Measurement and modeling of aircraft emissions consecutive to single runway operations

SESAR Exercise

Case Study - Orly Airport

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Chapter 1

Introduction

1.1 Contextualization and presentation of case study's objectives

This case study responds to different objectives and operational constraints that will be briefly presented in this paragraph. The challenge is to respond as effectively as possible in the developments that will be presented further on.

The context of this case study addresses an operational need of APOC[1] as part of the airport platform management activities. European regulations require aerodrome operators to perform runway inspections to ensure safety during operations. These inspections can be visual and/or technical, with a variable duration depending on the objective of the inspection. A regulatory visual inspection of a runway is performed 3 times a day at Orly with a minimum regulatory duration of 10 minutes . The minimum separation between two inspections, the interval considered being the time between the beginning of one inspection and the beginning of the next, is of 5 hours. Technical inspections, also required by regulation, are generally longer.

As these inspections are scheduled during the day, it is important to find the most optimal time slot to minimize the emissions generated while having the least possible impact on the management of flows on the platform.

1. The first objective is to quantify the emissions associated with a type of movement, given a given configuration of the airport. The particularity of Orly airport, as shown on the map 1.1leaving aside runway 02-20, lies in the fact that the configuration directly determines the runways in use. The objective is therefore with the information on the flight (the type of aircraft used) and a configuration[2],to be able to estimate the emissions generated. The volatile emissions to quantify are those of CO_2 and NO_x, as well as the consumption of d'AVTUR[3]. When a runway inspection is simulated, all movements that were allocated to the runway being inspected must be redirected to the other remaining runway.

2. One of the objectives of the study is also to quantify the operational impact related to the choice of runway inspection slots. Indicators on the number of flights impacted by this slot, the taxiing time/distance associated with the inspection scenario allow to quantify this impact.

1.2 Perspective of achievements

In order to minimize the pollutant emissions generated by aircraft during the LTO cycle on an airport platform, especially during the taxiing phase, it is necessary to have an accurate modeling and mapping of the taxiways

[1]Airport Operation Center
[2]East or West
[3]Aviation Turbine Fuel

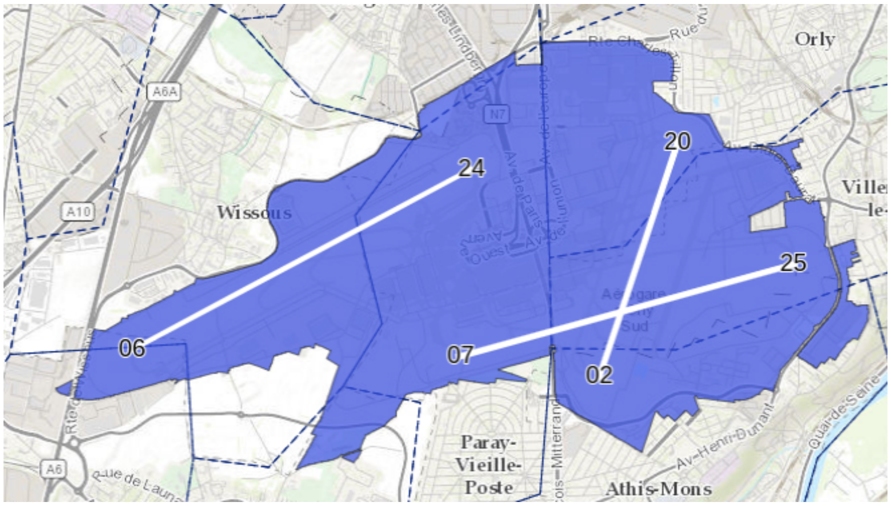


Figure 1.1: Map of runways at Orly airport

of the airport as well as a realistic modeling of the different waiting areas that may be encountered during the operation. Here the part of the LTO cycle specifically studied is limited to the taxiing phases, for a departure at the moment when the aircraft leaves its stand at the end of the push-back, until the moment when it leaves the runway threshold to align itself before take-off. For a landing, the interval considered is from the moment the aircraft leaves the Category III area at the runway clearance to the moment it reaches its stand. An accurate estimation of the distances that an aircraft has to travel when leaving or arriving at the platform, associated with the addition of the additional time encountered during the waiting phases on the taxiway, makes it possible to model all the emissions generated by the turbojet engines of an aircraft over the considered phases of the LTO cycle.

To obtain these different emission values, several methods are known and possible here:

- **Method 1 - Abstraction using Eurocontrol A-CDM milestones :** The turnaround milestone values from the Network Manager (Eurocontrol for the European area) can be used directly to obtain generic turnaround times, such as AOBT[4], ALDT[5] and thus estimate the average taxi time. Once these milestone durations are associated with the timestamp of their observation and the associated flight number, a learning process can be performed (by classical Machine Learning methods) to learn the different taxiing trends associated with the different times of the day and periods of the season. There are several caveats to this method.

  First, One of the first-order factors influencing taxi time (and thus ipso facto the amount of emissions generated) is simply the estimated distance between the aircraft's departure point and its arrival point.

  Secondly, the reliability of the milestones is difficult to estimate, apart from discarding outliers, not much cleaning and data preparation can be done. We thus have a method which gives at the end of the calculation chain very few details on how to obtain the result.

  Finally, trying to perform a learning on too generic data risks strongly to bring error-prone results. In this method the data of all departing and arriving aircraft will be mixed, independently of the usage QFU since this information is not present in the API. In addition, this method mixes the duration associated with runway pressure and taxiing.

- **Method 2 - Abstraction using the milestones calculated by ASW Analytics with the AVISO flow :** We can use directly the radar data of the ASTERIX flow present at Orly airport, and associated with a

[4] Actual Off-Block Time
[5] Acual Landing Time

large history of radar data we can try to estimate the emissions. Milestones of the different phases on the ground are dynamically detected by ASW[6] Analytics. Performing a learning process on these data would make it possible to overcome the limitations of the first method by refining the milestones obtained, by dissociating the duration resulting from the time spent moving on the taxiway from the waiting time not related to taxiing (for example, related to waiting at the threshold of the runway to obtain takeoff authorization). However, we quickly reach the same type of limitations as before with respect to the number of possible combinations of stands associated with the number of QFUs and also multiplied by the number of configurations. This does not allow us to obtain a high level of modelling accuracy with regard to such variability of the data by a matrix learning method (regression model, forest of decision trees). Even the use of so-called "boosted" models, which consist in the use of a large number of small simple estimators, risks reaching a performance ceiling because of this limitation.

- **Method 3 - Abstraction of airport dynamics using a taxiway graph and ASW milestones:** The last possibility considered would be to use the radar data from the ASTERIX flow again, but this time instead of abstracting the data and summarizing them by numerical values, the radar tracks would be directly used to automatically learn the set of possible routes on the taxiway. Once this rolling graph is obtained, one can define entry and exit points on the graph and by means of route heuristics, use the path that is the most faithful to the one observed in real situation. Often this path can be determined automatically by a classical shortest path algorithm (Dijkstra for instance).

  This allows us to obtain the distance component which directly determines the time spent travelling the distance between the arrival point and the departure point on the taxiway. An analysis of the distribution of the waiting times at the threshold in the different configurations allows us to estimate the waiting time at the runway threshold using a Monte-Carlo type method, by modeling this phenomenon by a normal distribution with parameters taken from the real statistical distribution.

1.3 Choice of Methodology and Associated Preliminary Achievements

With regard to the operational context of the case study, the different determining points between the different methods are :

- The sensitivity of the training model to the parameters of the operating configuration and the QFUs that are used or closed for inspection. The modification of one of these parameters must produce significantly different taxiing times, within the same orders of magnitude of what can be observed in real situation.

- The explicability of the model should make it easy to determine how this numerical value obtained (taxiing time, taxiing distance) was calculated by the model.

With regard to the first point, the 1st and 2nd methods may not be sensitive enough to these parameters, or the effort of complexity to be brought to obtain such a sensitivity may be too great, leading to a model that is intrinsically not very generic and generating important errors on certain situations (overfitting or short of variance). The 3rd method allows to take this specificity directly into account in its construction, without losing genericity.

Regarding the second point of attention, the two firsts methods suffer from a weak explicability, in the sense that one can explain the influence of each variable used in the model by different methods (SHAP Values[7] as described in (Lundberg and Lee, 2017), Dependency plots, Correlation matrix..) but not getting direct overview of a single forecast explanation. The 3rd method, by direct visualization of the chosen path on the taxiing graph allows a concrete explanation of the numerical value returned by the algorithm. Moreover, the strict separation

[6] AirsideWatch, radar flow analysis platform developed by Safety Line
[7] SHapley Additive Explanation

of the value obtained by the calculation of the pure taxiing and the value obtained by the calculation of the waiting at the runway threshold (for takeoffs only) allows to refine this output value.

Naturally, in order to meet the objectives of the study and considering the various elements mentioned above concerning sensitivity and explicability, the methodology of the case study that will be chosen will be that of the method N°3.

Chapter 2

Practical Case - August 2021 Study

2.1 Presentation and achievements of the preliminary work

In order to obtain a taxiing graph of the Orly platform, several methods exist:

- Retrieve a description file of the taxiways and extract the GPS coordinates.
- Use image processing and topological graph refinement methods from a radar data stream.
- Query objects stored in the APIs of Open Source geographic data repositories (Open Street Map) and process them to extract a graph.

As method n°2 is well documented and already performed on Roissy-Charles de Gaulle airport, this method (Biagioni and Eriksson, 2012) will be used and presented very briefly here. The mandatory input data are :

- Radar flow trajectories (with at least the GPS positions in WGS84 format) on the considered taxiing sections
- Aircraft types associated with these trajectories
- A stand and a QFU, point of departure or arrival depending on the type of movement (take-off or landing)

- **Step 1 :** Extraction of raw trajectories and transformation into a binary pixel matrix.

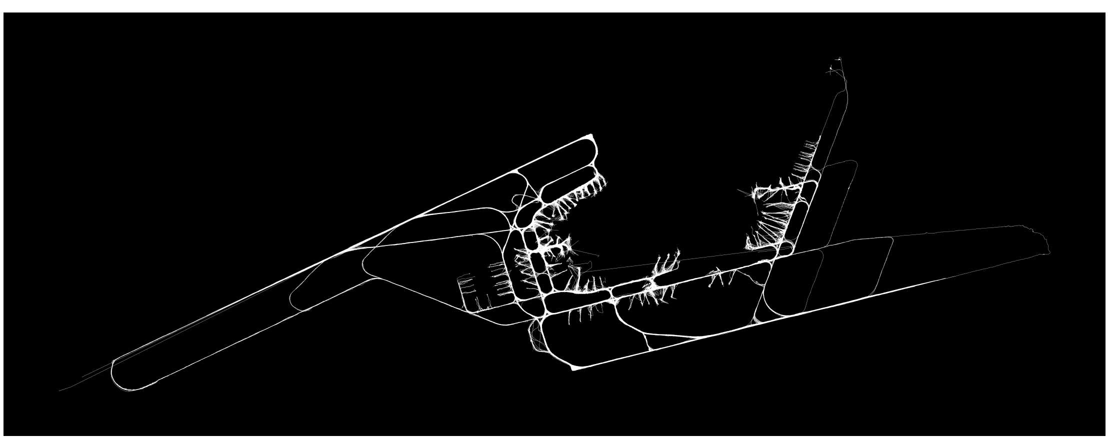


Figure 2.1: Binary matrix of all trajectories

- **Step 2 :**Estimation of the density on the platform by a Gaussian kernel estimator.

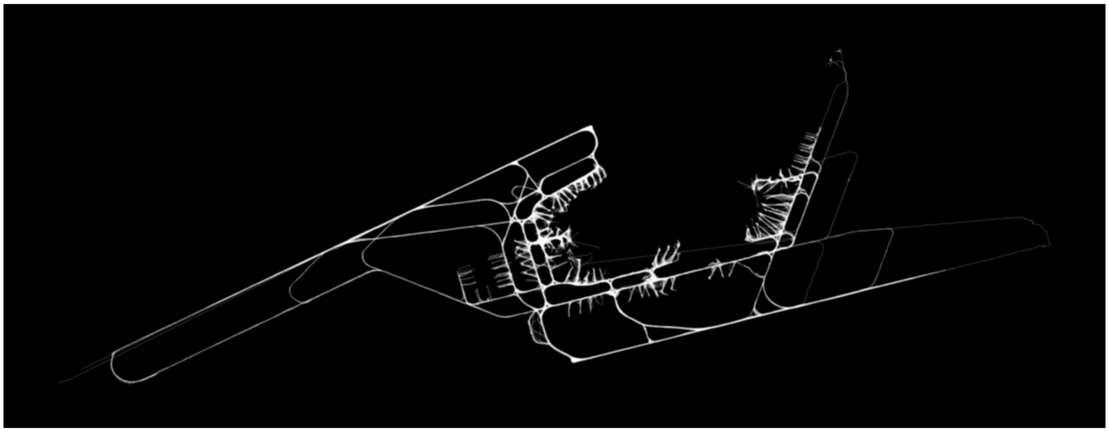


Figure 2.2: Density matrix using a Gaussian kernel estimator

- **Step 3 :** Extraction of the skeleton from the density matrix and generation of the graph from the obtained skeleton using the method (Zhang and Suen, 1984).

