PRELIMINARY EVALUATION OF FLIGHT DELAY PROPAGATION THROUGH AN AIRLINE SCHEDULE

Roger Beatty
American Airlines
P.O. Box 619617, MD875
D/FW Airport, TX 75261-9617 USA
(817)931-0951/r_beatty@compuserve.com

Rose Hsu
American Airlines
P.O. Box 619617, MD875
D/FW Airport, TX 75261-9617 USA
(817)967-4033/rose_hsu@amrcorp.com

Lee Berry
Oak Ridge National Laboratory
1099 Commerce Oark, MS- 7618
Oak Ridge, TN 37830 USA
(423)574-0998/berryla@ornl.gov

James Rome
Oak Ridge National Laboratory
1099 Commerce Oark, MS- 7618
Oak Ridge, TN 37830 USA
(423)574-1306/romeja@ornl.gov

Abstract

Airline flight schedules are particularly sensitive to individual flight delays because of the manner in which operating resources are linked together. Among the connective resources affected by delayed flight operations are crews, aircraft. passengers and gate space. Because of this branching connectivity the delay of one flights tends to propagate rapidly down line to many others. In order to evaluate an initial flight delay on an airline operating schedule this paper proposes the concept of a Delay Multiplier (DM).

Using American Airlines crew and aircraft connectivity through an actual airline operating schedule the DM demonstrates the value of delay (or delay reduction) on the operating schedule as a whole. The relationship between the duration of initial delay, the time of day of the delay occurrences and airline schedule connectivity are used to calculate the value of the DM.

Specifically, this process was developed to evaluate changes in the FAA's Air Traffic Management Ground Delay Program procedures.

Background

1. The Problem

When the flight arrival demand exceeds an airport's acceptance capacity, it is the job of the FAA's Air Traffic Control System Command Center (ATCSCC) to control demand. This is often done through the use of a technique called the Ground Delay Program (GDP). Under this program ATCSCC issues Controlled Times of Arrival (CTAs) to flights still on the ground but destined to arrive at the constrained airport to ensure the airport capacity is not exceeded. GDP can produce delays for individual flights ranging from a few minutes to several hours. These delays are of concern to any user, but are most disruptive to airline operators whose schedules are made up of tightly connected operating resources (i.e. aircraft and crews). Intuitively, large delays early in the operating day are most disruptive, while short delays (or delays late in the day) have little or no propagation through the schedule.

To better understand the total effect of airline flight delays produced by ATCSCC GDPs, American Airlines and Oak Ridge National Laboratory collaborated on a joint study to see if a numerical "delay multiplier" (DM) could be derived that was based on the length of the initial delay and the time of day it occurred.

This was not an attempt to predict the actual downline effect any given flight delay would produce, but rather to develop a "generic" total value of both the initial delay and its continuing consequences on the airline schedule. This total value could then be used in the evaluation of changes in GDP procedures.

It seemed obvious to those that operate airline schedules that reducing a 60 minute delay to 30 minutes is much more valuable than reducing a 30 minute delay to zero. The question is: How does the value of initial delay reduction vary based on both the length of the initial delay and the time of day at which it occurs?

It is important to note that, for an airline, the "value" of delay is not just its effect on an individual airframe but its effect on the operating schedule. It is this schedule that is the primary product offered to the traveling public. Passengers do not go out to the airport to fly on a specific airplane or with a specific crew. They go to catch the two o'clock flight to Chicago which is promised in the airline's published schedule. A significant part of the airline's day-to-day operational effort is expended in the attempt to keep that promise.

2. The Concept of Delay Multiplier (DM)

To establish the value of the DM we decided to analyze the conductivity of crew sequences and aircraft sequences though the American Airlines flight schedule. While these are the obvious and primary assets needed to operate flights, there are other resources that are affected by delayed flight operations that were not considered due to their complexity. Most notably, the affect of delayed operations on passengers, cargo and gate space were not considered. Each of these can induce delays in other flights. Therefore we believe our calculated DMs based on crew and aircraft only to be highly conservative.

