

Aircraft Taxi-Out Emissions at Congested Hub Airports and the Implications for Aviation Emissions Reduction in the United States

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Abstract

In this paper, we estimate the total aircraft taxi-out emissions over the course of a day at Newark Liberty International Airport. Departures currently have to wait up to 60 minutes to depart once they have pushed back from the gate, and most of this time is spent idling on the taxiways while emitting harmful pollutants into the atmosphere. A queuing model for aircraft waiting to depart was developed to test different emissions scenarios and was calibrated using data from the airport in August 2005, a peak travel month. These different scenarios include: (1) redistribution of flights over the course of the day, (2) fleet composition restructuring, and (3) variations in number of departures under current capacity. Each scenario's associated emissions benefits are computed. For instance, in an extreme case of redistributing departures evenly across flight hours of a day, a 43% emissions reduction from the base case scenario could be achieved. On the other hand, under a 2015 demand case of a 30% increase in departures, the emissions estimate increases by 50%. We conclude that emission reduction strategies addressing aircraft taxi-out emissions through congestion mitigation and fleet restructuring can lead to significant emissions benefits and play a critical role in meeting environmental challenges for future aviation.

1. INTRODUCTION

Criteria pollutant emissions from cars, trucks, and public transit have long been the focus of environmental quality organizations, decades of research, and countless legislative policies. On the other hand, aircraft emissions have only become the subject of major research initiatives within the past decade. The airline industry is growing at an extraordinary high rate, especially due to the emergence of low-cost carriers and the rising prices of gasoline for passenger vehicles. In 2005, domestic air passenger travel was up 4.1 % from the previous year (1) and is forecasted to increase at a rate of 3-5% over the next decade (2). More flights will be needed to cope with this additional demand, although this will be slightly offset by the introduction of larger aircraft such as the Boeing 787 and the Airbus A-380 into the fleets of airline companies. With more planes in our skies and the fact that many airports are already located in non-attainment zones, the issue of aviation emissions will become even more prevalent in years to come.

Within the airline industry, the primary research focus has been on network capacity issues and strategies to reduce system-wide delays. Nero and Black have focused on the downside of hub-and-spoke networks in the context of congestion, but looked at it from a purely economic perspective rather than from an environmental view (3). Congestion at hub airports has been studied in the context of overall delay reduction in the system without any motivation or conclusions on the environmental side (4). While these delay reductions do in fact help to alleviate some of the emissions problems, the research focus is not primarily from the environmental standpoint.

Despite the apparent lack of research in this area, there have been recent advances in terms of emissions reduction strategies at airports. One strategy consists of reducing the use of reverse thrust, which is commonly used to slow aircraft during landing, but also results in excess NO_x emissions (5). Generally airline companies do not advocate the use of reverse thrust since it is not essential for operations, but pilots are generally forced to use it during inclement weather or on shorter runways. Effectively, this is not much of a strategy as the only way to eliminate the use of reverse thrust would be to make runways longer or ensure perfect weather. Work has already been undertaken in the area of optimizing aircraft design in order to minimize environmental impact (6). Researchers found that there is a tradeoff between noise and emissions performance, and that in fact many aircraft sacrifice fuel efficiency for lower noise so they can meet strict noise abatement policies at various airports. Jamin et. al. analyzed the change in emissions resulting from three abatement policies, including (a) an aggressive reduction in aircraft NO_x emissions via technology, (b) substitution of air travel with high-speed rail, and (c) the replacement of hub-and-spoke system with direct flight connections (7). However, this final reduction strategy only considers emissions reductions due to the decline in average total trip length and the reduced number of takeoffs, but not the effects of reduced taxi-out time which will result from decreased congestion at hub airports. Finally, the actual emissions reductions we might see in the future from technological advances is expected to be overpowered by the actual growth in air traffic expected over the next several decades (8). Thus it is important to look at other means of effectively reducing emissions without necessarily changing engine technology.

The purpose of this paper is to quantify specific emissions benefits obtained by various traffic redistribution strategies at Newark Liberty International Airport (EWR), specifically related to reductions in taxi-out time from when the plane pushes back at the gate until the plane's wheels leave the ground. Although not one of the top ten airports ranked by domestic enplanements, the number of runways, airport layout, and the airlines' increasing need to schedule more flights during peak periods of the day contribute to the on-ground congestion.

Even without weather related delays, EWR is generally over capacity for a few hours each day. In fact, average taxi-out times at EWR are nearly 28 minutes, the greatest out of any airport in the U.S. (9). We focus on pollutant emissions during the taxi-out stage because of the inherent time variability and high emissions rate. Taxi-out times are the most variable because of ground congestion during peak periods of the day, likely effects of hubbing activities. This is also evident in the on-time performance database available from the Bureau of Transportation Statistics. According to Idris et. al., the primary factors affecting taxi-out time are runway configuration, terminal location, weather, and the takeoff queue size, the latter of which was found to be the most important (10). Even though the engine of an aircraft is generally in the idle mode (7% thrust) during taxi-out, the per minute CO and NOx emissions factors are higher than any other stage of flight (11). Coupled with the long duration of taxi-out times during peak periods of the day, the total emissions over the course of a day can add up to a substantial amount.