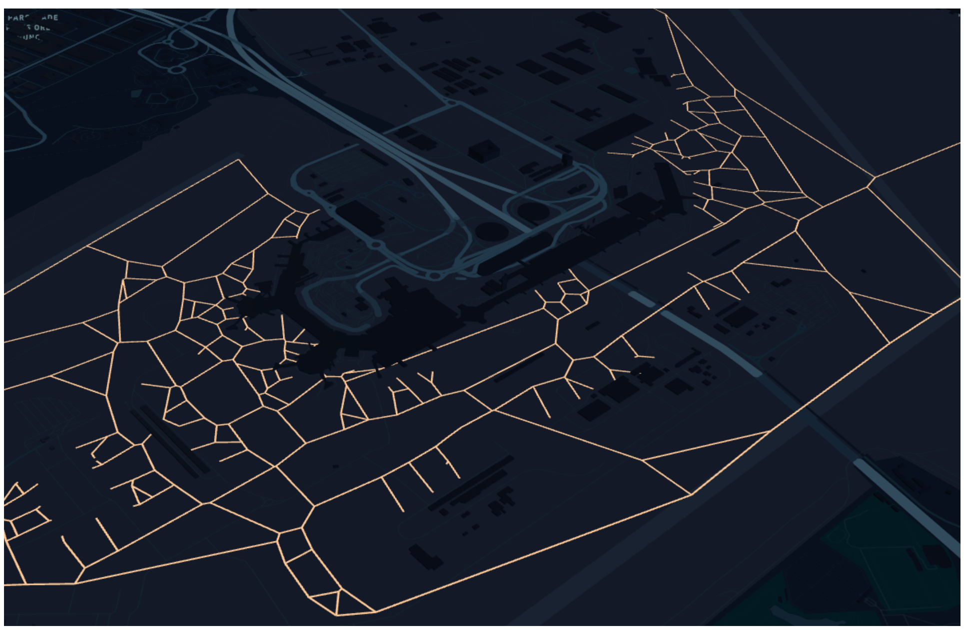


Figure 2.3: Taxiway graph of Orly airport

2.2 Analysis of the Orly data and modeling of the variables for the study

In order to calculate the emissions generated on the platform, different assumptions are used to characterize some variables of our problem. We will detail the calculation method and the list of assumptions considered.

2.2.1 Calculation of the emission indices associated with the different pollutants

First, we need to calculate the kerosene consumption of aircraft engines during movements on the airport taxiway. To perform this calculation, we need to model a function point of the turbomachinery mounted under the wing of our aircraft. The literature, as described by (Nikoleris et al., 2011) considers 4 distinct ground phases, for which are associated an operating point :

1. <u>**Constant speed**</u> These portions of trajectories are represented by positions where the aircraft is going in a straight line, for example, with a constant speed. It is usually observed in the QAR[1] data that the engine rates are constant on these phases. The scientific literature states that the *usual* engine speeds on these phases are of the order of 4%. When studying the QAR data, we find variations and these rates are rather of the order of 20%.

2. <u>**Acceleration**</u> These operating modes are characterized by phases where the pilot will increase the engine rate in order to increase speed value. With the same considerations as the previous phase we could observe that the average engine speed during these phases was about 35% where the literature recommended a speed of 9%.

3. <u>**Turns**</u> he QAR data shows that the average speed of these phases where the aircraft will make a turn (perpendicular turn) is substantially invariant with the phases at constant speed, while the literature tends towards an engine speed of about 7% for these phases.

4. <u>**Stops**</u> It is not uncommon that during taxiing phases, an aircraft must stop to let another aircraft pass, wait for a GH[2] to handle it, that an aircraft on takeoff remains at the threshold waiting for the ATC[3] clearance to line up on the runway. During these phases when the engine is at minimum speed, the literature states that the engine speed is around 4% while the QAR data tends to show that the engine speed is approximately the same as in the constant speed phase.

This study of the QAR data, carried out on the LFPG platform with 4 Boeing 777 Freighters performing the same trajectory, represented in figure 2.4 on the taxiway shows that depending on the way of piloting, depending on the load of the aircraft because of the generated inertia but also depending on the real performances of the turbojets under the wing, the consumption law in function of the the speed is not the same between them.

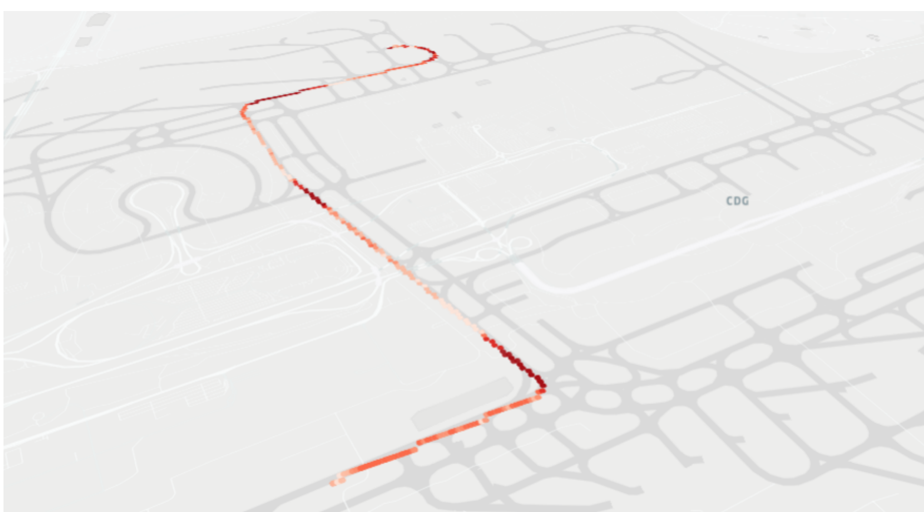


Figure 2.4: Considered trajectory (in red, the zones where the engine rate is high)

Indeed, for these same 4 trajectories, where we can see in the figure 2.5 that the steering profiles are not similar, where :

[1]Quick Access Recorder,data recorded by the sensors in flight
[2]Ground Handler
[3]Air Traffic Control

- The orange and green curves curves represent the 2 engine rates, in %.
- The blue represents the speed in km/h.

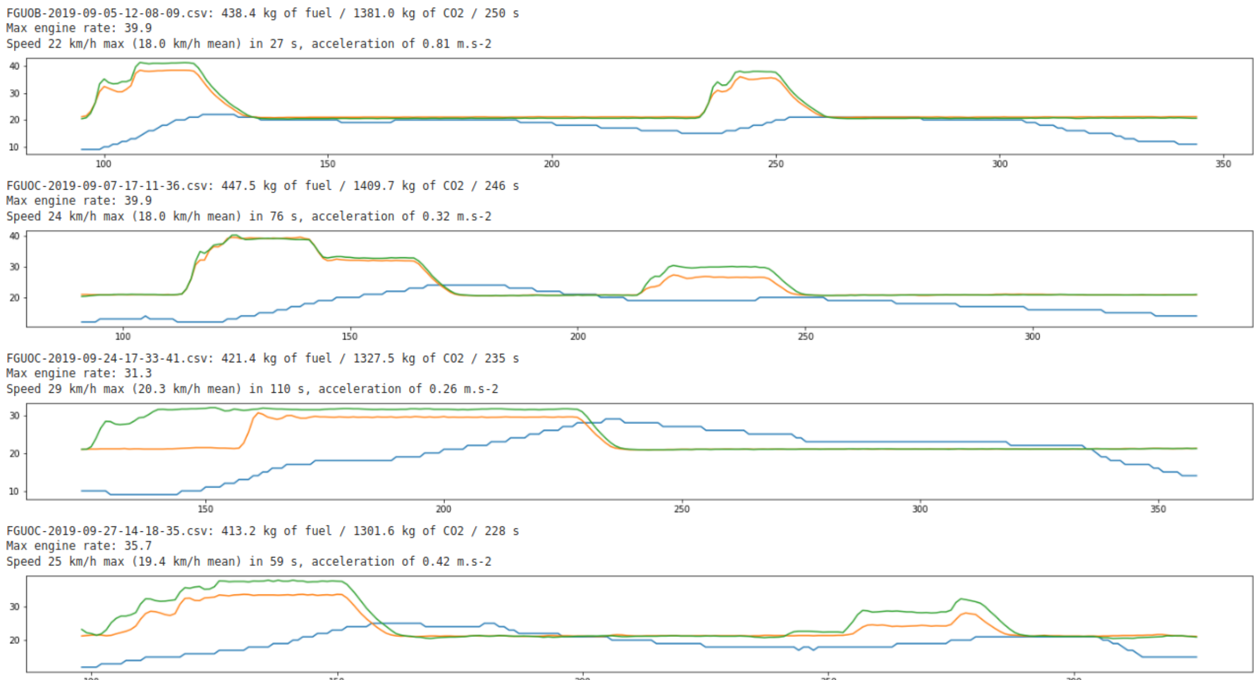
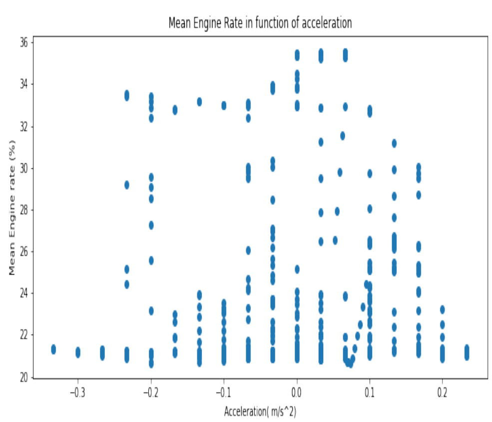
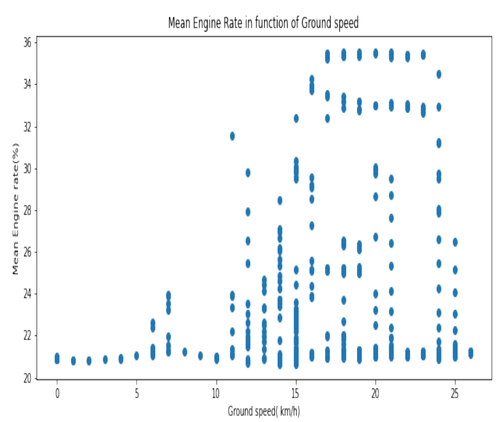


Figure 2.5: Different taxiing profiles for the same path

The difference in consumption represents magnitudes below 10% of the total kerosene consumption but this highlights that a direct and simple law cannot be obtained directly to obtain the engine speed by reading the speed of the aircraft. This is supported even more by the graphs of relation in figure 2.6 where relations of linearity (or at least of injectivity for the function which links the engine speed according to the speed or the acceleration) should have appeared if it had been the case.



(a) Average engine rate as a function of acceleration



(b) Average engine rate as a function of ground speed

Figure 2.6: Dependency plots of mean engine rate and speed/acceleration

For the case study, we will consider an average engine rate during taxiing (around 24%),the acceleration phases being a minority in the movements. This engine rate is associated with an average speed of 21.4 km/h.

From this average engine rate and the engine of our aircraft, we can deduce a value of kerosene flow consumed, by interpolating the consumption law and the various emission indices of each pollutant according to the engine rate provided by the*Aircraft Engine Emissions Databank* of ICAO. The emission indices, denoted EI, are values expressed in grams per kilogram of fuel, and their calculation is detailed in equation (2.1).

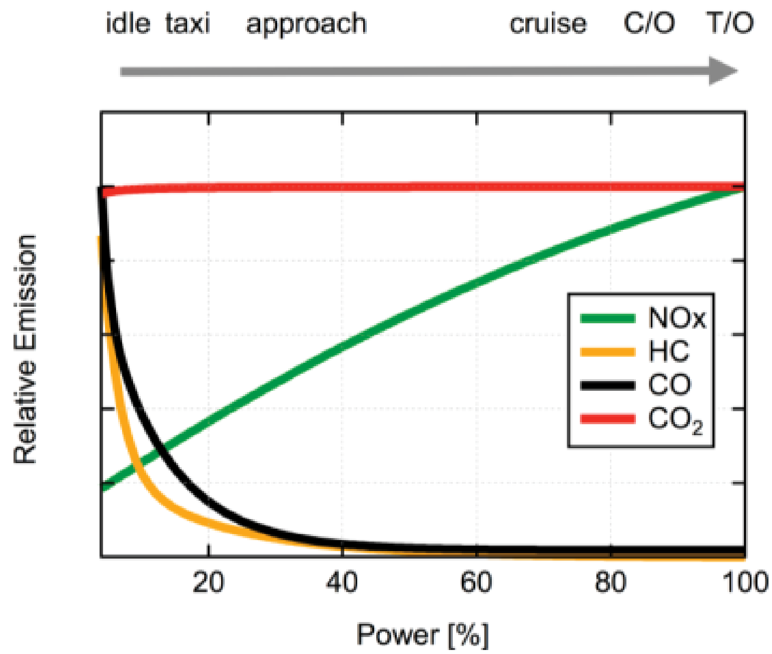


Figure 2.7: Example of emission index trends as a function of engine rate for a turbojet engine, from (Yacovitch et al., 2016)

Once this kerosene consumption associated with engine operation is known, it is therefore possible to deduce the CO_2 and NO_x emitted.