The concept of Delay Multiplier can be considered as that value, which when multiplied by the initial delay, would yield all of the potential downline delays (produced by resource connectivity) plus the initial delay, or, total delay. This could be shown as:

$$DM = (I+D)/I$$

Where: DM= Delay Multiplier I= Initial delay and D= Down line delay (all values of delay are in minutes)

For example, a flight into San Fransico (SFO) is delayed 30 minutes. It delays 2 flights out of SFO, one 10 minutes awaiting a crew and another 5 minutes awaiting the aircraft. In this case the initial delay is 30 minutes and the downline delay is 15 (10+5) minutes so the delay multiplier would be 1.5.

$$1.5 = (30+15)/30$$

As long as the resource connectivity and minimum turn time are known the initial delay can be varied by time increments, the downline delays re-calculated and new delay multipliers derived.

3. The Proposed Departure Report

American Airlines Operations personnel use a computer display that allows airlines themselves to "what-if" with initial delays and view the downline effects in a series of delay trees. This is done with what is called the "PRP" Command and a sample of this display is found in Figure 1 below.

The Column headers are decoded as follows:

FLT = flight number and departure date

DEP = 3 letter code of departure airport

SKD = Scheduled gate departure time (local time)

PRJ = Projected departure time reflecting either a manual entry or as calculated from minimum resource turn time

ARV = 3 letter code or arrival airport

SKA = Scheduled gate arrival time (local time)

PRJ = Projected arrival time (local time)

```
PRP 1237/22 ATL 0730 [ENTER]

   PRP 1237/22 ATL 0730
 FLT    DEP SKD   PRJ   ARV SKA  PRJ
1237/22 ATL 0700  0730  DFW 0822 0852

 710/22 DFW 0906  0927  LGA 1316 1337
            FLT 1237/22  EQ 22/0927
1178/22 DFW 0910  0927  MIA 1300 1317
            FLT 1237/22  CP 22/0927  FA 22/0927

 333/22 LGA 1359  1412  ORD 1529 1542
            FLT  710/22  EQ 22/1412
END
```

Figure 1

The abbreviated line below the flight line explains the reason for the projected downline delay. It shows the flight number of the delayed inbound flight and which resource(s) are causing the downline delay. EQ stands for equipment (read aircraft), CP stands for Cockpit Crew and FA stands for Flight Attendants.

In this example a flight from Atlanta (ATL) to Dallas (DFW) has a projected delay of 30 minutes. It causes two delayed flights out of DFW one to New York, LaGuardia (LGA) and one to Miami (MIA). The flight to LGA causes yet another delay.

When the initial delay is increased to two hours (see Fig. 2) many more minutes of downline delay are created and the delay tree expands.

```
PRP 1237/22 ATL 0900 [ENTER]

 FLT    DEP SKD   PRJ   ARV SKA  PRJ
1237/22 ATL 0700  0900  DFW 0822 1022

 710/22 DFW 0906  1057  LGA 1316 1507
            FLT 1237/22  EQ 22/1057
1178/22 DFW 0910  1057  MIA 1300 1447
            FLT 1237/22  CP 22/1057  FA 22/1057

 333/22 LGA 1359  1542  ORD 1529 1712
            FLT  710/22  EQ 22/1542

1453/22 MIA 1350  1522  AUS 1558 1730
            FLT 1178/22  EQ 22/1522

 354/22 ORD 1700  1747  LGA 2003 2050
            FLT  333/22  EQ 22/1747  CP 22/1747  FA 22/1747

 524/22 AUS 1655  1805  ORD 1928 2038
            FLT 1453/22  EQ 22/1805

 361/22 LGA 2100  2127  ORD 2231 2258
            FLT  354/22  EQ 22/2125  CP 22/2127  FA 22/2127

 524/22 ORD 2035  2113  RDU 2336 0014
            FLT  524/22  EQ 22/2113
END
```

Figure 2

It can be seen from these samples that as delay on the initial flight increase the number of flights affected increases as well. This is due to the branching nature of crew and aircraft sequences. Since the rules to optimize crew time are different than those used for aircraft utilization this separation of crew and aircraft routings is common at most airlines.

Over five hundred of these delay trees that resulted in thousands of delayed flights were provided to Oak Ridge National Laboratory for detailed analysis as detailed below.

4. The Analysis

Each of the PRP commands generates a group of delayed flights that includes the initial flight as designated by the PRP command as well as any subsequent flights that are delayed due to lack of equipment or crew. We call this group a primary delay tree. The tree can contain one flight if there is enough slack in the schedule to absorb the initial delay, or as many as 50–75 for a flight early in the day that is tightly connected to the rest of the system.