In this paper, we perform a case study analysis to show the extent of criteria pollutant emissions over the course of a day, and how extreme benefits can be reaped by only modest operational and strategic policy changes. The model also includes a queuing simulation component to help estimate expected taxi times over the course of a given day during the peak period of the year. Although this model is tailored specifically to operations at EWR, data is readily available from the Bureau of Transportation Statistics for any major airport in the United States. Thus, the model can be re-calibrated to determine emissions benefits at other airports.

Routing planes out of hub airports, redistribution of flights over the course of the day, as well as optimizing fleet composition are all valid strategies that can be used by both airlines and the government to achieve significant environmental benefits. While some of these alternatives might come at a huge cost to airlines, implementing them would not only reduce emissions, but also reduce congestions, delays, and improve the efficiency of the entire air transportation system. The environmental problems resulting from taxi time delay can be effectively implemented into network optimization models and used by the government to determine which airports are both prone to delays and suffer from severe emissions problems. Thus, the problem becomes a multi-criteria decision analysis, and the alternative chosen depends on how important the decision-makers believe environmental impacts are. Clearly, with the emergence of new green technologies, the threat of global warming, and an increase in the overall awareness of the environment, decision makers are likely to weight this analysis very heavily and thus it will be important to build upon this model and refine it so it meets the needs of its end users.

2. RELEVANT BACKGROUND

2.1 Hub & Spoke Networks

Hub airports are primarily the result of the deregulation of the airline industry, which occurred approximately 25 years ago. Airlines have since had the ability and power to choose where they want to fly, when they want to fly there, and how much to charge. Empirical studies have shown that airline costs are characterized by significant economies of density, so that average costs on a particular connection decline as the number of passengers increases (12). Accordingly, hub-and-spoke networks became a model adopted by many of the large carriers. Assuming demand between smaller “spoke” cities is not high enough to require frequent, point-to-point service, the airline can start a hubbing operation at an intermediate city to essentially bring the demand to a centralized location. Service between spoke cities will require a connection at the hub city. Thus

it is to and from the hub airport for which a carrier will have the bulk of their flights. Because of the nature of this system, bottlenecks develop during peak periods, resulting in increased congestion.

Airlines plan their schedules in such a way that maximizes the efficiency of the hub-and-spoke system. Of important concern is that passengers demand frequent service and have not enjoyed making connections because of the time gap between their arriving and departing flights. Hence, airlines have begun to create their schedules such that connection time is kept at a minimum. To achieve this, flights from spoke will arrive at the hub city around the same time during the day, and then within 45 minutes to an hour, departing flights to other spoke cities will leave. The net effect of this type of flight schedule is that a busy airport becomes even more congested during these periods, since aircraft enter the departure queue at a higher rate than with which they are leaving. Since this only occurs during a small portion of the day, the effects eventually wear off and departure times begin to level off. However, the nature of queues is such that it tends to take longer to dissipate than it does to form, and thus taxi times become extremely high as many aircraft are delayed.

The example of a hub airport used in this paper is Newark Liberty International Airport (EWR), which Continental Airlines uses as their major operational hub on the east coast. Over the period from May 2005 to April 2006, Continental Airlines (including ExpressJet Airlines which operates their regional flights) had almost 75% market share at EWR. Since their flights make up such a large percentage of the total airport operations, many of the delays incurred during peak periods can generally be attributed to Continental's flight schedule, organized in such a way to provide fast and easy connections to passengers. Thus, changes in their flight schedule are likely to have a significant impact on overall emissions at the airport. Furthermore, it is also likely that other airlines' operations at the airport will not have a major effect on overall emissions because the percentage of flights they operate is much smaller than the hub airline.

2.2 Airport Traffic Operations

The operations at any given airport in the United States are governed by the rules of air traffic control. There are different persons who are in control of various sectors of the ground and airspace. First and foremost there are ground controllers, who are the people with whom the pilots contact when they are ready to pushback from the gate and taxi to the active runway (13). The primary responsibility of the ground controller is to make sure taxiing aircraft remain clear of the active runways, so that aircraft that are taking off do not interfere with them. This requires careful coordination on the part of the ground controller, but also implies that the taxiways which aircraft use are for the most part established by which runways are currently active. Based on this fact, the typical flow of aircraft through the airport can be determined.