To compute, in the same manner as proprosed in (Yacovitch et al., 2016) the compound released X into the consumption by the turbomachine under the aircraft wing, an emission index EI_x, which is the value of increase in the concentration of compound X relative to the increase in the concentration of CO_2, is defined. The trends of the different EI for each compound emitted can be found on the graph 2.7.

- For the quantity of carbon, noted F_{CO_2} contained in the kerosene, we will take a classic Jet A fuel, with 3160 g of CO_2 per kilogram of fuel.
- The value 44 corresponds to molar mass of CO_2 in g/mol.
- MW_X is the molar mass of compound X in g/mol.
- In practice, the term $\frac{\Delta C_x}{\Delta CO_2}$ should be expressed in $\frac{\Delta C_x}{\Delta C_{Tot}}$ but this method of calculation considers that the CO_2 is the major carbon compound of the combustion. Indeed, this hypothesis is valid for turbojets, where the other carbon compounds (CO, CH_4, HC) are in the minority in the exhaust gases. This assumption is not valid for piston engines, which are not referenced in the ICAO database and are not calculated here.

$$EI_x\left[\frac{gX}{kgFuel}\right] = \frac{\Delta C_x}{\Delta C_{CO_2}} MW_X \frac{F_{CO_2}}{44} \tag{2.1}$$

For example, for a Boeing 777 Freighter powered by 2 GE-115B, here is the graph 2.8 showing CO_2 emission as function of engine rate,with interpolated emissions indices.

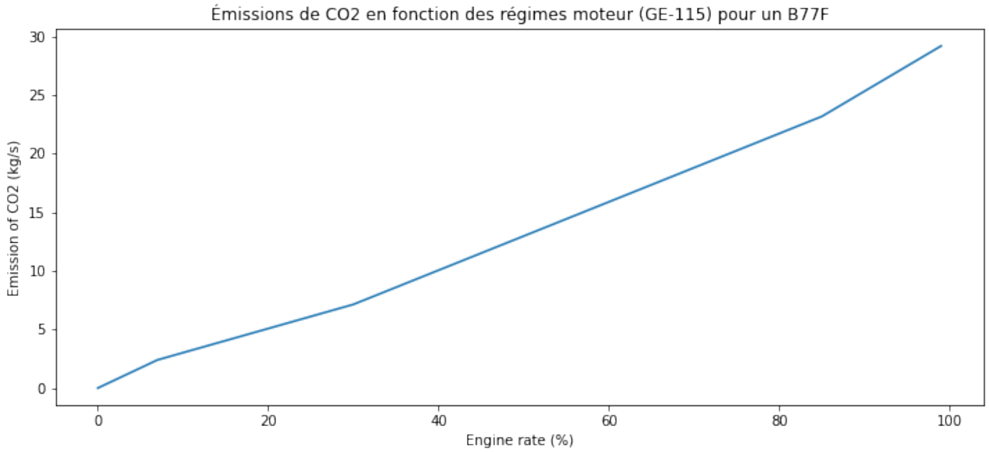


Figure 2.8: CO_2 emission graph for a B777 Freighter

2.2.2 Calculation of the waiting phases associated with stops at the runway threshold

When an aircraft presents itself at a runway threshold to perform its takeoff, it must be cleared by ATC to enter the runway and perform its alignment. This waiting time can be more or less long depending on the capacity of the runway and the number of movements, the different movements must respect a regulatory separation time.

These different events induce a waiting time at the threshold during which the turbomachines are running and thus consume kerosene and generate emissions, despite the fact that this consumption does not actively participate in the taxiing on the runway.

To model this phenomenon, we will distinguish two runway states, specific to the operation observed at Orly airport :

1. **Normal state :** Situation where the runway is in normal use, i.e. it receives only one type of movement from all flights to or from the platform. Its load is therefore lower and the waiting time at the runway threshold is therefore considered to be in its normal value.

2. **Mixed mode state** Situation where the runway is not in its classical use, it is receiving all the movements of the platform, because of an inspection on the other runway or because the other runway is temporarily closed. Its load is therefore higher than normal and the waiting time at the runway threshold will be on average higher.

This type of phenomenon is classically modeled by a normal distribution, whose parameters (mean μ and variance σ^2) will have to be adjusted to fit with the distributions of the real waiting times. Its probability law is written :

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{2.2}$$

Waiting at the runway threshold does not follow a normal distribution in its statistical distribution, it is strongly asymmetrical towards low values, with a concentration of values on zero (proportion of aircraft that will not wait). We will separate the planes into 2 categories and determine the distribution via a uniform distribution:

- Aircraft that experience a hold at the runway threshold, in proportion p

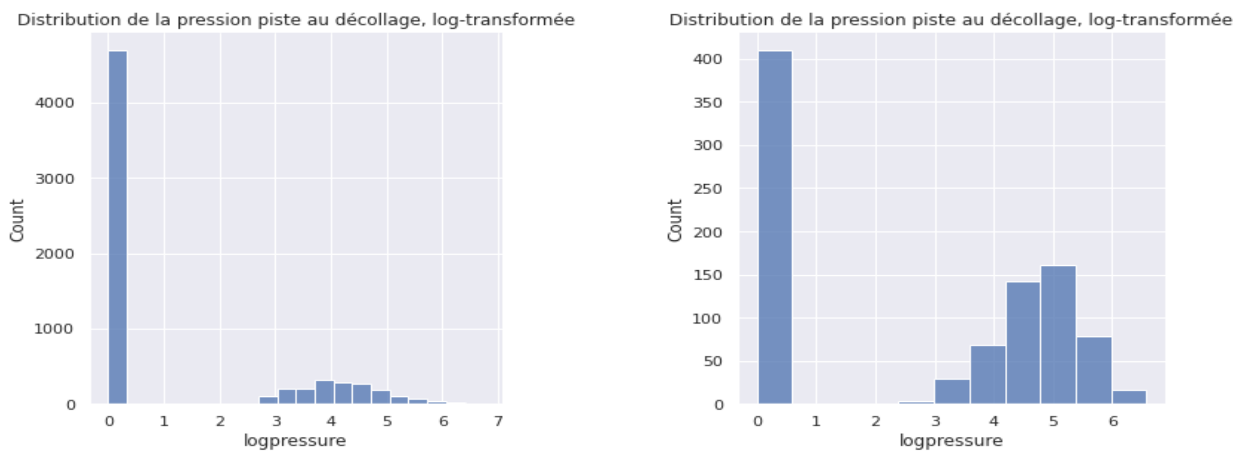
- Aircraft with no hold at the runway threshold, in proportion $1-p$.

For runway threshold expectation values strictly greater than zero, it will be necessary to perform a transformation to reduce the random variable to a normal distribution and to be able to use a Monte Carlo type modeling method (which assumes the mandatory condition of the application of the central limit theorem to the random variable associated with runway pressure).

To model correctly the phenomenon of this waiting time, a logarithmic transformation will be performed, with x_{log} the transformed runway pressure, called *logpressure*, and x_{real} the value of the real runway pressure, in seconds.

$$x_{log} = log(1 + x_{real}) \tag{2.3}$$

This gives the distribution presented in figure 2.9 according to the 2 states.



(a) Normal state

(b) Mixed mode state

Figure 2.9: Pressure distributions in the 2 operating modes

To obtain these distributions in order to estimate for each of the two modes the proportions of flights with and without waiting, as well as to parameterize the expected value and standard deviation of the normal distribution of the runway pressure according to the 2 operating states, days with a closure of one of the 2 QFUs and days without closures were selected to extract the distribution of the standard deviation.

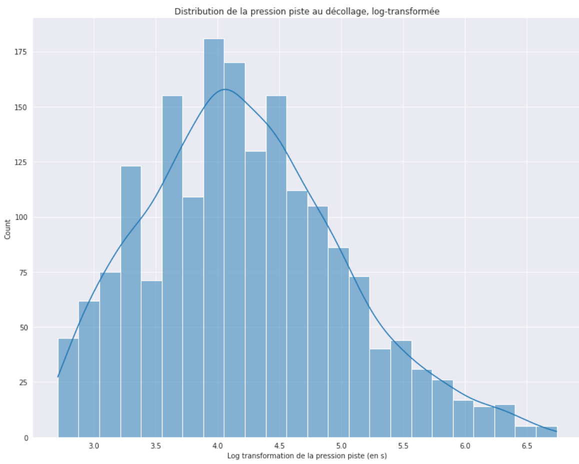
- For the data with runway closures, 5 days of August 2021 were selected, from Monday 9th to Thursday 12th when QFU 06/24 was closed, all flights were redirected to QFU 07/25. On these 926 flights we observe an average waiting time at the runway threshold for take-offs of about 80 seconds, and a median at 42 seconds. Flights without waiting represent about 45% of the cases.

- For the data without closures, all other days in August were selected. On these 6667 flights we observe a significantly lower average threshold wait of about 27 seconds, and a median at 0.Flights without waits now represent 70% of the cases.

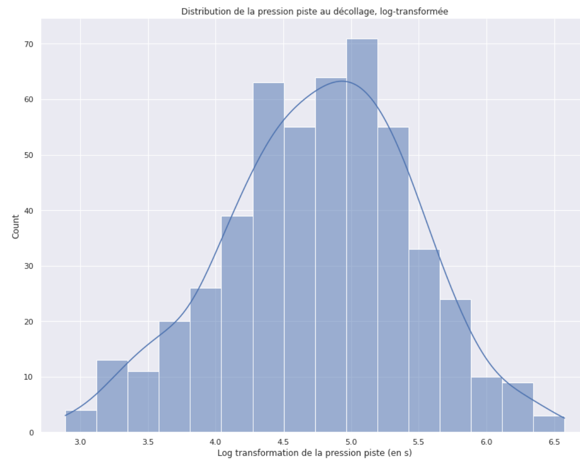
To determine the parameters of the normal distribution that will model each state for the proportion of flights that observe a wait at the runway threshold, it is necessary to focus on the right-hand side of the distribution. The normal distribution model can be determined in this way, as shown in figure 2.10

This modeling, once transcribed and converted into real pressure values (in seconds), allows to deduce for each flight a runway pressure, with a process where the pressure values are randomized according to a distribution adapted to the real data and faithful to what could be observed in real situation.

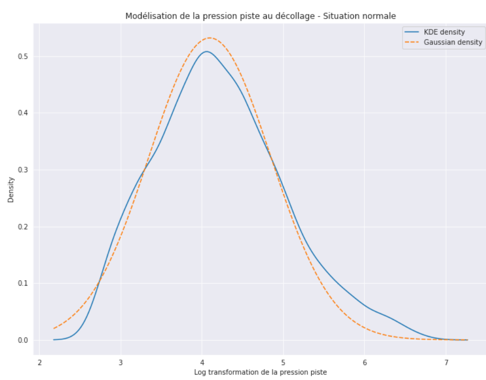
In order not to penalize some scenarios by a Monte-Carlo process, the values generated to compare the scenarios between them will be reduced to a simple average value penalty. In each scenario the average value will be weighted by the population size multiplied by the observed average track pressure. This will avoid



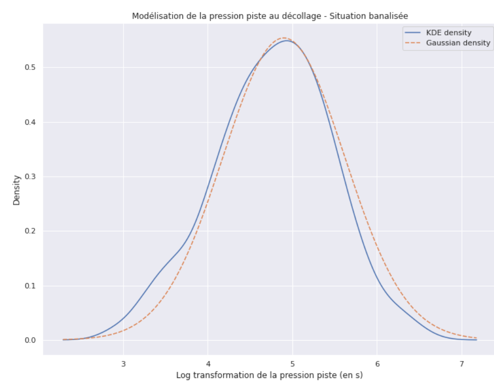
(a) Distribution in normal state



(b) Distribution in mixed mode state



(c) Modeling the distribution - normal state



(d) Modeling the distribution - mixed mode state

Figure 2.10: ressure distributions in the 2 operating modes

inducing errors in the comparisons. We will keep the values generated by the Monte-Carlo process to estimate the quantity of each scenario independently, as described in the flowchart in figure 2.11.