For the data set examined in this paper, there were a total of 521 primary delay trees that resulted from a four–hour delay of DFW-bound flights. Including these initiators, a total of 2729 (6.23 flights per primary tree) flights were delayed with an average delay of 152 minutes.

If delay multipliers were only calculated for the primary trees, there would not be sufficient data to represent the delay multiplier variation with both time of day and length of initial delay as independent variables. Secondary trees were generated in two ways. First, using the system model implicit in the four-hour delay trees, the length of the initial departure delay was reduced in 15 minute increments from the starting point of four hours. Each subsequent departure delay in the tree was reduced by the same time. If, for example, the initial PRP departure delay of four hours resulted in a flight that was 13 minutes late, a reduction in the departure delay to 3:45 would allow the flight to land on time and terminate the tree. Second, secondary trees were also formed by looking at each intermediate flight as the starting point of a tree. What happens downstream if this flight is independent (with the system model being used) of what caused its departure delay, and thus can be used to generate another delay multiplier datum. The addition of these secondary trees has the benefit of adding departure airports other than DFW to the analysis thus giving us a better representation of the AAL system.

Using the primary and secondary trees as described above, over 34,000 delay-multiplier data points were calculated. They were put into bins that covered 15 minutes of departure delay and 30 minute arrival time. For the period 0600 to 2330, the number of points in a bin varied from none (one bin) to over a 100 with typical values in the 20–100 range. These ranges suggest that we should expect that the average values of delay multiplier calculated for each bin have statistical uncertainties in the range of 10-20% using the crude $N^{0.5}/N$ estimator where N is the number of points in each bin. It is these sampling variations that result, in some cases, in the delay multiplier apparently decreasing when the departure delay is increased.

While for any given flight, the delay multiplier must increase for increased departure delay, the data that we calculate is based on implicit sampling of a large number of flights. The bin for a longer departure delay contains not only the flights which were also in the shorter delay bin, but also those with, perhaps, smaller delay multipliers that are a result of different connectivity properties for those different trees.

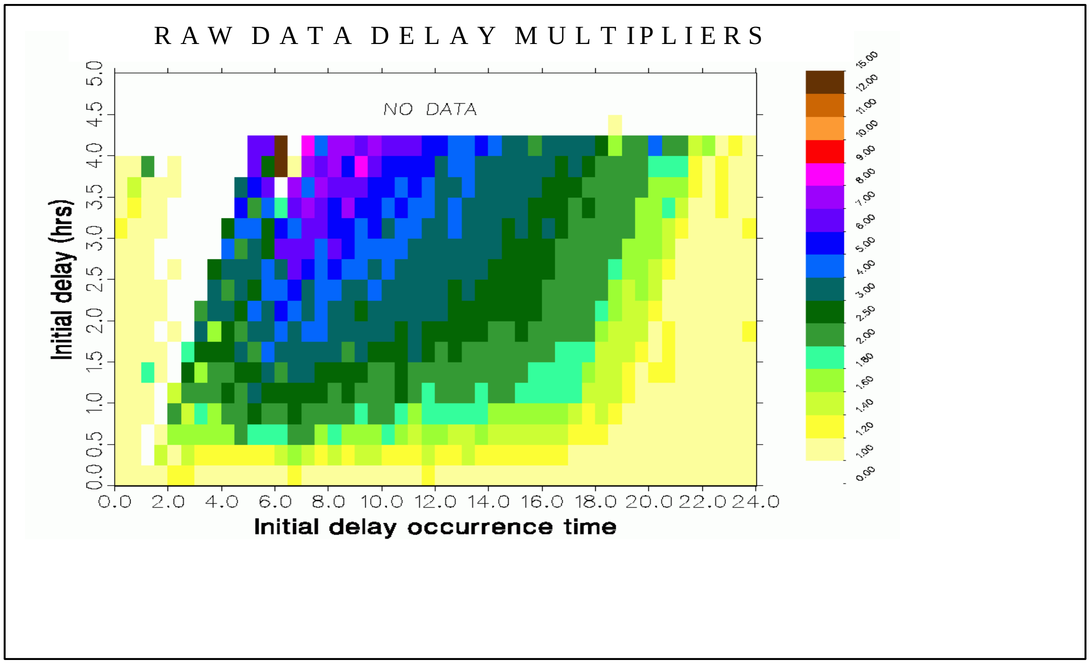
In order to better understand the underlying trends for this data set, various linear and nonlinear regression models were fit to the data. Even though more complex dependencies were tried, the simple model of a linear increase in delay multiplier with increased departure delay was found to work well. Specifically, for each time-of-day data set, a model of the form $DM = 1 + S * DD$ where DM is the delay multiplier, DD the departure delay, and S the slope of the line, was used. This model forces a delay multiplier of “1” for an on–time departure. In order to account for the varying statistical error, a weighted least squares technique was used to solve for S.