Once aircraft are instructed to taxi to the active runway, they are usually required to hold short of the runway to maintain a buffer between any aircraft that might be using that runway for departure or takeoff. After the immediate area is clear, aircraft will typically be told to "position and hold" on the runway before taking off so that they can immediately depart when told to do so by the controller. Aircraft separation between departing commercial aircraft is typically governed by maintaining an airborne separation of five miles, which translates into approximately 90 seconds between the takeoff roll of two subsequent departures. If there is a situation of a heavy jet producing wake turbulence, this amount of time may need to be increased to 2 minutes (13).

Taxi-out times have a higher mean and higher variability because as soon as an aircraft lands, it immediately proceeds off the runway via a taxiway that leads directly to the carrier's

gate. Operations are structured in such a way that gates for incoming aircraft are almost always available at the time the aircraft arrives. This assumes that aircraft previously at the gate have left and are already in queue for takeoff, even if the queue is in excess of 30 aircraft long. From studying operations at airports across the country, this seems to be the standard procedure (13).

2.3 Aircraft Emissions Inventory

In order to prepare an emissions inventory for aircraft, the EPA focuses on the emissions characteristics which ultimately affect ground level pollutant concentrations. This portion of the atmosphere is often referred to as the mixing zone (11). Thus we can categorize emissions from aircraft into the different stages they arise from during the landing and takeoff cycle, when they are close to the ground. There are five distinct stages: approach, taxi/idle-in, taxi/idle-out, takeoff, and climbout. As mentioned earlier, during each of these stages, the aircraft engines operate at a relatively constant power setting and thus total emissions can be calculated by knowing emissions factors for specific aircraft engines used in a given airline's fleet.

Aircraft pollutants of extreme significance are hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), sulfur dioxide (SO₂), and particulates (PM). For each of these pollutants, there are three factors that affect the total quantity that is emitted. These factors are the emissions index (given in weight per amount of fuel consumed), the fuel consumption rate, and the duration of each operating mode. HC and CO emission indices are extremely high during the taxi/idle stages when aircraft engines are typically at low power. These indices tend to fall when the aircraft changes into a higher power operating stage, such as takeoff and climb-out. From this, we see that taxi operations are a significant factor affecting both HC and CO emissions. Sulfur emissions are not typically measured when aircraft engines are tested, because it is assumed that all sulfur in the fuel combines with oxygen during combustion to form SO₂. Thus, these values are constant among a variety of aircraft engines. Furthermore, particulate emissions are also not tested by the EPA because of their inherent difficulty to measure (11).

For evidence of this result, Figure 1 shows emissions indices as a function of flight stage for the Airbus A-310 aircraft, which has either two Pratt & Whitney PW4152 engines or two General Electric CF6-80 turbofans (14). Both engine types have similar emissions characteristics, but for the purposes of this illustration, we assume the aircraft has Pratt & Whitney engines. This aircraft is a typical member of many airlines' fleets and thus provides a good representation of how intense emissions are during various stages of flight. It is evident that on a per minute basis, the emissions for NO_x are clearly the highest during the takeoff and climbout stages, but these stages last only 0.7 minutes and 2.2 minutes on average. Thus total emissions are not as high as those that arise from taxiing, which takes approximately 20 minutes on average (11).

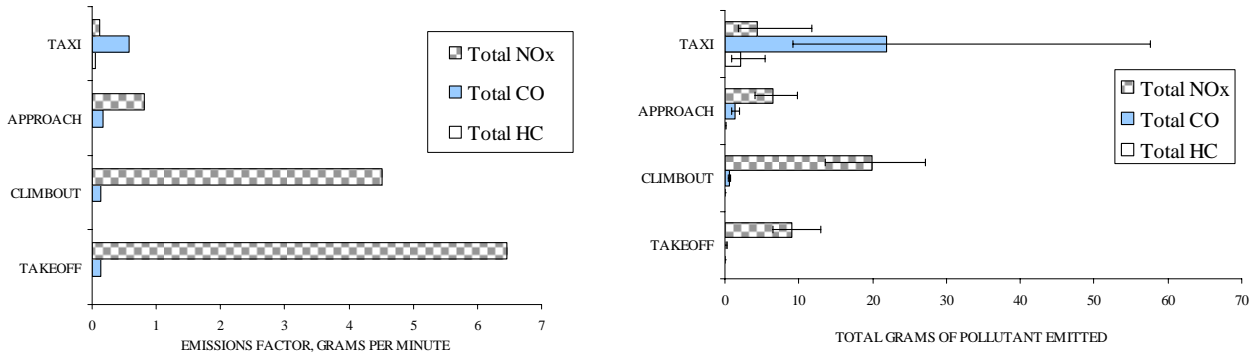


FIGURE 1 Airbus A-310 emissions as a function of flight stage (15)