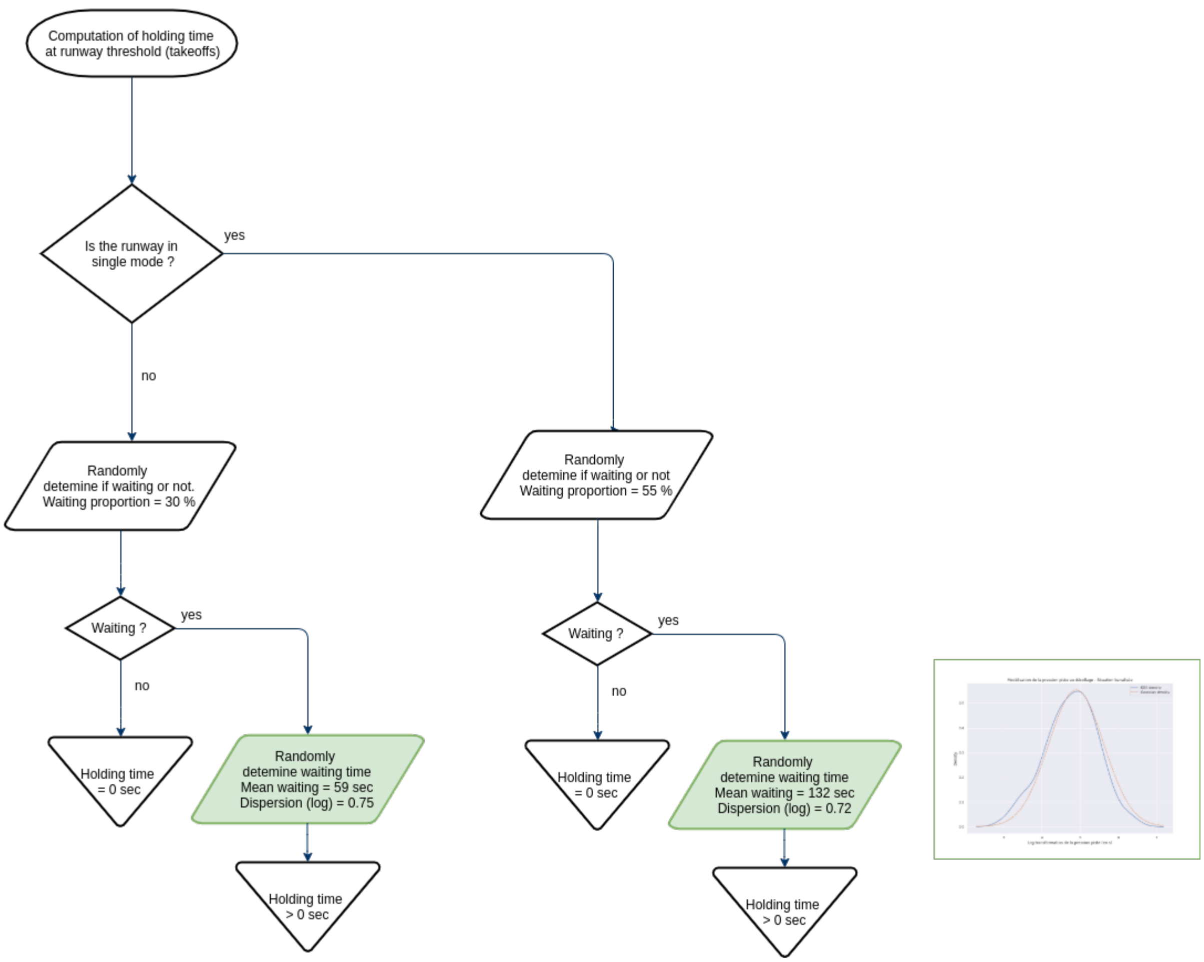


Figure 2.11: Monte-Carlo process flowchart for modelling wait time at the runway threshold

Chapter 3

Results of the case study

3.1 Emissions reduction

3.1.1 Qualitative study

The study has been be done on one day in August on2021, for a specific time slot, here from 11am to 12pm.

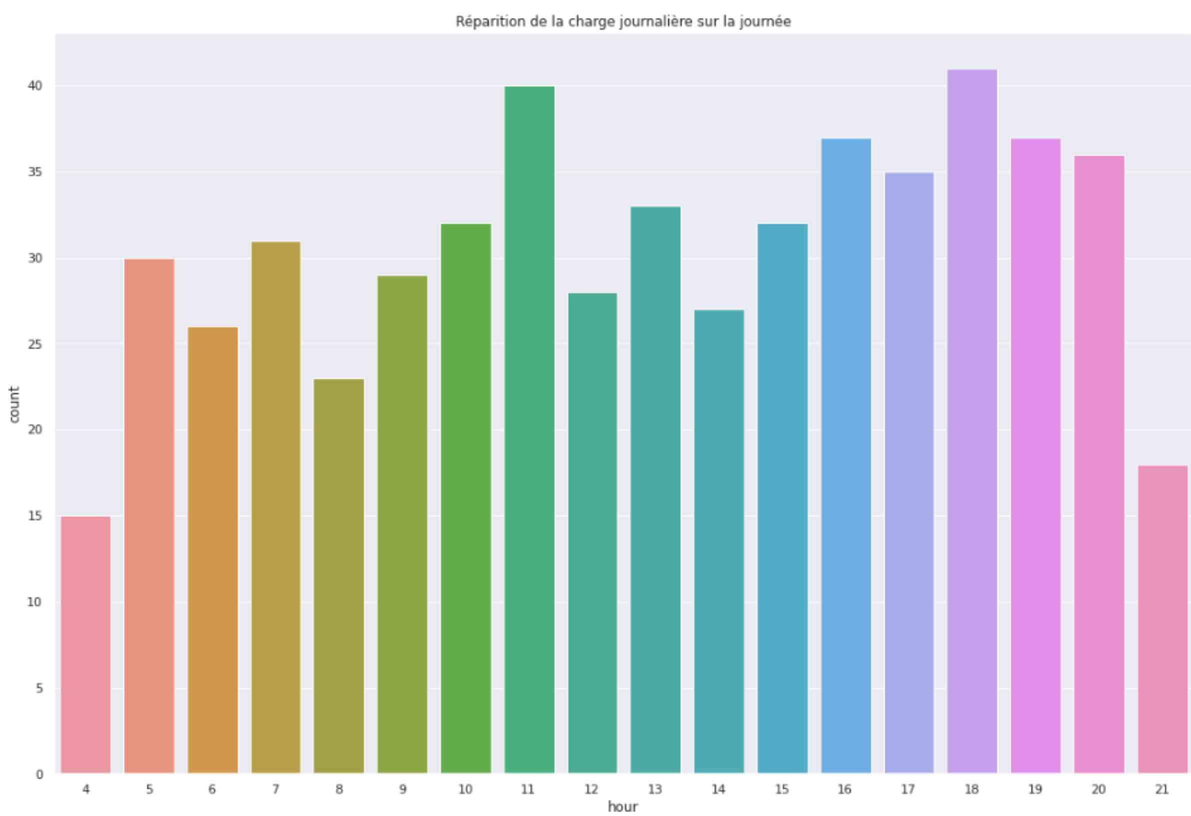


Figure 3.1: Distribution of the different flights on Sunday August 1st 2021

1. <u>Without runway inspection :</u> PFirst hypothesis, there is no runway inspection between 11am and 12pm, so during the whole observed time the airport is in a single configuration, the same as the real configuration observed that day, *Westerly*, the flights take off on the QFU 24 and land on the QFU 25.

   Takeoffs - The following values are obtained:

- 10 takeoffs over the period
- Total duration of the movements (taxiing and waiting at the threshold) : 3787 seconds
- Total taxiing distance : 20228 m
- Kerosene consumed : 2859 kg
- CO2 emitted : 9035 kg
- NOx emitted : 96 kg

Landings - The following values are obtained :

- 18 landings over the period
- Total duration of movements : 3357 seconds
- Total taxiing distance : 20143 m
- Kerosene consumed : 2142 kg
- CO2 emitted : 6770 kg
- NOx emitted : 67 kg

Total on all movements - We obtain the following values:

- 28 mouvements
- Total duration of the movements (taxiing and waiting at the threshold) : 7144 secondes
- Total taxiing distance : 40371 m
- Kerosene consumed : 5002 kg
- CO2 emitted : 15085 kg
- NOx emitted : 163 kg

We will assume that we will intersperse runway inspections of the maximum possible duration (of the 7 regulatory minutes and the 3 additional minutes, thus a total inspection duration of 10 minutes). The different values of kerosene, of CO_2 and NO_X, distance and duration are expressed in relative terms compared to the scenario without runway inspection.

$$Value_{scenario} = Value_{realscenario} - Value_{scenario \varnothing RWY Inspection} \tag{3.1}$$

A positive value means that the scenario generates more quantity of the considered element than the scenario without runway inspection. A negative value indicates that the inspection scenario generates less of the item under consideration than the scenario without runway inspection. All values are rounded to the unit.

Inspection scenarios							
Inspection of 07/25 runway	Fuel quantity (kg)	CO_2 quantity (kg)	NO_X quantity (kg)	Distance (m)	Duration (s)	Redirected flights	Impacted flights
11h00 - 11h10	17.6	55.8	0.5	0.0	37.0	0	2
11h10 - 11h20	67.3	212.9	2.1	436.0	109.0	1	2
11h20 - 11h30	122.0	385.6	3.7	1271.0	230.0	3	1
11h30 - 11h40	944.9	2985.8	29.9	5666.0	963.0	4	1
11h40 - 11h50	624.1	1972.1	20.0	6425.0	1108.0	5	2
11h50 - 12h00	669.2	2114.6	21.1	6138.0	1060.0	5	2

Table 3.1: Impact of different inspection scenarios

Generally speaking, imposing a runway inspection tends to generate more emissions due to redirections and additional waiting time at runway thresholds. However, not all situations are equal in terms of both operational and environmental impact.

- **Operational Impact :** There are two types of metrics that can help to identify the impact of each scenario. Redirected flights are flights initially scheduled on the QFU to be inspected, which must therefore be switched to the single runway in use. Impacted flights represent all flights that do not require to modify their runway but for which the runway is the single in use at the time of the movement (thus generating more runway pressure, as the runway must absorb all the movements of the platform). The distance and time metric measures the time and distance required to travel over and above what was initially planned for the no inspection scenario.

- **Environmental Impact :** The distance and time metrics allow us to assess the quantity of kerosene over-consumed by each scenario, and to deduce the quantity of CO_2 de NO_X emitted. The time considered here is associated with the time needed to cover the distance of the movement, but also the waiting time at the runway threshold for take-offs, as the turbojet engines generate emissions since they are always running, even if the aircraft is stopped.

For an equivalent operational impact, it can be seen that disparities can occur, as is the case between scenarios n°4 and n°5 in the table 3.1, where inspections take place respectively between 11:40AM and 11:50AM, and between 11:50AM and 12:00PM on runway 07/25. This is explained by the destination of certain redirected movements, in this case landings, which can be relatively distant compared to the initial destination.

In detail on figure 3.2 2 trajectories are displayed. Here is the legend :

- The blue trajectory is the trajectory actually observed during this landing.

- The orange trajectory is the trajectory abstracted thanks to the learnt taxiing graph, taking the same starting and ending points as the real trajectory. It is this trajectory that allows to compute the reference scenario without runway inspection.

- The yellow corresponds to the trajectory resulting from the scenario with inspection on runway 07/25, the landing being redirected to the QFU 24.

(a) Landing on the QFU 25,situation without inspection

(b) Landing redirected to the QFU 24 due to the inspection

Figure 3.2: Comparison with low distance variation of two trajectories

In this scenario, the redirected flight covered 400m more than the flight that landed on the QFU 25, so it took 66 seconds longer to cover this extra distance and according to the engine of the aircraft considered, here an A320, which is considered to be equipped with 2 CFM56-5B4, the aircraft consumed 34,9 kg more kerosene than the non-redirected landing, generating an extra emission amount of 110,2 kg of CO_2 and 1 kg of NO_X. This flight accounts for only 5.6% of this scenario overconsumption.

Some flights are much more penalizing and contribute largely to the considered overconsumption of the scenario compared to a scenario with no inspection, because of a much greater distance to cover. For example on the figure 3.3with the same color code of legends, on this flight of a B738. We observe an additional distance of 1186 m, considering that it is equipped with two CFM56-7B26 avec with an overconsumption of 112,3 kg of fuel, an excess of CO_2 of 354,9 kg and 3.6 kg of NO_X, participating for about 18% of the total overconsumption of the scenario.

Nevertheless the distance and the additional times do not allow to explain totally the disparities encountered, we can see for example that the inspection of *11h30 - 11h40* emitted a lot of CO_2 et de NO_X due to a large quantity of kerosene consumed. Indeed, we can see in the data that a large A332 carrier, belonging to the FAA[1] category B class, was largely redirected and generated an overconsumption of 513.5 kg of fuel

(a) Landing on the QFU 25,situation without inspection (b) Landing redirected to the QFU 24 due to the inspection

Figure 3.3: Comparison with large distance variation of two trajectories

3.1.2 Quantitative study

In order to estimate the average impact of a runway inspection, all the scenarios were played over the day, which gives a total of 90 scenarios. We find different characteristic values, in terms of distribution in the figure 3.4.

