

## MODELING TIME AND SPACE METERING OF FLIGHTS IN THE NATIONAL AIRSPACE SYSTEM

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### ABSTRACT

Metering flights at key points such as sector crossings is an important operational procedure in mitigating National Airspace System (NAS) traffic congestion due to high demand or changing weather conditions. The authors combine a mathematical model for minutes-in-trail or miles-in-trail (MIT) metering with discrete event simulation in a newly developed tool that can be used by analysts to examine or predict existing or developing bottlenecks within NAS. We define a penalty function recursively in terms of MIT delays between leading and following flights. With discrete event simulations, it is possible to examine the anticipated MIT delays for all the flights scheduled to arrive at any crossing point. Impacts of flight cancellations, route changes, and additional enroute delays as results of airport or sector congestion can all be evaluated during each simulation by updating the scheduled flight crossing times and the expected MIT delay penalties for all the trailing flights.

### 1 INTRODUCTION

The National Airspace System (NAS) handles over 50,000 daily flights. Scheduled flights may be connected through itineraries that show the flight legs traversed by a single airframe during the course of a day. If the originally intended itinerary is disrupted, e.g., by bad weather or excessive congestion, flights may be terminated, delayed, diverted, replaced, or rerouted to their departure airports. Flights may also be delayed, diverted, or metered while en route at key control points such as sector crossings, fixes, or waypoints. In addition, flights are also subject to handoff, sequencing, and metering, for events such as takeoff, landing, and sector crossing. Air traffic flow management (TFM) (Ball, Connolly, and Wanke 2003) procedures such as Ground Delay program (GDP), Ground Stop (GS), or Miles-in-Trail (MIT) metering are options available to the Air Traffic Management (ATM) authority to manage airway congestion and to respond to anticipated weather conditions (Wanke et al.

2003). The impacts of specific TFM actions on overall NAS performance can be measured with metrics such as flight delays and fuel use. Multiple simultaneous TFM actions may be highly interdependent, and the effects of a TFM action can ripple to other NAS resources and other flights during the day (Ostwald et al. 2003). The effects of such complex interactions can potentially be quantified with either discrete event simulation or mathematical models or both. In this analysis, the authors developed a recursive MIT penalty function to quantify the ripple effects of specific MIT programs over relevant sets of flights and flight restrictions within the NAS. In conjunction with discrete event simulation, it is possible to examine and quantify the total impacts of various TFM programs for alternatives analysis and provide a comparison across several alternative TFM programs available to air traffic flow management decision-makers. Combining the MIT penalty function with fast event-driven simulation, it is demonstrated that potential congestion “hot spots” in the NAS can be identified based on flight schedules. Potential or developing bottlenecks also can be simulated for anticipated or real weather conditions and the impacts of alternative GDP, GS, or MIT programs quantified either individually or collectively.

### 2 A RECURSIVE MIT PENALTY FUNCTION

Safety is the ATM authority’s ultimate reason for keeping aircraft separated. In some cases, aircraft separations may need to be maintained at distances significantly larger than minimum separation standards to accommodate flow control or other operational requirements. In principle, aircraft may be separated in time or space or both. When both aircraft type and instantaneous speed are known, spatial and time separation are theoretically interchangeable, although in actual operations, ATM procedures mandate minimum spatial separation standards for aircraft in en route and terminal airspace (Beaton, et al. 2002). The enforcement of aircraft separation for a given pair of flights may ripple through the remainder of the flights’ itineraries and affect

other nearby flights as well. The net impact of such ripple effects can be modeled and quantified with a recursive penalty function that links all the relevant flights. In this paper, spatial separation is defined in terms of miles-in-trail (spatial MIT) restrictions while time separation is defined in terms of minutes-in-trail or time-based metering (TBM) i.e., temporal MIT restriction. In this sense, MIT restrictions encompass both time and space separations.