Least squares techniques are based on minimizing the square of the difference between model predications and the data (the variance). The variance for each point is multiplied (weighted) by the number of trees that comprise the average for that bin to account for the varying statistical significance. In the present model only one parameter is needed, and it is found by setting the derivative of the variance with respect to S to zero. The resulting models are statistically very significant and account for 80–95% of the variance in the data.

Some of the results of this fitted DM calculations can be found in Table 1 located at the end of this document,. In this table the right hand column consists of time buckets from 6:00 to 23:30 local time in 30 minute increments. The time value is in hours and tenths of hours. For example the value of 6.25 is the center of the time bucket that runs from 6:00 to 6:30. Initial delay is found in the top row, again in hours and tenths increasing in 15 minute increments with the value shown as the center of the time bucket. For example the delay multiplier for an initial delay of 2 hours on a flight arriving at 8:00 would be 4.28. (Down to 8.25 over to 2.125)

4. Viewing the Data

The color box chart seen in Figure 3 below is a plot of the raw DM data. By observing the distribution of the darker colors the trend of large DMs is obvious but anomalies of increasing initial delay and decreasing DMs exist.



The fitted data in Table 1. is shown in Figure 4. below and the anomalies are eliminated.

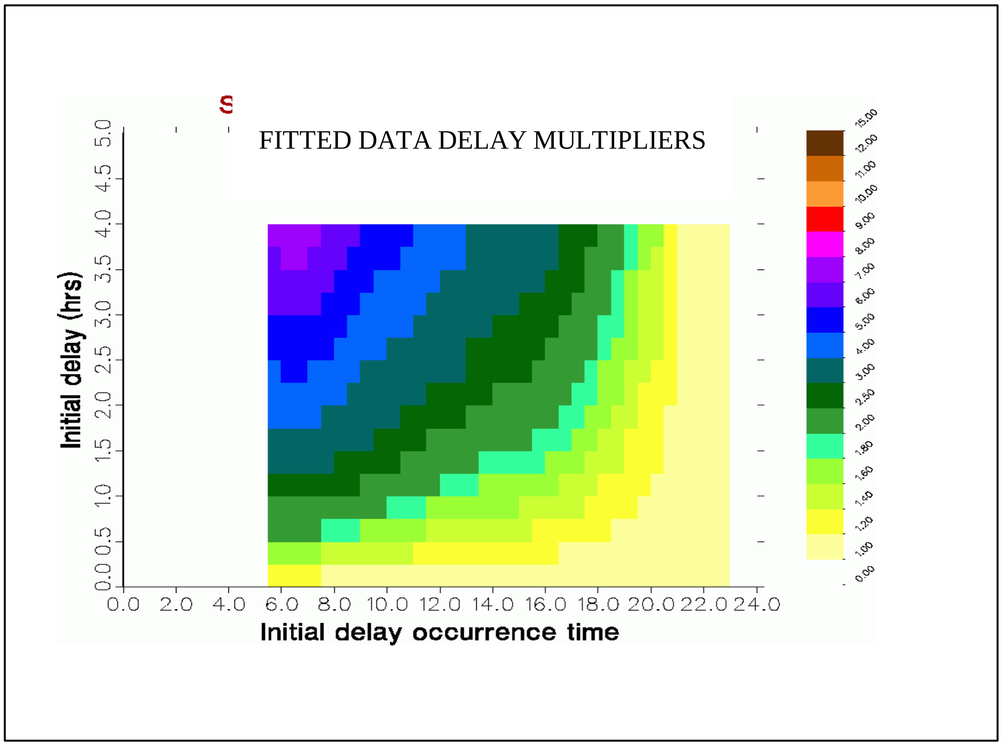


Figure 4

Figure 5. below allows a simpler view of DM as a function of initial delay and only three times of day: 08:00, 13:00 and 18:00 local time. Of interest is both the magnitude of the DMs and the slope of the trend line.