- In terms of duration, the average duration of a scenario is 429 seconds, with a median value of 386 seconds.The first quartile is for scenarios with a taxiing time of less than 167 seconds. Scenarios with a large increase in movement duration are in the 3rd quartile with cumulative 608 seconds of taxiing and waiting time at the threshold.
- For the taxiing distance part, we find an average value of impact on taxiing of 2200 meters, with a median at 2009 meters. The low values, below the first quartile, are around 825 meters, while the high values are around 3.3 kilometers of additional distance compared to the scenarios without inspection.
- In environmental terms, the average kerosene consumption is 296kg and the average CO_2 emissions are 937 kg and NO_x at 9.7 kg. The first quartile values are around 76kg of kerosene, 241 kg of CO_2 and lastly 2.2 kg of NO_x. The last quartile is 429 kg for kerosene, 1356 kg for CO_2 and 13.3 kg for NO_x.
- The impact of runway inspections on overall traffic is measured in terms of redirected flights with an average value of 2.3 redirected flights for each scenario, where the Q1[2] values are at 1 flight and where Q3[3] values at 3 flights exactly. The number of flights simply impacted is on 2.6 average per scenario, with Q1 and Q3 values respectively of 2 and 3.25.

[1] Classification RECAT - Wake Turbulence Re-categorisation of Federal Aviation Administration
[2] first quartile
[3] third quartile

By carefully selecting the flights that consume the least fuel and emit the least CO_2 and NO_x, we find interquartile differences of about 353 kg of fuel, and 1115 kg of CO_2. These gains are easy to obtain as the tool allows to directly measure the expected impact of a scenario and to choose the least emitting ones.

Different correlations already expressed during the qualitative study can be found, here expressed in the correlation matrix in figure 3.5. It can be seen that the distance and duration metrics are very strongly correlated (the only difference that can remain in the evolution of these two variables is materialized by the waiting at the runway threshold, which generates negligible values compared to the impact of the driving distance). The values of kerosene, of CO_2 and NO_x are fully correlated, the emissions being related by a coefficient in their generation. Flight redirection is strongly correlated with distance and duration (impact of taxiing).

This shows that the choice of runway closures is largely dependent on the first order factor, which is the number of redirected flights, however, the correlation coefficient shows that this single metric does not explain everything. All in all, a great variability can occur depending on the impacted trajectories.

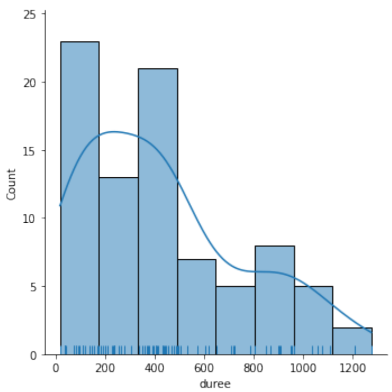
3.2 Confrontation with a real case

According to the elements communicated by the Orly teams, on Sunday August 1st, the following inspections have been scheduled on QFU 06/24:

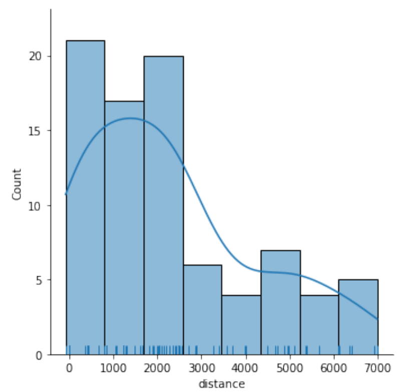
- From 10:01 to 10:08, generating 124.3 kg of additional kerosene. The 10:50 to 11:00 slot could have been selected to consume only 35.4 kg of additional fuel. A gain of 88.9 kg would have been possible.
- From 15:22 to 15:29, generating 246.9 kg of additional kerosene. The slot in a nearby time slot, spaced 5 hours apart with the other proposal that could have been considered is from 16h to 16h10, generating only 75.8 kg of additional kerosene, so the potential gain is 171.1 kg.

NB: Be careful, here the selected hypotheses are of a 10 minutes runway inspection slot, gains could be really made by supposing that an aircraft could carry out its movement in the 3 additional minutes not covered by the real runway inspection. Moreover, the sequence of the inspection of the two runways is not taken into account, here we focus on one of the two runways.

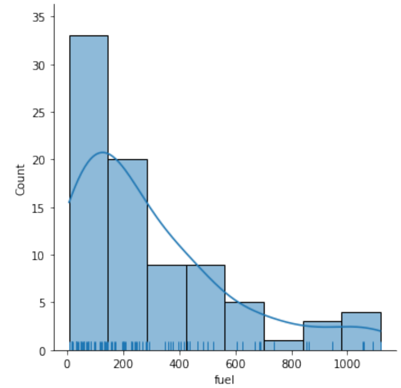
Nevertheless, a total of 830 kg of CO_2 could have been saved by optimizing the inspection operations with respect to their impact on the movements at the platform level, within the framework of our assumptions.



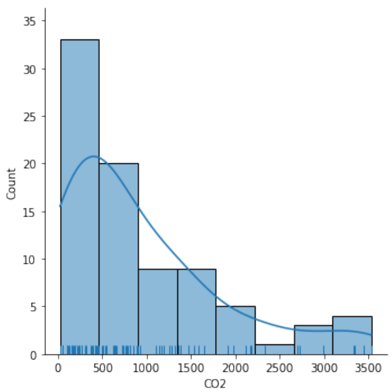
(a) Distribution of the cumulative duration, in seconds



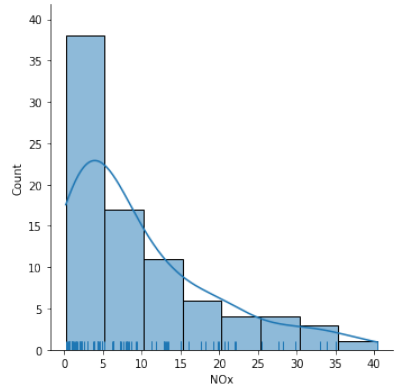
(b) Distribution of the cumulative distance, in meters



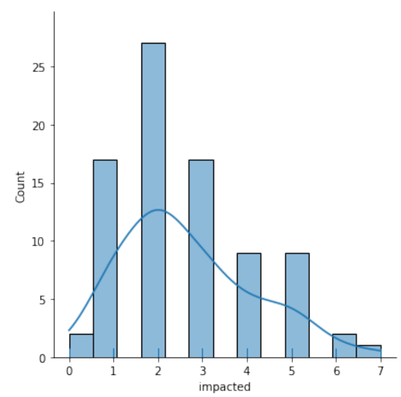
(c) Distribution of the cumulative fuel consummed, in kilograms



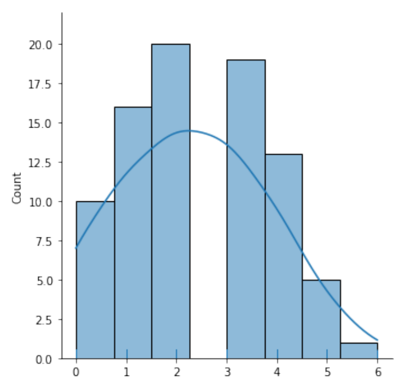
(d) Distribution of the cumulative CO_2 emitted, in kilograms



(e) Distribution of the cumulative NO_x emitted, in kilograms



(f) Distribution of the cumulative number of flights impacted but not redirected



(g) Distribution of the cumulative number of flights redirected

Figure 3.4: Distribution of various variables of the scenarios

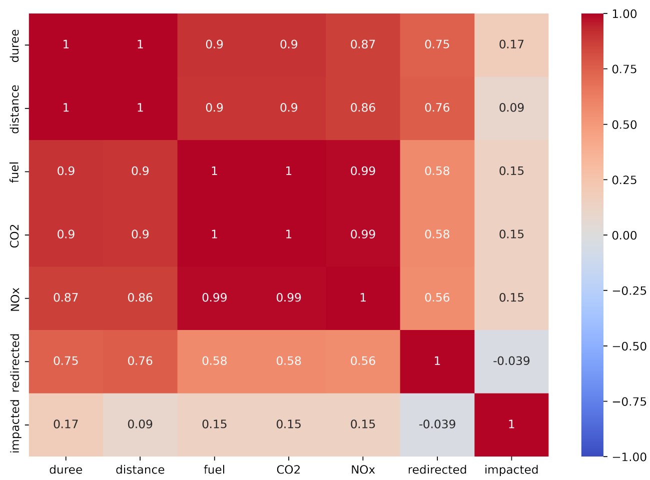


Figure 3.5: Correlation matrix

Chapter 4

Conclusion

4.1 Conclusion of the study

4.1.1 Previously to the exercise

The impact of different operational scenarios, modeled by different constraints and different hypotheses on the operation of the turbomachinery and on certain operational phenomena (waiting at the runway threshold) can be quantified fairly precisely. In order to characterize them, the distance, duration, kerosene consumption and CO_2 and NO_x emissions quantities allow to project the impact of the scenario choices on the operational and environmental plan.

We can estimate the potential gains, in view of the average and interquartile values, at several hundred kilograms of CO_2 and fuel per day (by scheduling two daily inspections). With the tool it is possible to systematically target the lowest values (below Q1), while scheduling a "blind" inspection will tend to give average values, we can expect to obtain an average gain for each scenario equivalent to

$$Gains = Value_{average} - Value_{Q1} \tag{4.1}$$

The gains that can be reasonably envisaged, per day and per type, are of the order of :

- 440 kg of fuel
- 1400 kg of CO_2
- 15 kg of NO_x
- 2700 meters less taxiing
- 8 minutes and 40 secondes less time to run and wait at the runway threshold
- 2.6 flights on average for which redirection was avoided
- 1.2 flights on average whose operation has not been impacted by a runway inspection

4.1.2 Post-Ops to the exercise

As the exercise has been conducted, the day of the 1st June has been took as a reference to conduct a new stochastic quantitative and qualitative interpretation of possible expectations using the runway inspection scheduler tool. The same methodology using quartiles to extrapolate possible savings have been followed to conduct this conclusion. The reviewed gains that can be reasonably envisaged, with 2 runway inspections per day and per type, are of the order of, with upstream traffic regulation (low load on the airport, typically during the COVID era) :

- 628 kg (WEST) - 628 kg (EAST) of fuel
- 1985 kg (WEST) - 1985 kg (EAST) of CO_2
- 18 kg (WEST) - 19 kg (EAST) of NO_x
- 6100 meters (WEST) - 5989 meters (EAST) less taxiing
- 16 minutes and 30 secondes (WEST) - 16 minutes and 36 secondes (EAST) less time to run and wait at the runway threshold
- 2 (WEST) - 2.5 (EAST) flights on average for which redirection was avoided
- 2 (WEST) - 2 (EAST) flights on average whose operation has not been impacted by a runway inspection

And without upstream traffic regulation (intensive flight activity period) :

- 485 kg (WEST) - 715 kg (EAST) of fuel
- 1530 kg (WEST) - 2260 kg (EAST of CO_2
- 18 kg (WEST) - 23 kg (EAST) of NO_x
- 6240 meters (WEST) - 7190 meters (EAST) less taxiing
- 19 minutes and 8 secondes (WEST) - 21 minutes (EAST) less time to run and wait at the runway threshold
- 3 (WEST) - 2.75 (EAST) flights on average for which redirection was avoided
- 3.5 (WEST) - 3 (EAST) flights on average whose operation has not been impacted by a runway inspection

On this basis, using an anual distribution of configuration of 60% West and 40% East, expected savings for a year are 210.6 tons of fuel (equivalent to 665 tons of CO_2) without upstream regulation, which represents 0.41% of total fuel consumption for taxiing operations.

With an upstream regulation, the elements are superseded by 229.2 tons of fuel (equivalent to 724 tons of CO_2) which represents 0.45% of total fuel consumption for taxiing operations.