Incorporating the information on average time in each stage, coupled with the variability of the time spent in each stage, we can develop the total emissions graph shown above. Variability was estimated from data regarding actual taxi-out times for aircraft at EWR. The EPA currently does not consider time-of-day variations in taxi-out time when determining emission inventories related to aircraft (16). Using the average taxi-out time value across all airports can be misleading because more congested airports can have higher than normal taxi-out times during peak periods. Clearly, the pollutant with the most emissions variability is for CO during the taxi stage of aircraft departure. This is due to a combination of higher emissions rates during low engine thrust and high variability in taxi-out times. The emissions for HC and NOx are also variable, but on a much smaller magnitude. NOx emissions are high for climbout due to increased engine thrust, but is not extremely variable because once an aircraft has taken off, it immediately continues on to cruising altitude.

3. METHODOLOGY & MODEL DEVELOPMENT

The research plan consists primarily of two components. We first wish to estimate fleet emission factors for aircraft in use at EWR. These emissions factors are combined with “travel activity” to determine the total emissions inventory for commercial jets at the airport on a given day. As discussed earlier, a queuing simulation model is used to determine the expected taxi times of aircraft as a function of their time of departure. This model shall be based on average arrival/departure data over a series of days. Finally, all of these results will be put together to quantify emissions reductions from a variety of mitigation strategies.

3.1 Emissions Inventory

Calculating emissions inventories is an important step in the model. They are calculated by the following formula given by the EPA:

$$E_{ij} = (TIM_{jk}) \times \left(\frac{FF_{jk}}{1000} \right) \times (EI_{ijk}) \times (NE_j) \tag{1}$$

- where: TIM_{jk} refers to the time spent by aircraft type j in mode k
- FF_{jk} refers to the fuel flow into the engine of aircraft type j in mode k
- EI_{ijk} refers to the emissions index for pollutant i produced by aircraft type j in mode k
- NE_j refers to the number of engines used by aircraft j

Since we only consider pollutants due to the taxi-out stage, we can eliminate the mode index (k) in the above formulation and thus use the following formula to determine the total emissions for a given pollutant from a given aircraft in the taxi-out stage of its flight.

$$E_{ij} = (TIM_j) \times \left(\frac{FF_j}{1000} \right) \times (EI_{ij}) \times (NE_j) \tag{2}$$

To use the above formula to determine the emissions at an airport on a given day, we require the knowledge of emissions factors for each different aircraft that is operated. The specific aircraft operated on a given flight on a given day could be determined via conversations with airline officials or through government databases. For illustrative purposes, however, we assume that on a typical day, the airport sees aircraft types in proportion with the weighted average of the carrier’s respective fleets. That is to say, if on average, carriers who use a particular airport have a fleet mixture of approximately 40% Boeing 737’s, then we assume that during the course of the day 40% of the flights are flown by Boeing 737’s. This assumption does not account for emissions produced by specific planes. There could possibly be an outlier of a departing aircraft with very high emissions indexes that ends up taxiing for a very long time, thereby skewing the results. On the average, however, we expect this assumption to hold true because the number of flights is sufficiently large over the course a day (on the range of 500 flights per day). Furthermore, since Continental Airlines dominates EWR in terms of daily number of flights, we just use their fleet mixture and assume it is representative of the entire airport’s operations. In general, this is a reasonable assumption because their market share at EWR is over 70%.

TABLE 1 Weighted Emission Factors for Taxi Time, Continental Airlines’ Fleet

Aircraft type	# in fleet	% of fleet	Fuel flow (lb/min)	Emissions rates (lb/1000lb)			Emission factor (lb/min) ^a		
				HC	CO	NOx	HC	CO	NOx
Boeing 777	18	3.06%	27.51	1.92	21.86	4.80	0.106	1.203	0.264
Boeing 767	26	4.42%	27.38	8.99	41.66	3.79	0.492	2.281	0.207
Boeing 757	50	8.5%	25.13	2.85	15.44	4.30	0.143	0.776	0.216
Boeing 737	253	43.03%	16.01	1.83	31.00	3.90	0.059	0.992	0.125
Regional Jets ^b	241	40.99%	10.25	0.55	20.15	3.10	0.011	0.413	0.063
							0.067^c	0.800^d	0.115^e

^a Emissions factor is given per engine; we assume 1 engine is used for taxi-time

^b Emissions rates are weighted average of ERJ-135 and ERJ-145 aircraft

^c Total weighted HC emissions for Continental Airlines, given in lbs per minute of taxi time per engine

^d Total weighted CO emissions for Continental Airlines, given in lbs per minute of taxi time per engine

^e Total weighted NOx emissions for Continental Airlines, given in lbs per minute of taxi time per engine

Fleet composition and weighted emission factors for Continental Airlines are shown in table 1, broken up by three of the primary criteria pollutants emitted by aircraft: hydrocarbons, carbon monoxide, and nitrous oxides. Fuel flow and emissions rate for each aircraft type is readily available from the EPA’s document on emissions inventory preparation procedures (11) and has further been updated by the International Civil Aviation Organization as new engine types are tested (15). As can be seen in the table, each aircraft type has different fuel flows and emissions rates, which consequently causes the total emissions factor to be different. In terms of CO emissions, the Boeing 767 factor is approximately two times more than that for the Boeing

737. This difference has an impact on the weighted emission factors shown in bold above. These emissions factors will be combined with the total amount of daily taxi-out time to determine the emissions inventory for Newark Liberty International Airport.