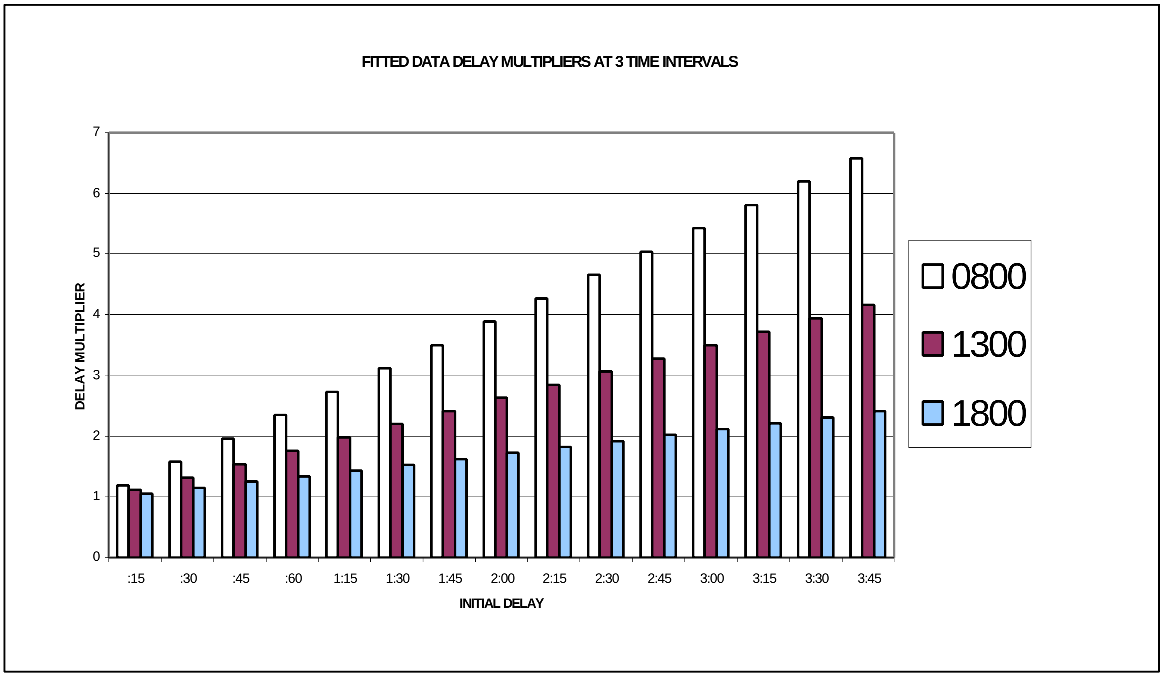
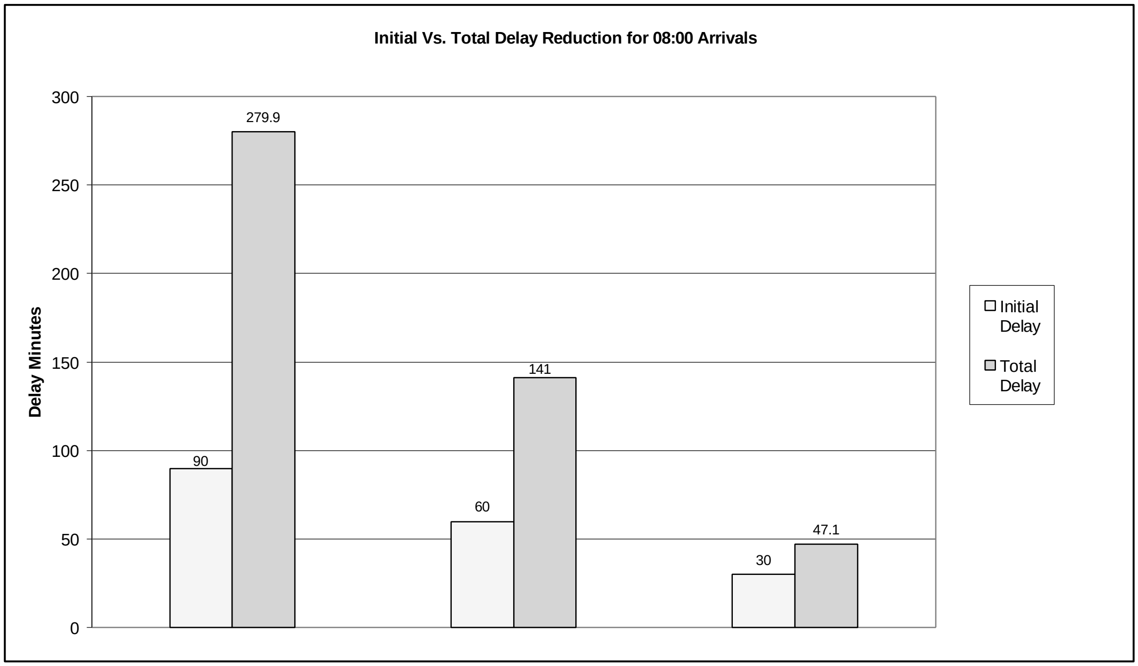