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Appendix A

Table of all single runway inspection scenarios

Inspection scenarios							
Inspection of 07/25 runway	Fuel quantity (kg)	CO_2 quantity (kg)	NO_X quantity (kg)	Distance (m)	Duration (s)	Redirected flights	Impacted flights
06:00 - 06:10	133.1	420.5	4.3	1311.0	237.0	1	1
06:10 - 06:20	17.7	55.8	0.6	0.0	37.0	0	2
06:20 - 06:30	17.8	56.0	0.6	0.0	37.0	0	2
06:30 - 06:40	523.0	1652.7	16.0	2484.0	432.0	1	1
06:40 - 06:50	502.1	1586.4	20.7	2484.0	488.0	1	4
06:50 - 07:00	360.3	1138.3	12.9	2267.0	396.0	2	1
07:00 - 07:10	463.9	1466.0	19.8	2191.0	457.0	2	5
07:10 - 07:20	691.0	2183.6	25.5	2483.0	506.0	1	5
07:20 - 07:30	60.0	189.8	1.7	399.0	122.0	1	3
07:30 - 07:40	133.8	423.1	4.3	1219.0	240.0	1	2
07:40 - 07:50	50.0	158.2	1.4	-0.0	110.0	0	6
07:50 - 08:00	18.3	58.0	0.5	-0.0	37.0	0	2
08:00 - 08:10	429.4	1356.8	19.3	1879.0	350.0	3	2
08:10 - 08:20	861.5	2722.2	27.7	6104.0	1036.0	4	1
08:20 - 08:30	19.0	59.9	0.6	0.0	37.0	0	2
08:30 - 08:40	855.3	2702.8	28.3	5359.0	949.0	4	3
08:40 - 08:50	399.2	1261.4	17.7	1807.0	338.0	3	2
08:50 - 09:00	15.1	47.8	0.4	0.0	37.0	0	2
09:00 - 09:10	232.3	734.0	7.2	2508.0	436.0	4	1
09:10 - 09:20	464.2	1466.6	15.0	4731.0	807.0	6	1
09:20 - 09:30	295.1	932.5	9.4	2876.0	534.0	3	3
09:30 - 09:40	1088.5	3439.6	33.1	5403.0	955.0	3	3
09:40 - 09:50	33.0	104.1	0.9	0.0	73.0	0	4
09:50 - 10:00	1052.6	3326.2	33.9	5122.0	909.0	3	3
10:00 - 10:10	124.3	392.9	3.8	1220.0	240.0	1	2
10:10 - 10:20	115.5	365.1	3.8	1220.0	203.0	1	0
10:20 - 10:30	739.3	2336.4	22.1	4967.0	902.0	2	4
10:30 - 10:40	158.1	499.7	4.9	1619.0	307.0	2	2
10:40 - 10:50	686.2	2168.4	22.0	6925.0	1210.0	3	3
10:50 - 11:00	35.4	112.0	1.0	399.0	85.0	1	1
11:00 - 11:10	17.6	55.8	0.5	0.0	37.0	0	2
11:10 - 11:20	67.3	212.9	2.1	436.0	109.0	1	2

11:20 - 11:30	122.0	385.6	3.7	1271.0	230.0	3	1
11:30 - 11:40	944.9	2985.8	29.9	5666.0	963.0	4	1
11:40 - 11:50	624.1	1972.1	20.0	6425.0	1108.0	5	2
11:50 - 12:00	669.2	2114.6	21.1	6138.0	1060.0	5	2
12:00 - 12:10	1117.4	3531.2	40.4	6351.0	1077.0	5	1
12:10 - 12:20	403.9	1276.4	12.9	3978.0	719.0	4	3
12:20 - 12:30	248.4	785.1	8.4	2002.0	408.0	2	4
12:30 - 12:40	86.0	272.0	2.5	798.0	170.0	2	2
12:40 - 12:50	76.5	241.9	2.0	835.0	176.0	2	2
12:50 - 13:00	376.1	1188.6	11.2	3703.0	710.0	2	5
13:00 - 13:10	173.3	547.8	4.9	1928.0	414.0	4	5
13:10 - 13:20	279.4	883.0	8.6	2875.0	498.0	3	1
13:20 - 13:30	350.3	1106.9	11.3	3274.0	620.0	4	4
13:30 - 13:40	437.1	1381.2	13.2	4666.0	852.0	4	4
13:40 - 13:50	367.6	1161.6	11.8	3576.0	652.0	3	3
13:50 - 14:00	83.6	264.3	2.3	835.0	158.0	2	1
14:00 - 14:10	147.0	464.6	4.6	1220.0	277.0	1	4
14:10 - 14:20	33.4	105.5	0.9	0.0	73.0	0	4
14:20 - 14:30	136.9	432.6	4.3	1081.0	235.0	1	3
14:30 - 14:40	62.1	196.3	2.0	436.0	109.0	1	2
14:40 - 14:50	99.5	314.4	3.0	835.0	194.0	2	3
14:50 - 15:00	1057.0	3340.1	35.0	6996.0	1276.0	5	6
15:00 - 15:10	230.8	729.4	7.2	2401.0	492.0	3	5
15:10 - 15:20	202.9	641.1	6.3	2054.0	379.0	3	2
15:20 - 15:30	246.9	780.2	7.9	2439.0	443.0	2	2
15:30 - 15:40	141.4	446.9	4.5	1219.0	258.0	1	3
15:40 - 15:50	256.5	810.6	8.0	2717.0	471.0	3	1
15:50 - 16:00	196.7	621.6	6.2	2054.0	361.0	3	1
16:00 - 16:10	75.8	239.3	2.3	835.0	140.0	2	0
16:10 - 16:20	417.3	1318.6	13.3	4013.0	725.0	4	3
16:20 - 16:30	438.9	1386.8	13.0	4980.0	867.0	3	2
16:30 - 16:40	256.4	810.2	8.2	2347.0	447.0	2	3
16:40 - 16:50	72.1	227.9	2.1	670.0	149.0	2	2
16:50 - 17:00	204.6	646.4	6.3	1656.0	369.0	2	5
17:00 - 17:10	161.6	510.6	5.1	1488.0	267.0	3	1
17:10 - 17:20	210.0	663.8	6.3	2091.0	404.0	3	3
17:20 - 17:30	42.2	133.5	1.3	398.0	85.0	1	1
17:30 - 17:40	202.3	639.3	6.3	2017.0	373.0	3	2
17:40 - 17:50	485.5	1534.2	15.0	4888.0	907.0	3	5
17:50 - 18:00	228.4	721.8	7.4	1655.0	405.0	2	7
18:00 - 18:10	57.5	181.7	1.1	1053.0	212.0	4	2
18:10 - 18:20	241.6	763.2	7.7	2363.0	431.0	4	2
18:20 - 18:30	97.8	308.8	3.0	670.0	185.0	2	4
18:30 - 18:40	429.4	1356.7	13.4	4501.0	787.0	4	2
18:40 - 18:50	167.6	529.5	4.6	2145.0	394.0	4	2
18:50 - 19:00	32.1	101.3	1.1	-81.0	42.0	1	3
19:00 - 19:10	603.8	1908.1	18.3	2882.0	573.0	2	5
19:10 - 19:20	54.0	170.8	1.6	-0.0	92.0	2	5
19:20 - 19:30	269.9	853.0	8.1	3402.0	604.0	5	3
19:30 - 19:40	285.7	903.0	9.2	2546.0	480.0	3	3

19:40 - 19:50	49.7	157.2	1.5	354.0	96.0	2	2
19:50 - 20:00	8.1	25.9	0.2	-0.0	19.0	0	1

Table A.1: Impact de tous les scénarios d'inspection du 1er Août

Appendix B

Table of 1st June various double runways inspection scenarios

B.1 Without upstream regulation

B.1.1 West Configuration

	fuel_kg	co2_kg	nox_kg	duration_s	distance_m	impacted	redirected
07h00-12h00	1948.9	6158.4	55.9	3910	21471	7	11
07h03-12h03	1355.6	4283.7	38.3	2753	14527	8	10
07h06-12h06	1248.4	3944.9	37.5	2370	12451	5	11
07h09-12h09	2679.1	8465.9	80.4	5213	29063	5	15
07h12-12h12	3469.0	10962.1	101.3	7024	39265	9	17
07h15-12h15	3201.5	10116.7	93.5	6502	36248	11	14
07h18-12h18	2655.3	8390.8	79.2	5172	28710	10	11
07h21-12h21	1444.2	4563.5	41.8	2949	15813	11	6
07h24-12h24	1357.6	4290.0	40.3	2671	13481	15	8
07h27-12h27	516.7	1632.8	15.4	1052	3769	17	6
07h30-12h30	508.9	1608.2	15.3	1028	3844	14	7
07h33-12h33	908.4	2870.5	39.3	865	3532	11	4
07h36-12h36	930.2	2939.3	40.1	892	4021	6	6
07h39-12h39	1299.7	4107.1	49.0	1883	9751	8	6
07h42-12h42	2087.8	6597.5	61.6	4202	23219	6	12
07h45-12h45	3064.6	9684.3	92.3	5979	33548	7	14
07h48-12h48	2428.9	7675.5	75.4	4463	25230	4	10
07h51-12h51	2712.5	8571.6	90.0	4017	22334	6	10
07h54-12h54	2019.2	6380.7	69.7	2638	14391	6	7
07h57-12h57	2231.3	7050.8	75.1	3135	16489	12	9
08h00-13h00	2306.5	7288.5	77.4	3278	17010	14	10
08h03-13h03	2438.3	7705.2	84.6	3812	20439	10	12
08h06-13h06	2159.4	6823.8	78.2	3094	16350	10	10
08h09-13h09	2076.1	6560.3	75.6	2933	15829	7	9
08h12-13h12	1235.0	3902.5	36.5	2371	12346	9	8
08h15-13h15	1275.6	4030.8	35.8	2712	14279	10	8
08h18-13h18	1238.0	3912.0	35.1	2643	13758	12	7
08h21-13h21	972.4	3072.6	29.3	1974	10185	10	5

08h24-13h24	432.5	1366.6	14.9	679	2966	9	1
08h27-13h27	562.6	1777.7	16.9	1080	5374	8	2
08h30-13h30	246.4	778.5	6.3	567	2408	8	1
08h33-13h33	440.0	1390.4	12.2	932	4486	7	3
08h36-13h36	-107.7	-340.2	-5.9	251	621	5	3
08h39-13h39	1152.8	3643.0	35.1	2407	13333	1	9
08h42-13h42	1893.5	5983.5	57.4	3818	21246	2	13
08h45-13h45	2457.5	7765.8	77.8	4394	24814	1	13
08h48-13h48	1184.9	3744.3	36.5	2201	12102	3	7
08h51-13h51	425.8	1345.4	14.0	713	3611	3	3
08h54-13h54	376.3	1189.0	12.3	643	2529	9	3
08h57-13h57	1319.5	4169.6	43.4	1914	9159	13	8
09h00-14h00	1304.9	4123.3	42.9	1914	9159	13	8
09h03-14h03	1208.4	3818.5	39.9	1727	8700	7	8
09h06-14h06	143.6	453.8	4.6	266	1042	3	2
09h09-14h09	85.4	269.9	2.7	161	521	3	1
09h12-14h12	559.5	1768.0	17.7	988	4708	8	3
09h15-14h15	559.5	1768.0	17.7	988	4708	8	3
09h18-14h18	912.9	2884.8	28.2	1664	8657	8	4
09h21-14h21	586.2	1852.4	18.8	1330	7205	2	5
09h24-14h24	1872.3	5916.4	60.0	3589	20318	1	10
09h27-14h27	1889.9	5972.2	60.5	3626	20318	3	10
09h30-14h30	1266.6	4002.4	41.0	2505	13815	3	8
09h33-14h33	1478.3	4671.3	60.7	1597	8365	4	7
09h36-14h36	2428.7	7674.6	91.4	3227	17594	5	11
09h39-14h39	3514.9	11107.0	125.8	5209	28267	10	17
09h42-14h42	2013.5	6362.8	64.2	3892	20919	10	12
09h45-14h45	1415.7	4473.5	44.2	2911	15366	8	11
09h48-14h48	1492.9	4717.6	47.9	2938	15970	7	8
09h51-14h51	953.3	3012.3	30.8	1658	8177	11	5
09h54-14h54	1202.0	3798.4	38.0	2165	10445	17	6
09h57-14h57	1201.4	3796.6	34.8	2379	12173	12	7
10h00-15h00	1191.4	3764.7	34.4	2361	12173	11	7
10h03-15h03	1059.1	3346.7	31.2	2048	10741	8	6
10h06-15h06	108.0	341.4	2.1	538	2233	5	4
10h09-15h09	441.3	1394.7	12.0	1179	5859	6	5
10h12-15h12	799.6	2526.9	23.7	1798	9242	7	7
10h15-15h15	2165.0	6841.4	68.2	4134	22815	7	11
10h18-15h18	2833.1	8952.5	91.0	4991	27846	6	13
10h21-15h21	2612.9	8256.7	83.8	4591	25775	4	12
10h24-15h24	600.9	1899.0	17.8	1181	5756	5	7
10h27-15h27	-141.3	-446.4	-4.2	35	-1009	7	4
10h30-15h30	533.2	1684.9	17.2	1230	5611	11	5
10h33-15h33	1305.9	4126.7	41.9	2606	13421	13	7
10h36-15h36	1774.7	5608.2	56.3	3170	17029	12	6
10h39-15h39	1116.6	3528.4	34.8	2061	10930	7	6
10h42-15h42	1473.5	4656.4	43.2	2969	16377	4	9
10h45-15h45	846.9	2676.1	23.2	2125	11201	5	9
10h48-15h48	1035.7	3272.7	29.3	2432	12935	7	8
10h51-15h51	448.3	1416.6	11.0	1380	7064	6	5