Figure 1 illustrates the relationship of a given flight to all the flights that will arrive at the point where a specific MIT restriction is applied during the time interval of interest in a simulation. In this Figure, time runs along the horizontal axis and different flights arrive at the point of the MIT restriction  $x$  at different times. Each black arrow represents a flight scheduled to arrive at a specific MIT restriction on the time axis associated with the restriction. Delayed flights or rescheduled flights are represented by arrows in red. Flights that do not arrive at the restriction on time are deleted and reinserted accordingly during the simulation as these events occur. Hence, an up-to-date sequencing of flights anticipated to arrive at a given restriction is always available and maintained during the simulation

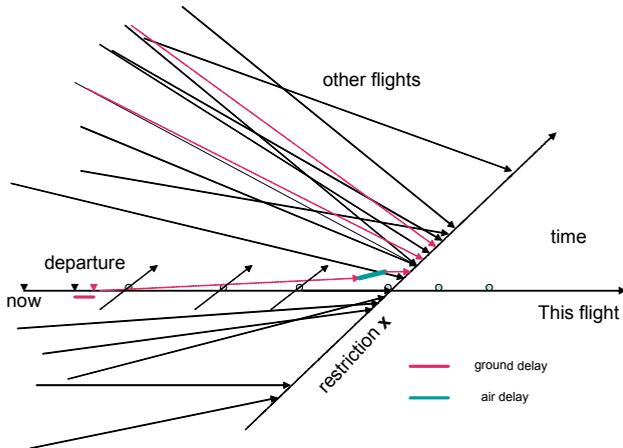


Figure 1: MIT Restrictions Simulation

From Figure 1, it is possible to anticipate the degree of congestion or potential MIT violations based upon initial scheduled flight plans during the simulated period. Such information is very important in identifying hot spots within the NAS that are results of scheduling conflicts. Ground delay/stop and/or air delay may then be designed to alleviate the anticipated hot spots or bottlenecks.

However, flights may be delayed, cancelled, diverted, or replaced by airlines due to various factors such as developing weather conditions, congestion at airports, procedural delays, or mechanical problems. From Figure 1, it is also clear that for any flight delay, there are ripple effects over the initial computed NAS MIT restrictions profile. First, the MIT delay will ripple down the remainder of the flight itinerary for each airframe. Second, for each restriction encountered, the MIT delay may also ripple over the

group of flights anticipated to arrive at the point of restriction. To quantify these ripple effects, we take advantage of the recursive relationship between the expected MIT delays for each flight and the leading flight ahead of it.

- Let  $t_i$  = estimated (scheduled or adjusted) arrival for flight  $f_i$  at restriction  $X$ .
- $p_i$  = actual (recorded or simulated) arrival time for flight  $f_i$  at restriction  $X$ .
- $v_i$  = speed of flight  $f_i$  at restriction  $X$ .
- $S$  = Miles-In-Trail (spatial MIT) separation enforced at restriction  $X$ .
- $d_i$  = MIT delay (penalty) for flight  $f_i$  at restriction  $X$ .

From Figure 2, it is clear that we have the following recursive relation among flights subject to a given MIT restriction  $X$ :

$$d_i = \text{MAX}\{0, d_{i-1} + t_{i-1} + S/v_{i-1} - t_i\} \quad (1)$$

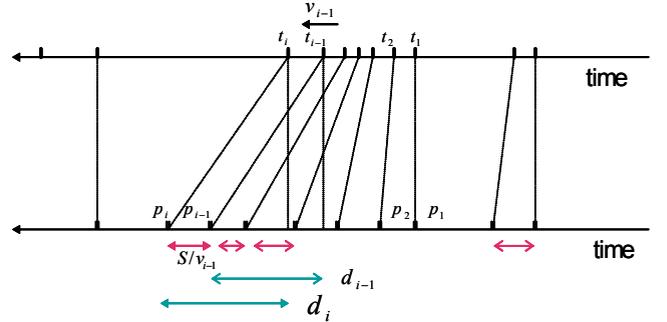


Figure 2: A Recursive MIT Penalty Relation

Equation (1) defines an MIT penalty function for NAS. From the family  $\{d_i\}_{i=1}^{|F|}$  where  $F$  is the family of all the flights scheduled to arrive at restriction  $X$ . Whenever  $t_i$  is adjusted or modified by a GSP, GDP, or other TFM action,  $\{d_i\}_{i=1}^{|F|}$  is updated according to the MIT penalty function (1) for all the relevant flights in  $F$ . Note that the ripple effects are embedded implicitly within the MIT penalty function. Note that in equation (1)  $t_i$  stands for scheduled arrival time at the restriction for flight  $f_i$ ; initially,  $t_i$  is simply the scheduled arrival time at restriction  $X$ , however, during a simulated period, flight  $f_i$  may be delayed as a result of airport or en route congestion, or GS, or GDP.