Figure 5

Figure 6. demonstrates an important conclusion about using DMs to evaluate delay reduction. That is, that reducing large initial delay by even small amounts can have a significant affect on total delay in an airline schedule



.Figure 6

In the example above, for 08:00 arrivals, a reduction in initial delay from 90 to 60 minutes, or 33%, results in a total delay reduction of 279.9 to 141 minutes, or a 49.62% reduction in overall delay. When the initial delay is further reduced for m 90 to 30 minutes, or 66%, total delay is reduced by 83.17%.

5. Summary.

The calculation of DMs here is really a look at the connectivity of one airline's operating resources through its schedule. It may be typical of other major hub and spoke airlines but further analysis is required. It also can be assumed that other airline scheduling strategies would yield different results. The DMs at a large international operator with long turn times and little crew and aircraft branching would be much smaller, while a high frequency, short turn time operator might be much larger.

It is also understood that airlines react to large delays by canceling flights and reassigning resource to minimize delay propagation. These reactions are also costly to the airline as resources are de-optimized and passenger revenue is lost. So, while it may be difficult or impossible to calculated these costs, it is possible to use the cost calculated by DMs as a conservative surrogate.

It is important to have some way to assess the value of delay on the operating schedule as a whole. Otherwise, the cost of delays, especially large delays, are grossly underestimated by using initial delay as the only metric.

While further analysis is required, we feel that due to the conservative nature of this analysis it may be useful as an initial step in understanding the effects of delay on schedule integrity.