3.2 Airport Operations

All of the procedures outlined in section 2.2 entirely dictate the flow of traffic in and out of the airport. A simulation model was developed in a software package called ProModel and can be readily replicated in any other simulation package. In the model we take into account all of the airport features that have a direct impact on taxi-times, including taxiway configuration, runway usage data, terminal layout, and air traffic control rules. Specifically, for Newark Liberty International Airport, we assume a two parallel runway configuration where aircraft can perform simultaneous operations. Thus, an aircraft can be departing from one runway while an aircraft arrives on the parallel. Runways 22L and 22R are considered in this analysis because the prevailing winds usually dictate their use during peak periods of the day where weather is optimal (17). This is shown in the airport diagram of Figure 2. Occasionally, the runway configuration will switch directions and aircraft will use 4L and 4R for departures and arrivals, but the model developed does not include a possible change in runways. However, since the same runways are in use and only the direction of travel changes, there should not be a significant change in the results. It may be noted that the particular runway configuration (22L/22R) is used approximately 60% of the time (17). This number seems low because runway configuration will change when there are adverse weather conditions or changes in the wind. The model incorporates the three terminals at EWR, labeled A, B, and C. The majority of Continental's flights depart from terminal C, and other carriers' flights depart from terminals A and B. Finally, the air traffic control procedures discussed in the previous section are also incorporated into the model.

The model results presented in the following section assume that only one engine is used on taxi-out. This is known as reduced engine taxiing and is commonly practiced among the major carriers to save fuel (11). Additionally, for any redistribution plans we assume an 18 hour flight day from 6:00am to 12:00am. Based on our analysis of current departure times, this is a reasonable assumption as there are few departing flights during the remaining 6 hours of the day.

Data for the model were obtained from the Bureau of Transportation Statistics detailing the aircraft departures from EWR on a summer day in 2005. Table 2 shows a summary of this data. Some clear trends can be observed. EWR experiences a peak hubbing period in the morning hours between 6:00 and 10:00am, where the number of departures per hour is approximately 35. During this period, average taxi time increases to an average of 54.4 minutes, with maximums exceeding 60. By the time the early afternoon period comes, the number of departures decreases as Continental does not fly a lot of flights at that time. Expected wait times until takeoff remains under control until the peak evening period around 6:00pm, when taxi times increase once again. In general, higher estimates of average taxi-out time correspond to higher variability between data points. In the simulation model, a non-stationary Poisson process was used to account for the variation in actual departure times over the course of a day.

TABLE 2 Departure Data from Newark Liberty International Airport, 8/10/05

2h time interval	Number of departures	Average taxi-out time	Comments
6:00am to 8:00am	72	32.5 minutes	Peak AM period
8:00am to 10:00am	68	54.4 minutes	Peak AM period
10:00am to 12:00pm	40	27.4 minutes	Low taxi times
12:00pm to 2:00pm	51	18.0 minutes	Low taxi times
2:00pm to 4:00pm	55	22.6 minutes	
4:00pm to 6:00pm	55	26.2 minutes	
6:00pm to 8:00pm	59	46.1 minutes	Peak PM period
8:00pm to 10:00pm	43	39.8 minutes	
	444	32.20 minutes	Over whole day