When such events occur, the delayed flights are removed from the ordered list of the flights and reinserted back to the ordered list such that correct and up-to-date  $t_i$  and  $d_i$  are maintained. The ripple effect of each change in every flight will automatically be reflected in the recomputed  $\{d_i\}_{i=1}^{|F|}$ .

If equation (1) is implemented in a discrete event simulation package for the NAS, it will be possible for analysts to perform the following three tasks:

First, artificial MIT restrictions may be placed at key strategic points such as sector crossings, way points, or fixes to identify NAS bottlenecks resulting from scheduled demand. The hot spots and the extent of MIT space/time separation violation contributed by scheduling alone can be quantified in this way.

Second, once hot spots or bottlenecks within the NAS are identified, corrective actions or procedures may be designed to alleviate the problems. When alternative action plans are available, a comparison of their pros and cons can be assessed based on quantified performance metrics in simulated scenarios capturing the ripple effects of adjusted MIT restrictions over the entire NAS.

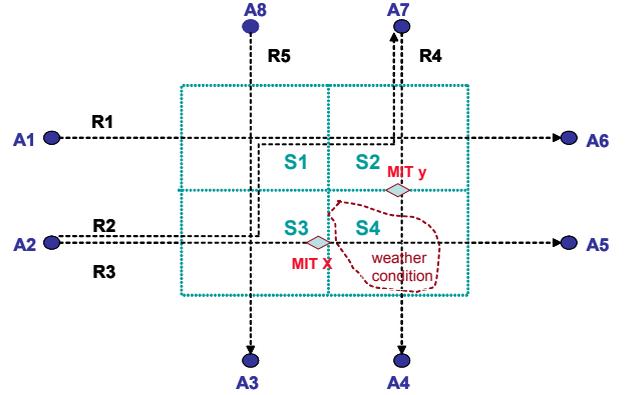
Third, such a tool will be able to evaluate or predict the overall NAS performance impact due to developing weather conditions, increased traffic demand, or reduced airport or airspace (sector) capacities. Furthermore, quantified NAS performance metrics can be captured in simulations to assess the relative merits of individual potential GS, GDP, MIT, or other TFM programs.

### 3 TEST SCENARIOS

The implementation of the proposed MIT penalty function for all flights is made simpler with the use of Simulation Language with eXtensibility (SLX) (Brunner 2003). We have already developed a NAS simulation in SLX, and the MIT capability was implemented in the context of the NAS simulation (Wieland 2004). In our NAS simulation, a flight follows its scheduled itinerary from airport to airport. Various en route models with different degrees of detail for a wide range of aircraft types are available to analysts. In this study, flights follow a string of sectors. Takeoff, sector crossing, and landing are simulated with handoff request and acceptance. A handoff may be rejected or delayed if the target sector or airport has exceeded its capacity. We implemented two complementary data sets for MIT restrictions in the SLX simulation: the set of restrictions for each flight and the set of flights for each restriction. For any delay or change in scheduled flights, the MIT penalty is computed for all the relevant flights in these two sets.

Several scenarios were tested to provide quantified MIT-related delay profiles for baseline scenarios, with and without weather-related MIT restrictions. Figure 3 illustrates one such test scenario with 4 neighboring sectors, 8 airports, and 5 distinct routes with 2 MIT restrictions. In the baseline scenario, all sectors have identical capacity, identical Poisson flight arrival rates are maintained over all distinct routes. Weather conditions on S4 were simulated with reduced sector capacity and increased sector occupancy time. The impacts of imposing MIT restrictions at sector crossings, the interdependency between MIT penalties, reduced sector capacities, and ripple effects over

neighboring sectors and flight streams were quantified with simulation for comparative analysis. When all relevant flights are tabulated for their end-to-end performance, it is possible to develop better understanding of and justification for specific GDP, GS, or other TFM options.



Legends : Ai : Airports, Si : Sectors, Ri : routes, MIT : space/time restrictor

Figure 3: MIT restrictions Simulation with SLX

### 4 SIMULATION RESULTS

In this section, we discuss the computed spatial MIT penalty profile for scheduled flights, the impacts of reduced sector capacity at S4, and the sensitivity to MIT space separation settings for MIT restrictions at x and y (see Figure 3). We also demonstrate cases when the penalty from MIT restrictions clearly exceeds its benefits. However, we also identified cases when a significant reduction in total trip time can be achieved with properly fine-tuned MIT restrictions.