10h54-15h54	399.7	1263.0	9.3	1306	6510	6	6
10h57-15h57	249.4	788.0	5.8	700	2652	9	5
11h00-16h00	282.7	893.4	8.0	579	2035	9	4
11h03-16h03	278.9	881.3	7.9	561	2035	8	4
11h06-16h06	382.2	1207.9	11.4	730	3492	5	3
11h09-16h09	639.8	2021.6	19.0	1225	6243	6	4
11h12-16h12	917.6	2899.6	27.5	1769	9394	5	6
11h15-16h15	1606.8	5077.3	48.3	3070	17200	4	7
11h18-16h18	576.4	1821.3	14.6	1856	9921	4	7
11h21-16h21	127.7	403.7	1.2	994	5077	3	5
11h24-16h24	-600.9	-1898.8	-20.7	-388	-2994	4	2
11h27-16h27	51.1	161.5	1.5	111	0	6	0
11h30-16h30	725.9	2293.7	21.6	1407	7446	7	2
11h33-16h33	1221.4	3859.6	36.7	2294	12437	7	5
11h36-16h36	1205.0	3807.9	36.3	2257	12437	5	5
11h39-16h39	512.6	1619.7	15.6	924	4991	2	3
11h42-16h42	1067.0	3371.7	30.9	2114	12133	0	5
11h45-16h45	764.1	2414.7	21.6	1856	10252	2	6
11h48-16h48	1685.7	5326.8	52.0	3701	20547	5	10
11h51-16h51	972.1	3072.0	31.6	2263	12364	5	6
11h54-16h54	639.4	2020.6	21.7	1621	8838	3	5
11h57-16h57	1111.2	3511.5	30.8	2309	12527	5	7

B.1.2 East Configuration

	fuel_kg	co2_kg	nox_kg	duration_s	distance_m	impacted	redirected
07h00-12h00	2874.2	9082.6	85.4	5569	31198	7	13
07h03-12h03	3322.7	10499.7	99.7	6364	35858	6	15
07h06-12h06	2321.1	7334.8	71.5	4314	24112	6	10
07h09-12h09	3187.3	10071.8	97.5	5999	33338	10	14
07h12-12h12	3285.1	10380.8	98.9	6334	35237	10	15
07h15-12h15	2626.2	8298.9	78.4	5147	28113	13	12
07h18-12h18	2805.1	8864.1	82.9	5587	30425	15	13
07h21-12h21	1970.7	6227.4	58.4	3914	21382	10	9
07h24-12h24	2063.1	6519.6	62.3	4029	21628	14	9
07h27-12h27	2154.0	6806.8	66.3	4082	21834	15	9
07h30-12h30	1811.0	5722.8	66.1	2625	13759	12	6
07h33-12h33	1396.9	4414.1	53.7	1836	9136	13	4
07h36-12h36	1363.1	4307.4	52.7	1759	9113	9	4
07h39-12h39	1974.8	6240.4	62.6	3567	19519	9	8
07h42-12h42	2059.1	6506.7	63.4	3936	21625	9	9
07h45-12h45	2033.2	6425.0	63.0	3840	21382	6	9
07h48-12h48	2434.1	7691.8	75.0	4605	25968	4	11
07h51-12h51	3012.1	9518.3	104.7	3754	21085	4	9
07h54-12h54	3164.6	10000.2	106.5	4253	23524	8	10
07h57-12h57	3267.1	10324.1	111.8	4290	23638	9	10

08h00-13h00	3672.9	11606.3	140.9	4759	26342	9	11
08h03-13h03	3328.5	10517.9	132.4	3977	21651	11	9
08h06-13h06	3323.8	10503.2	132.0	3921	21537	9	9
08h09-13h09	2328.5	7358.2	71.7	4284	23490	10	10
08h12-13h12	2096.0	6623.5	64.5	3876	21155	10	9
08h15-13h15	2198.9	6948.4	66.2	4279	23351	11	10
08h18-13h18	1074.4	3395.0	31.0	2244	11916	9	5
08h21-13h21	698.6	2207.6	21.4	1383	6972	9	3
08h24-13h24	843.3	2664.7	23.8	1812	9320	10	4
08h27-13h27	505.2	1596.4	15.0	986	4697	9	2
08h30-13h30	712.4	2251.3	20.8	1427	7124	10	3
08h33-13h33	1337.4	4226.3	44.6	1773	9641	5	4
08h36-13h36	1857.4	5869.3	62.2	2625	14754	3	6
08h39-13h39	2736.2	8646.4	88.9	4283	24149	4	10
08h42-13h42	2755.5	8707.5	86.2	5019	28566	2	12
08h45-13h45	2297.1	7258.7	72.3	4147	23446	3	10
08h48-13h48	1894.2	5985.6	60.4	3346	18749	4	8
08h51-13h51	799.2	2525.4	26.0	1376	7262	6	3
08h54-13h54	2532.2	8001.8	85.4	3514	19090	10	8
08h57-13h57	2535.2	8011.2	85.4	3551	19090	12	8
09h00-14h00	2521.0	7966.4	85.0	3518	19114	10	8
09h03-14h03	2257.3	7133.1	76.6	3043	16596	8	7
09h06-14h06	265.9	840.2	8.5	478	2426	3	1
09h09-14h09	791.7	2501.9	25.3	1386	7100	8	3
09h12-14h12	791.7	2501.9	25.3	1386	7100	8	3
09h15-14h15	791.7	2501.9	25.3	1386	7100	8	3
09h18-14h18	1107.5	3499.6	34.7	1424	7438	7	3
09h21-14h21	1881.8	5946.5	57.8	2964	16897	1	7
09h24-14h24	1899.5	6002.3	58.4	3001	16897	3	7
09h27-14h27	2600.2	8216.5	81.1	4212	23831	3	10
09h30-14h30	3362.0	10623.9	131.3	4186	23676	3	10
09h33-14h33	3589.1	11341.6	138.1	4602	26062	3	11
09h36-14h36	4296.0	13575.2	160.0	5953	33395	7	14
09h39-14h39	3315.9	10478.4	103.4	5510	30848	7	13
09h42-14h42	3581.8	11318.4	111.9	5988	33274	10	14
09h45-14h45	2304.6	7282.5	73.9	3493	18969	10	8
09h48-14h48	1527.8	4827.7	49.5	2670	14140	11	6
09h51-14h51	1364.9	4313.1	44.8	2330	11875	14	5
09h54-14h54	1652.7	5222.6	49.9	3131	16573	13	7
09h57-14h57	1871.8	5915.0	56.4	3553	18884	14	8
10h00-15h00	1520.4	4804.6	43.8	3045	16613	8	7
10h03-15h03	1736.5	5487.5	55.4	2633	14470	6	6
10h06-15h06	1402.6	4432.3	48.1	1795	9773	5	4
10h09-15h09	2148.1	6788.1	72.3	3099	17042	7	7
10h12-15h12	2170.4	6858.6	73.3	3098	16927	8	7
10h15-15h15	2958.8	9349.8	100.9	4713	26288	7	11
10h18-15h18	2680.5	8470.2	91.2	4251	23733	6	10
10h21-15h21	3197.6	10104.4	109.1	5059	28586	4	12
10h24-15h24	3023.2	9553.3	97.7	4677	26068	7	11
10h27-15h27	1594.1	5037.4	51.0	2235	12085	7	5

10h30-15h30	1833.2	5793.0	58.5	2679	14190	11	6
10h33-15h33	1006.3	3180.0	31.7	1825	9398	10	4
10h36-15h36	1819.4	5749.5	55.2	3514	18874	12	8
10h39-15h39	2583.4	8163.5	76.9	5123	28191	11	12
10h42-15h42	2664.2	8418.9	80.8	4643	26085	5	11
10h45-15h45	2368.9	7485.6	74.2	3844	21402	6	9
10h48-15h48	1790.6	5658.4	54.8	2999	16779	4	7
10h51-15h51	1695.3	5357.3	52.8	2685	14562	8	6
10h54-15h54	1372.7	4337.7	41.2	2744	14470	12	6
10h57-15h57	1376.4	4349.5	41.4	2725	14470	11	6
11h00-16h00	1240.5	3920.0	38.7	2272	12085	9	5
11h03-16h03	761.8	2407.4	23.8	1394	7255	7	3
11h06-16h06	756.5	2390.5	23.7	1375	7255	6	3
11h09-16h09	1406.8	4445.6	43.6	2613	14349	6	6
11h12-16h12	1159.5	3663.9	35.6	2175	11831	6	5
11h15-16h15	2519.0	7959.9	80.5	3417	19063	5	8
11h18-16h18	2075.6	6558.8	67.3	2561	14373	3	6
11h21-16h21	1628.8	5147.1	53.4	1739	9658	3	4
11h24-16h24	471.6	1490.2	14.0	918	4623	6	2
11h27-16h27	42.2	133.5	1.2	92	0	5	0
11h30-16h30	569.9	1800.7	18.1	993	4853	8	2
11h33-16h33	974.0	3077.9	30.2	1764	9476	6	4
11h36-16h36	1167.2	3688.4	36.0	2130	11787	4	5
11h39-16h39	1472.9	4654.5	43.0	2897	16384	2	7
11h42-16h42	1575.9	4979.8	46.4	2490	14278	0	6
11h45-16h45	2343.6	7405.8	69.6	3369	19107	2	8
11h48-16h48	2149.7	6793.1	63.8	3002	16796	4	7
11h51-16h51	2032.7	6423.4	63.0	2583	14281	5	6
11h54-16h54	2174.6	6871.7	64.4	4216	23416	7	10
11h57-16h57	1967.1	6216.1	58.2	3794	21104	6	9

B.2 With upstream regulation

B.2.1 West Configuration

	fuel_kg	co2_kg	nox_kg	duration_s	distance_m	impacted	redirected
07h00-12h00	2367.9	7482.5	69.2	4663	25989	17	19
07h03-12h03	1476.7	4666.4	42.2	2966	15805	16	13
07h06-12h06	1402.0	4430.4	42.4	2646	14106	18	13
07h09-12h09	2832.7	8951.5	85.2	5489	30718	18	17
07h12-12h12	3715.4	11740.5	108.8	7505	42154	19	22
07h15-12h15	3706.1	11711.2	109.0	7459	41990	26	24
07h18-12h18	3006.3	9499.8	89.7	5853	32796	17	19
07h21-12h21	2371.4	7493.7	70.7	4639	25950	18	19
07h24-12h24	2284.9	7220.1	69.2	4361	23618	22	21
07h27-12h27	1350.8	4268.6	41.4	2581	12944	20	16

07h30-12h30	1754.4	5544.0	54.3	3287	17396	23	22
07h33-12h33	1484.9	4692.3	57.4	1910	9800	18	11
07h36-12h36	1492.0	4714.6	58.0	1891	10017	15	13
07h39-12h39	1861.5	5882.4	66.9	2883	15747	17	13
07h42-12h42	2353.8	7437.9	70.1	4675	26057	12	15
07h45-12h45	3688.2	11654.7	111.9	7124	40419	13	23
07h48-12h48	2902.1	9170.6	90.2	5339	30483	7	17
07h51-12h51	3203.5	10123.2	105.1	4944	27894	9	19
07h54-12h54	2510.2	7932.3	84.8	3565	19950	9	16
07h57-12h57	2719.0	8592.0	90.2	4030	21857	18	15
08h00-13h00	2794.2	8829.8	92.6	4172	22378	23	16
08h03-13h03	2792.7	8824.9	95.7	4452	24281	16	15
08h06-13h06	2404.4	7597.8	86.1	3520	18905	15	13
08h09-13h09	2321.0	7334.3	83.5	3359	18384	12	12
08h12-13h12	2191.6	6925.5	66.7	3535	19327	13	14
08h15-13h15	2498.2	7894.2	74.6	4348	24098	15	17
08h18-13h18	2215.6	7001.4	65.9	3854	21022	15	13
08h21-13h21	1366.8	4319.1	41.8	2679	14413	15	10
08h24-13h24	826.9	2613.1	27.5	1383	7194	14	6
08h27-13h27	835.7	2640.7	25.4	1582	8386	18	6
08h30-13h30	551.7	1743.3	15.6	1142	5856	21	6
08h33-13h33	616.8	1949.1	17.4	1275	6544	16	6
08h36-13h36	401.4	1268.3	9.5	1233	6511	10	8
08h39-13h39	1661.9	5251.5	50.5	3388	19223	6	14
08h42-13h42	2809.2	8877.2	84.7	5627	32099	11	23
08h45-13h45	3504.2	11073.3	109.0	6447	37135	14	26
08h48-13h48	1754.8	5545.1	53.1	3346	18969	14	16
08h51-13h51	635.5	2008.1	20.4	1096	5914	13	8
08h54-13h54	586.0	1851.7	18.7	1027	4832	19	8
08h57-13h57	2025.5	6400.7	65.4	3227	17036	23	17
09h00-14h00	2799.0	8844.7	89.4	4118	22384	23	21
09h03-14h03	2623.7	8290.9	83.9	3792	21091	11	19
09h06-14h06	1430.3	4519.9	45.2	2035	11655	4	12
09h09-14h09	1372.1	4335.9	43.3	1929	11134	4	11
09h12-14h12	1338.7	4230.4	42.2	2409	13239	15	13
09h15-14h15	1338.7	4230.4	42.2	2409	13239	19	13
09h18-14h18	1193.5	3771.4	36.7	2209	11923	18	8
09h21-14h21	771.7	2438.5	24.8	1656	9162	8	6
09h24-14h24	2057.8	6502.5	66.0	3916	22276	7	11
09h27-14h27	2365.9	7476.2	75.3	4500	25564	10	17
09h30-14h30	1971.1	6228.7	63.2	3777	21444	15	19
09h33-14h33	1997.3	6311.5	76.9	2542	14035	14	17
09h36-14h36	2738.6	8653.9	101.5	3757	20773	13	17
09h39-14h39	3824.8	12086.3	136.0	5739	31447	18	23
09h42-14h42	2436.0	7697.9	77.8	4631	25352	16	19
09h45-14h45	2017.3	6374.6	63.2	4001	21905	18	23
09h48-14h48	2013.2	6361.6	64.2	3895	21711	14	18
09h51-14h51	1493.8	4720.4	47.8	2654	14151	16	13
09h54-14h54	1742.6	5506.6	54.9	3161	16419	22	14
09h57-14h57	1893.7	5984.2	56.8	3626	19656	17	13