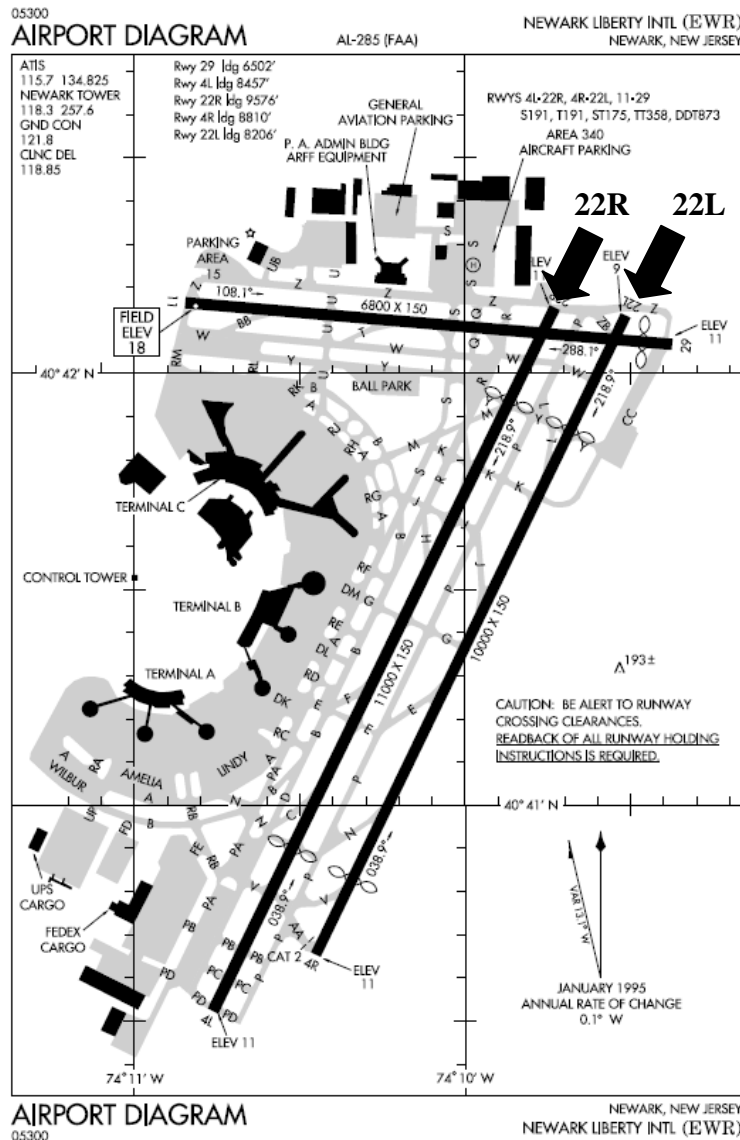


Figure 2 Airport diagram of Newark Liberty International Airport (18)

Departure data shown in Table 2 is shown pictorially in Figure 3. The same trends as discussed above can be seen in this figure below. One noteworthy observation is that increased

taxi times tend to lag the increase in number of departures by approximately 30 minutes to an hour. This occurs because the departure queue increases in length at a faster rate than with which it dissipates. Thus queues tend to build up even after the number of hourly departures starts to decrease. After the morning peak period ends, it takes over an hour to see a substantial reduction in average taxi times.

The simulation model was run for 100 iterations to generate statistically valid results at the 95% confidence level. The results give us an approximate idea of how the taxi-out times experienced by aircraft over the course of the day relate to the amount of traffic at the airport. Using the base case data, the simulation results compare favorably to what is actually experienced at the airport.

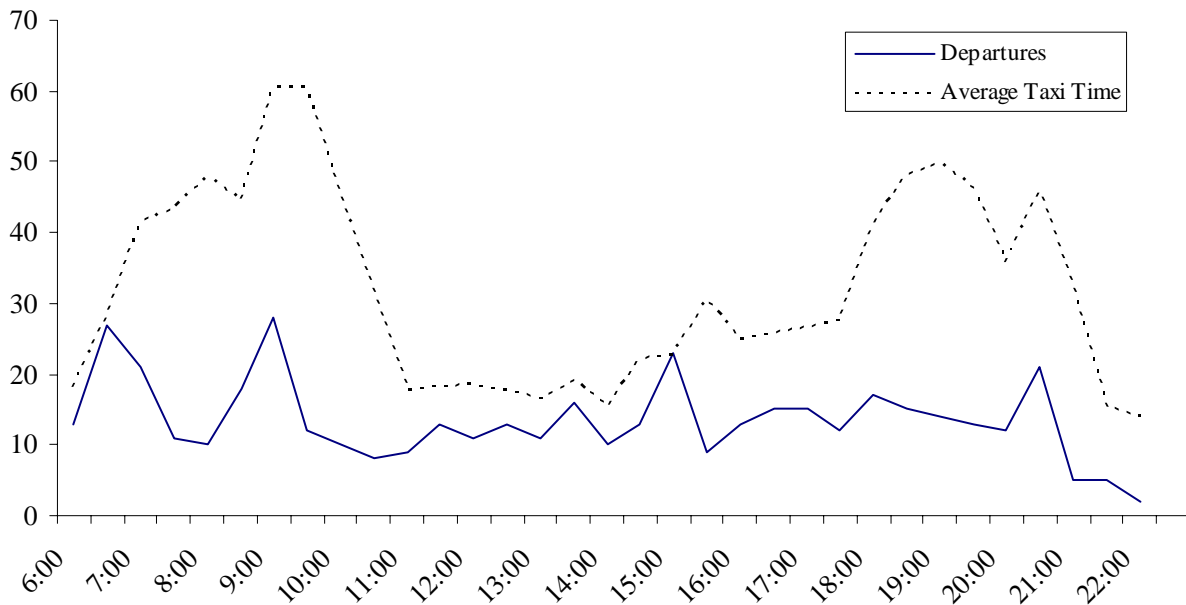


Figure 3. Number of departures and corresponding average taxi times for EWR, 8/10/05 (9)