Key parameters that determine the distribution of the MIT penalty  $\{d_i\}_{i=1}^{|F|}$  given in equation (1) are:

- $C_j$  : the sector capacity at  $S_j$
- $t_j$  : the sector occupancy time at  $S_j$
- $R_x$  and  $R_y$  : the value of MIT separation at x and y.
- $\lambda_k$  : the intensity of traffic rate for each route  $R_k$ .

The key measurements of the MIT penalty are:

- n: the total number of flights with  $0 < d_i$
- m: the instantaneous MIT metering queue size
- D: total MIT metering penalty ( $= \sum_{i=1}^{|F|} d_i$ )

For a given scenario, m, n, and D can be determined by simulation. Figures 4, 5, 6 illustrate such a test case with various intensities of flights scheduled as Poisson arrivals for each route from 8 to 20 flights per route per hour. Note that the artifice of scheduling flights with exponential inter-departure times is only a reference point. In the real world flights can be scheduled more or less regularly than simulated here.

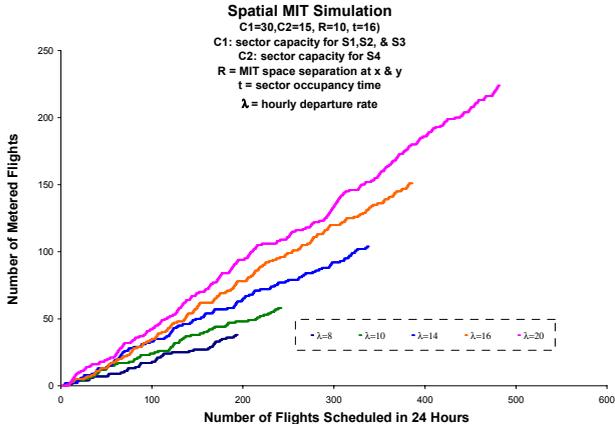


Figure 4: Intensity of MIT Metering Simulation

quence with ripple effects on the computed D for the remaining flights. In Figure 7, all model parameters for sector capacity, scheduled flights, sector occupancy time, and MIT restriction at x are fixed; while the value of spatial separation at MIT restriction x varies from 1 mile to 20 miles. Note that the more flights are separated at x, the larger the total MIT metering penalty D becomes and the later the last flight will be arriving at its destination. This illustrates how unnecessary MIT restrictions can produce large cumulative penalty across multiple flights.

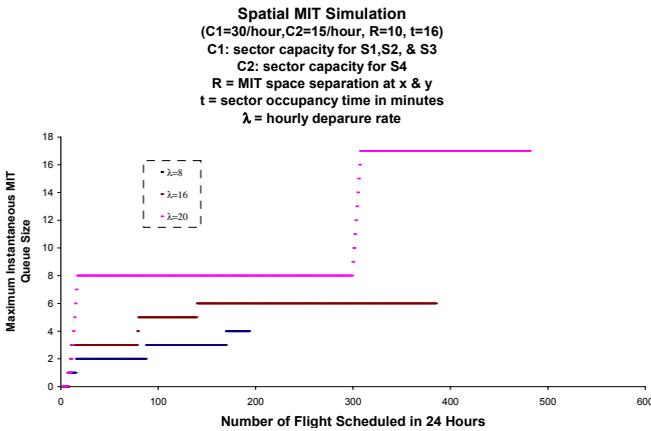


Figure 5: Instantaneous MIT Metering Queue Size

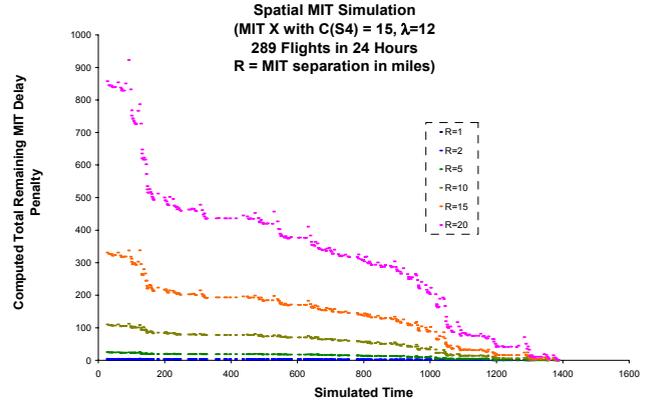


Figure 7: Sensitivity of D with Respect to R

One can also examine the relationship between sector capacity at S4 and the total MIT penalty across all relevant flights for a given MIT restriction x. Figure 8 is the result of such a simulation for MIT x in Figure 3, given the specific model parameter settings shown in Figure 8.