10h00-15h00	2128.5	6726.2	63.3	4147	22893	18	17
10h03-15h03	1634.8	5166.0	48.5	3190	17591	14	13
10h06-15h06	387.8	1225.5	10.0	1144	5869	8	9
10h09-15h09	721.1	2278.7	19.9	1785	9495	9	10
10h12-15h12	1144.6	3616.9	34.6	2422	12981	11	12
10h15-15h15	2649.1	8371.3	83.5	4972	27841	16	18
10h18-15h18	3282.3	10372.2	105.2	5763	32474	14	19
10h21-15h21	3265.6	10319.3	103.9	5219	29545	13	15
10h24-15h24	1253.7	3961.6	37.9	1809	9526	14	10
10h27-15h27	641.0	2025.6	19.9	937	4407	11	8
10h30-15h30	1579.5	4991.2	49.6	2574	13676	18	14
10h33-15h33	1838.7	5810.2	58.7	3536	19003	16	15
10h36-15h36	2377.7	7513.5	75.4	4213	23286	20	15
10h39-15h39	1719.5	5433.7	53.9	3104	17187	15	15
10h42-15h42	1812.5	5727.4	54.1	3571	19985	11	13
10h45-15h45	1379.7	4360.0	40.2	3078	16918	12	16
10h48-15h48	1229.6	3885.5	35.4	2784	15044	9	11
10h51-15h51	817.2	2582.3	22.2	2076	11241	7	13
10h54-15h54	768.6	2428.7	20.5	2002	10687	7	14
10h57-15h57	725.4	2292.1	20.6	1575	7898	14	12
11h00-16h00	758.7	2397.5	22.7	1453	7281	22	11
11h03-16h03	579.9	1832.6	17.6	1090	5213	20	6
11h06-16h06	497.8	1573.0	15.1	933	4712	15	4
11h09-16h09	755.3	2386.7	22.8	1428	7463	16	5
11h12-16h12	1372.5	4337.2	41.2	2647	14664	10	11
11h15-16h15	2411.2	7619.3	73.3	4550	26081	12	20
11h18-16h18	1265.2	3998.1	36.0	3133	17582	10	19
11h21-16h21	683.3	2159.2	19.0	1974	10956	10	15
11h24-16h24	-45.3	-143.2	-3.0	591	2885	11	12
11h27-16h27	359.1	1134.9	10.8	694	3501	15	5
11h30-16h30	1287.0	4066.9	39.1	2470	13822	21	10
11h33-16h33	1576.5	4981.6	47.8	2979	16546	17	11
11h36-16h36	1600.9	5058.7	48.7	3009	16945	11	12
11h39-16h39	908.4	2870.5	28.1	1675	9499	8	10
11h42-16h42	1645.0	5198.2	47.8	3270	19070	1	14
11h45-16h45	1868.8	5905.3	54.4	4044	23378	6	20
11h48-16h48	2647.6	8366.4	80.5	5617	32041	8	20
11h51-16h51	2012.3	6358.7	63.1	3709	21037	13	12
11h54-16h54	1679.6	5307.4	53.2	3066	17511	11	11
11h57-16h57	1624.8	5134.2	46.5	2723	15010	12	8

B.2.2 East Configuration

	fuel_kg	co2_kg	nox_kg	duration_s	distance_m	impacted	redirected
07h00-12h00	4244.9	13414.0	128.3	8070	46205	17	21
07h03-12h03	3972.7	12553.7	120.7	7507	42720	14	18

07h06-12h06	2455.0	7757.8	75.5	4569	25644	19	12
07h09-12h09	3321.1	10494.8	101.5	6254	34870	23	16
07h12-12h12	3911.7	12361.0	116.4	7706	43470	20	20
07h15-12h15	4027.9	12728.0	119.0	7996	45212	28	22
07h18-12h18	4072.8	12870.2	119.5	8182	45992	22	21
07h21-12h21	3431.8	10844.6	103.4	6602	37508	17	22
07h24-12h24	3524.3	11136.8	107.3	6717	37755	21	22
07h27-12h27	2916.8	9217.2	90.0	5465	30133	18	19
07h30-12h30	3131.2	9894.6	107.4	4993	27965	21	21
07h33-12h33	2030.8	6417.4	73.2	2994	16081	20	11
07h36-12h36	2133.3	6741.3	76.7	3149	17455	18	11
07h39-12h39	2745.0	8674.3	86.6	4957	27862	18	15
07h42-12h42	2271.1	7176.5	69.7	4340	24051	15	12
07h45-12h45	3053.7	9649.8	92.9	5911	33805	12	18
07h48-12h48	3241.8	10244.1	98.5	6269	35956	7	18
07h51-12h51	4288.2	13550.8	142.2	6311	36430	7	18
07h54-12h54	4440.7	14032.7	144.0	6810	38869	11	19
07h57-12h57	3671.0	11600.5	123.8	5064	28280	15	16
08h00-13h00	4076.8	12882.7	152.9	5533	30983	18	17
08h03-13h03	3264.8	10316.9	130.4	3860	20945	17	12
08h06-13h06	3674.5	11611.3	143.7	4507	25051	14	12
08h09-13h09	2679.2	8466.3	83.3	4869	27004	15	13
08h12-13h12	2188.1	6914.4	68.7	4380	24175	14	15
08h15-13h15	2502.9	7909.1	76.8	5187	28798	16	19
08h18-13h18	1027.7	3247.6	29.9	2566	13848	12	11
08h21-13h21	1164.9	3681.1	35.5	2262	12243	14	8
08h24-13h24	1309.6	4138.2	37.9	2690	14592	15	9
08h27-13h27	913.8	2887.7	26.8	1794	9548	19	6
08h30-13h30	1247.9	3943.5	35.8	2521	13690	23	8
08h33-13h33	1618.6	5114.9	51.8	2393	13363	14	7
08h36-13h36	1986.0	6275.8	65.9	2859	16158	8	11
08h39-13h39	2864.8	9052.8	92.6	4517	25553	9	15
08h42-13h42	3152.0	9960.2	98.5	5719	32766	11	22
08h45-13h45	3269.6	10331.9	103.2	5837	33583	16	23
08h48-13h48	2865.0	9053.4	90.8	5088	29197	15	17
08h51-13h51	1788.7	5652.3	57.9	3086	17520	16	8
08h54-13h54	3521.7	11128.6	117.4	5223	29348	20	13
08h57-13h57	3355.9	10604.5	111.9	4987	27708	22	17
09h00-14h00	3154.1	9966.8	106.5	4994	27973	20	21
09h03-14h03	2476.9	7827.1	84.8	3799	21134	12	18
09h06-14h06	847.8	2679.1	28.0	1873	10794	4	11
09h09-14h09	1373.7	4340.8	44.7	2781	15468	9	13
09h12-14h12	1975.8	6243.5	63.5	3419	19297	15	13
09h15-14h15	1975.8	6243.5	63.5	3419	19297	19	13
09h18-14h18	1522.0	4809.5	48.5	2103	11509	17	7
09h21-14h21	1779.1	5622.0	54.5	2783	15813	7	8
09h24-14h24	1796.8	5677.8	55.1	2820	15813	9	8
09h27-14h27	3447.7	10894.6	105.4	5891	33907	10	17
09h30-14h30	4949.3	15639.7	179.7	7136	41375	15	21
09h33-14h33	5279.1	16681.9	189.8	7732	44845	13	21

09h36-14h36	5534.4	17488.7	200.7	8039	45907	15	20
09h39-14h39	4554.4	14391.8	144.2	7596	43360	15	19
09h42-14h42	4761.7	15047.1	150.2	8009	45400	16	21
09h45-14h45	4374.6	13823.8	139.7	7200	41209	20	20
09h48-14h48	3099.2	9793.3	98.6	5562	31491	18	16
09h51-14h51	2241.2	7082.1	71.7	4004	21922	19	13
09h54-14h54	2529.0	7991.6	76.7	4805	26620	18	15
09h57-14h57	1859.9	5877.2	55.1	3617	19266	19	14
10h00-15h00	2005.9	6338.7	59.2	3921	21866	15	17
10h03-15h03	2235.8	7065.2	71.5	3520	19789	12	13
10h06-15h06	2113.8	6679.5	71.2	3014	17088	8	9
10h09-15h09	2859.3	9035.3	95.4	4318	24358	10	12
10h12-15h12	2704.4	8546.0	89.6	4083	22839	12	12
10h15-15h15	3677.6	11621.3	122.8	6017	34112	16	18
10h18-15h18	3185.6	10066.3	106.7	5147	29112	14	16
10h21-15h21	2971.5	9390.1	102.1	5047	28510	13	15
10h24-15h24	2797.1	8838.9	90.7	4664	25993	16	14
10h27-15h27	1341.7	4239.6	42.5	2252	12182	11	9
10h30-15h30	2424.8	7662.4	76.4	4180	23201	18	15
10h33-15h33	2008.8	6347.8	62.2	3658	20396	13	12
10h36-15h36	3001.2	9483.9	92.0	5626	31541	20	17
10h39-15h39	3765.2	11897.9	113.7	7234	40858	19	21
10h42-15h42	3001.9	9486.1	91.2	5268	29839	12	15
10h45-15h45	3131.1	9894.3	97.3	5279	30014	13	16
10h48-15h48	2215.2	6999.9	67.5	3809	21637	6	10
10h51-15h51	3057.3	9661.0	92.8	5330	30433	9	14
10h54-15h54	2734.6	8641.5	81.3	5389	30342	13	14
10h57-15h57	2210.3	6984.5	65.4	4378	24390	16	13
11h00-16h00	2074.4	6555.0	62.7	3925	22004	22	12
11h03-16h03	658.3	2080.2	20.5	1211	6162	19	5
11h06-16h06	755.6	2387.7	23.7	1374	7246	16	4
11h09-16h09	1406.0	4442.9	43.6	2611	14340	16	7
11h12-16h12	1365.2	4314.0	41.3	2595	14353	11	10
11h15-16h15	4310.7	13621.8	137.7	6565	37952	13	21
11h18-16h18	3868.2	12223.4	124.5	5711	33270	9	18
11h21-16h21	3314.5	10473.8	108.1	4648	27111	10	14
11h24-16h24	2157.3	6816.9	68.7	3827	22076	13	12
11h27-16h27	683.2	2158.9	20.0	1345	7516	14	5
11h30-16h30	1308.0	4133.2	40.0	2569	14309	22	10
11h33-16h33	1612.5	5095.5	48.9	3159	17845	16	10
11h36-16h36	2055.5	6495.3	62.7	3962	22776	10	12
11h39-16h39	2361.2	7461.4	69.8	4728	27373	8	14
11h42-16h42	2545.4	8043.3	74.6	4403	25756	1	15
11h45-16h45	3267.0	10323.6	96.3	5200	30093	6	22
11h48-16h48	2281.9	7211.0	66.9	3325	18732	7	17
11h51-16h51	1585.1	5008.8	49.3	2178	11848	13	12
11h54-16h54	1726.9	5457.0	50.7	3811	20983	15	16
11h57-16h57	1565.6	4947.3	46.0	3470	19163	13	10