4. RESULTS

4.1 Base Case Scenario

Based on the fleet composition estimated in section 3, total emissions during the taxi-out stage were calculated over the course of the entire day for each of the three criteria pollutants. HC emissions were estimated to be 1026 lbs, CO emissions 12,251 lbs, and NO_x emissions 1767 lbs. In further sections of this paper, this is referred to as the base case scenario.

To determine the significance of these results, two separate periods during the day were analyzed further—both a peak period and an off-peak period. Specifically, we chose the periods such that the number of departures was the same so that the only difference would be the average taxi time over the period. Between 7:00 and 9:30 am, there were 100 departures with an average taxi time of 50.5 minutes, whereas between 11:00 and 2:30pm, there were 96 departures with an average taxi time of 18.26 minutes. Corresponding CO emissions for each period was 3053 lbs and 1137 lbs respectively, which represents a difference of nearly a factor of three. Similar results were found for both HC and NO_x. Thus, the average amount of emissions per aircraft

during the peak period is almost 3 times higher than the average emissions per aircraft during the non-peak periods. This finding suggests that not only are peak periods at hub airports the source of extreme departure delays, but also that they are the source of much higher levels of taxi-out pollutant emissions.

The levels of pollutant emissions over the course of the day can be attributed to the variation in number of departures, which consequently affects taxi-out time. This variation is shown in Figure 3 and results in airlines capitalizing on the hub-and-spoke system. One possible solution to this problem would be to redistribute the flights over the course of the day. We can assume that an extremely high proportion of flights would be scheduled between 6:00am and 12:00am, an 18 hour period. Generally flights are not scheduled in the remaining 6 hours since it is during the middle of the night. The analysis assumes that flights would be redistributed at uniform intervals, which is something that could be mandated by the FAA if congestion levels get too high. If the approximately 450 daily departures were spread over the assumed 18 hour period, simulated average taxi times would be 20 minutes. This corresponds to total CO emissions of 7200 lbs, a 43% emissions reduction from the base case scenario. Again, similar reductions are achieved for the other two criteria pollutants. Clearly, from an environmental standpoint, the redistribution of flights can be a useful strategy in reducing emissions. On the other hand, there are likely to be issues of equity among the airlines. If only one departure slot is available at 8:35am, how can one determine which airline should receive that slot? Furthermore, how should the airline that gets that particular slot incorporate it into their flight schedule? Clearly there are implicit tradeoffs here that are beyond the scope of this paper, but should be incorporated into any further analyses.

Up to this point we have been making associations between reducing delays and reducing emissions from excessive taxi time. However there is an important distinction between the two. Note that not all of the taxi time directly corresponds to delays. Clearly, it takes a certain amount of time for the aircraft to taxi from the gate to the runway in perfect conditions, and this number can not be reduced unless the layout of the airport changes. For EWR, this number is estimated to be approximately 5-10 minutes depending on the runway configuration. For the purposes of this analysis however, the effect on emissions remains the same.

4.2 Variations in Fleet Composition

One important question to ask is how the fleet composition of various airlines will change over the next decade. Can they afford to purchase new aircraft or will they need to remain with the older types that have higher emissions? It is possible that low-cost start-up airlines will tend to buy newer aircraft with lower emissions, whereas the bankrupt legacy carriers will have no choice but to make do with the aircraft they have and keep their current fleet for an extended period of time. If the latter is the case, fault can not be put onto the struggling airlines, but rather to the FAA and other governmental organizations that need to work quickly in updating air traffic control procedures and redesign the airways so that our country can effectively handle the forecasted increase in traffic.

Still, we can quantify the emissions differences between one airlines' fleet and another airlines' fleet. Currently the differences are varied, as some airlines have a mixed fleet of a variety of Boeing and Airbus planes, along with regional jets, whereas some carriers such as Southwest and JetBlue have a single aircraft type. For illustrative purposes, we compare two different fleet composition scenarios to that of Continental Airlines. This could arise due to a fleet upgrade, engine retrofitting policies, or a requirement by EPA to purchase newer, more fuel efficient equipments. Environmental improvement need not be the motivation behind any of

these scenarios; instead it may be the case that specific aircraft are cheaper to operate or are able to transport more passengers.