Delay Multiplier Table

	Initial															
	Delay															
time	0.125	0.375	0.625	0.875	1.125	1.375	1.625	1.875	2.125	2.375	2.625	2.875	3.125	3.375	3.625	3.875
6.25	1.21	1.62	2.03	2.44	2.86	3.27	3.68	4.10	4.51	4.92	5.33	5.75	6.16	6.57	6.98	7.40
6.75	1.21	1.64	2.06	2.48	2.91	3.33	3.76	4.18	4.61	5.03	5.45	5.88	6.30	6.73	7.15	7.57
7.25	1.21	1.63	2.06	2.48	2.90	3.33	3.75	4.17	4.59	5.02	5.44	5.86	6.28	6.71	7.13	7.55
7.75	1.20	1.61	2.02	2.43	2.84	3.25	3.66	4.07	4.48	4.89	5.30	5.71	6.12	6.53	6.94	7.35
8.25	1.19	1.58	1.96	2.35	2.73	3.12	3.50	3.89	4.28	4.66	5.05	5.43	5.82	6.20	6.59	6.97
8.75	1.18	1.53	1.88	2.24	2.59	2.94	3.30	3.65	4.00	4.36	4.71	5.06	5.41	5.77	6.12	6.47
9.25	1.17	1.51	1.85	2.19	2.53	2.87	3.22	3.56	3.90	4.24	4.58	4.92	5.26	5.60	5.94	6.28
9.75	1.16	1.47	1.79	2.10	2.42	2.73	3.05	3.36	3.68	3.99	4.31	4.62	4.94	5.25	5.57	5.88
10.25	1.14	1.43	1.72	2.01	2.30	2.59	2.88	3.17	3.46	3.75	4.04	4.32	4.61	4.90	5.19	5.48
10.75	1.14	1.42	1.69	1.97	2.25	2.53	2.80	3.08	3.36	3.64	3.92	4.19	4.47	4.75	5.03	5.30
11.25	1.13	1.40	1.66	1.93	2.20	2.46	2.73	2.99	3.26	3.52	3.79	4.06	4.32	4.59	4.85	5.12
11.75	1.13	1.38	1.63	1.88	2.13	2.39	2.64	2.89	3.14	3.40	3.65	3.90	4.15	4.40	4.66	4.91
12.25	1.11	1.34	1.56	1.79	2.01	2.24	2.47	2.69	2.92	3.14	3.37	3.59	3.82	4.04	4.27	4.49
12.75	1.11	1.33	1.55	1.77	1.99	2.21	2.43	2.65	2.87	3.09	3.31	3.53	3.75	3.97	4.19	4.41
13.25	1.11	1.33	1.54	1.76	1.98	2.20	2.41	2.63	2.85	3.07	3.28	3.50	3.72	3.94	4.16	4.37
13.75	1.09	1.28	1.47	1.66	1.85	2.03	2.22	2.41	2.60	2.79	2.98	3.16	3.35	3.54	3.73	3.92
14.25	1.09	1.26	1.44	1.62	1.79	1.97	2.15	2.32	2.50	2.68	2.85	3.03	3.20	3.38	3.56	3.73
14.75	1.09	1.26	1.43	1.60	1.77	1.95	2.12	2.29	2.46	2.64	2.81	2.98	3.15	3.32	3.50	3.67
15.25	1.09	1.26	1.43	1.60	1.77	1.94	2.11	2.28	2.45	2.62	2.79	2.97	3.14	3.31	3.48	3.65
15.75	1.08	1.24	1.40	1.55	1.71	1.87	2.03	2.19	2.35	2.50	2.66	2.82	2.98	3.14	3.30	3.45
16.25	1.08	1.23	1.38	1.53	1.68	1.83	1.98	2.13	2.28	2.43	2.58	2.73	2.88	3.03	3.18	3.33
16.75	1.07	1.21	1.35	1.48	1.62	1.76	1.90	2.04	2.18	2.32	2.45	2.59	2.73	2.87	3.01	3.15
17.25	1.06	1.19	1.32	1.45	1.57	1.70	1.83	1.96	2.08	2.21	2.34	2.47	2.59	2.72	2.85	2.98
17.75	1.06	1.17	1.29	1.41	1.52	1.64	1.75	1.87	1.98	2.10	2.22	2.33	2.45	2.56	2.68	2.79
18.25	1.05	1.15	1.24	1.34	1.44	1.53	1.63	1.73	1.82	1.92	2.02	2.12	2.21	2.31	2.41	2.50
18.75	1.04	1.12	1.21	1.29	1.37	1.46	1.54	1.62	1.71	1.79	1.87	1.96	2.04	2.12	2.20	2.29
19.25	1.04	1.11	1.18	1.25	1.33	1.40	1.47	1.55	1.62	1.69	1.76	1.84	1.91	1.98	2.05	2.13
19.75	1.03	1.09	1.14	1.20	1.26	1.32	1.37	1.43	1.49	1.55	1.60	1.66	1.72	1.78	1.83	1.89
20.25	1.02	1.07	1.11	1.15	1.20	1.24	1.29	1.33	1.37	1.42	1.46	1.50	1.55	1.59	1.64	1.68
20.75	1.02	1.06	1.10	1.14	1.18	1.22	1.26	1.29	1.33	1.37	1.41	1.45	1.49	1.53	1.57	1.61
21.25	1.01	1.04	1.06	1.09	1.11	1.14	1.16	1.18	1.21	1.23	1.26	1.28	1.31	1.33	1.36	1.38
21.75	1.00	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10	1.11	1.12	1.12	1.13	1.14
22.25	1.00	1.01	1.02	1.02	1.03	1.03	1.04	1.05	1.05	1.06	1.07	1.07	1.08	1.09	1.09	1.10
22.75	1.00	1.01	1.02	1.03	1.04	1.05	1.05	1.06	1.07	1.08	1.09	1.10	1.11	1.11	1.12	1.13
23.25	1.00	1.01	1.02	1.02	1.03	1.04	1.04	1.05	1.06	1.06	1.07	1.08	1.08	1.09	1.10	1.10