AC packs. At airports where large temperature variations are observed, the increase in pollutant emissions could be up to 6%.

The study highlights the need for further work in reducing turnaround emissions and encourages researchers and operations specialists to find solutions that will reduce departure delays at the stand. In the future, such delays are likely to increase due to ATM capacity constraints. Very few studies have so far considered the impact of climate change on aviation operations. This study suggests that the increase in airport emissions due to a warming climate is not insignificant. Further research is required to investigate how other aircraft operations at airports may contribute to emissions.

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