We consider two alternative scenarios in which the fleet composition is different than the base case presented in Table 1. Scenario A considers an airline whose fleet is made up of 56.5% Airbus A-320s, 6.5% Boeing 757s, 20% Boeing 737s, and the remaining percentage of regional jets. This composition is loosely based on US Airways fleet, which makes it a somewhat realistic number for this analysis. Scenario B considers an airline whose fleet is made up of solely Airbus A-320s. This figure is based on JetBlue Airways who, as of July 2005, operates only one type of aircraft.

Both Continental Airlines and US Airways are similar airlines in that they operate hub-and-spoke systems, although their focus airports are different. US Airways operates a smaller number of regional jets, whereas regional service is a primary focus of Continental. JetBlue generally does not operate a hub-and-spoke system as elaborate as Continental or US Airways.

Table 3 shows the effect of fleet composition on total emissions for a given airline. Implementing these fleet composition changes tends to decrease both HC and CO emissions, but actually has the opposite effect on NO_x. This is solely due to the variation in engine design among the different aircraft that are used in each of the scenarios. We see, however, that the percentage decreases in emissions from the base case for both pollutants are approximately 30%. Remember that these reductions only change the fleet composition and do not consider changes in the redistribution of flights as discussed above. One can imagine that these effects would be multiplied if both strategies were implemented simultaneously. Furthermore, while NO_x emissions does increase, it is negligible compared to reductions achieved in both HC and CO.

TABLE 3 Effect of Fleet Composition on Total Emissions

Scenario	Total emissions per airline (lbs)			Percentage change from base case		
	HC	CO	NO _x	HC	CO	NO _x
Base case	777	9248	1334	N/A	N/A	N/A
Scenario A ^a	554	7110	1405	- 28.7%	- 23%	+ 5.3%
Scenario B ^b	511	6055	1467	- 34.2%	- 34.5%	+ 10%

^a This scenario corresponds to a fleet with approximately 55% Airbus A-320 aircraft

^b This scenario corresponds to a fleet made up of all Airbus A-320 aircraft

4.3 Variations in Number of Departures

As domestic air travel is expected to increase substantially over the next decade, it is important to understand those effects on emissions. The simulation model developed can be used to determine the taxi-out times at an airport when the daily demand is increased. Similarly, we can use the model to understand what happens if an airline (e.g. Continental) decided to abandon a traditional hub-and-spoke system and redistribute their traffic more evenly in the network. This may happen in the future as there is increased demand between smaller cities that can now support mainline flights, rather than connecting through a hub airport.

Table 4 shows the emissions effects when the number of daily departures both decreases and increases. Note that this assumes the flights are distributed evenly over the course of the day. The decrease can be considered to come from a network distribution where Continental Airlines removes their hub flights to and from EWR and replaces with them direct point-to-point service between the other cities. It is estimated that approximately 33% of Continental's EWR flights are so-called hub flights, so we thus consider a 33% reduction, resulting in 315 daily departures.

Emissions benefits are modest in this case because, as mentioned earlier, there is a limit as to how low the taxi times can be, based on airport layout.

TABLE 4 Effect of Number of Daily Departures on Total Emissions

Daily departures	Simulated average taxi time	Percentage change of emissions	Percentage change of departures
315	15 minutes	- 25%	- 33%
450 (base case)	20 minutes	N/A	N/A
570	35 minutes	+ 50%	+ 30%

The increase of daily departures is representative of the forecasted demand in the year 2015. The worst case scenario in terms of number of departures would be an approximate 30% increase, corresponding to about 570 daily departures. Thus, there would need to be extreme system improvements to handle this excess demand; however we assume that there are neither capacity improvements nor changes in the current fleet compositions for the sake of illustration. Furthermore, we do not consider technological changes which may decrease actual emissions factors. Still, these results provide a glimpse into how overcrowded our nation's airports are becoming and how this affects total emissions. For this case where there is a 30% increase in departures, the amount of emissions increases by 50%. It is important to note that these analyses were just performed on the average number of flights per day rather than considering the actual duration of taxi time for each individual aircraft.

5. CONCLUSIONS & FUTURE RESEARCH

This study has shown that airlines using less congested airports and don't rely on hub-and-spoke systems generally have lower taxi-out times and thus lower emissions. From an environmental standpoint, this is extremely critical. We also determined that up to a 40% reduction in CO emissions can be achieved by simply redistributing the flights over the course of the 18 hour work day. Reductions of 20% to 30% in both HC and CO emissions can be achieved by changing the fleet composition, albeit with a slight increase in NOx emissions. Clearly, as the number of departures increase and congestion gets worse in years to come, emissions will increase at an alarming rate. Emission reduction strategies addressing aircraft taxi-out emissions through congestion mitigation and fleet restructuring can lead to significant emissions benefits and could play a critical role in meeting environmental challenges for future aviation. A natural following-up research can look into the specific implementation and operation layers of airport congestion mitigation and airline fleet management strategies to accommodate future aviation demands as well as environmental needs.

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