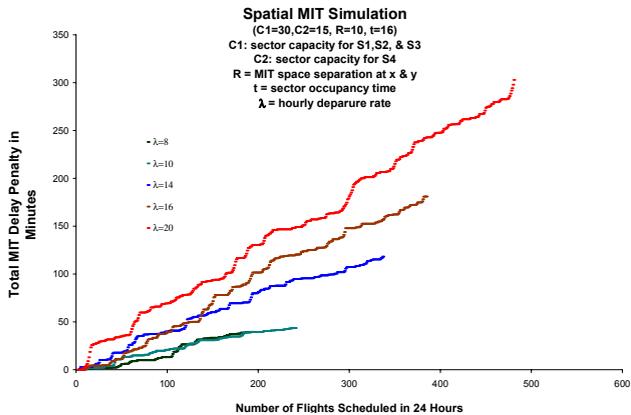


Figure 6: Total MIT Metering Penalty Simulation

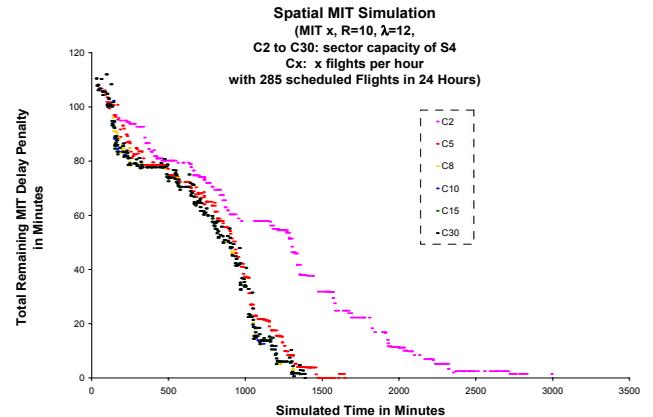


Figure 8: Sector Queuing Delay vs. MIT Penalty

The sensitivity of expected total MIT metering penalty over time to the value of MIT spatial separation restriction (or metering) is illustrated in Figure 7. As the simulation clock moves ahead, flights are metered at the restriction x, and the expected total MIT delay penalty for the remaining flights scheduled to arrive at x is gradually reduced. Delayed flights will result in a reordering of the arrival se-

Figure 8 suggests that MIT penalty can be beneficial only if the reduction of target sector queuing delay and sector occupancy time are larger than the expected or computed total MIT metering penalty D. Otherwise, the MIT metering penalty will become a real penalty as an added penalty to the total trip time for all flights. In Figure 8, we changed the capacity of the target sector, S4, from 2 to 30

flights per hour as C2 to C30. However, we did not increase the sector occupancy time of 16 minutes per flight. Clearly, the sum of MIT delays for all flights increases noticeably as the target sector's capacity is reduced from C5 to C2. To demonstrate the feasibility of such MIT metering benefits, we increased the sector occupancy for S4 from 16 minutes to 36 minutes and reduced the sector capacity of S4 from 15 to 5 flights per hour. We also provided sufficient sector capacity at the neighboring sectors S2 and S3 so that the MIT restrictions at x and y will not penalize flights with queuing delays at S2 and S3. Such a scenario mimics the situation of a severe thunder storm at S4. With increasing spatial separation at MIT restriction x, we observe that the reduction of queuing delay at S4 is greater than the total MIT metering penalty incurred at x. Figures 9 to 11 illustrate the results of such a scenario for  $R_x=0$  to 40. Figure 9 tabulates flight arrival times. Figure 10 compares trip delay for all flights. Figure 11 quantifies the net benefit as reduction in total trip time for the entire population of 768 flights among all different routes. Figures 9 to 11 illustrate the feasibility of quantifying global benefits from implementing two spatial MIT restrictions around an area of poor weather conditions.

**Spatial MIT Benefit Simulation**  
 (C1 = 90, C2=5, t1=16, t2= 36, R = 0 to 40,  $\lambda=8$ )  
 C1: sector capacity for S1, S2, and S3  
 C2: sector Capacity for S4  
 t1: sector occupancy time for S1,S2,& S3  
 t2: sector occupancy time for S4

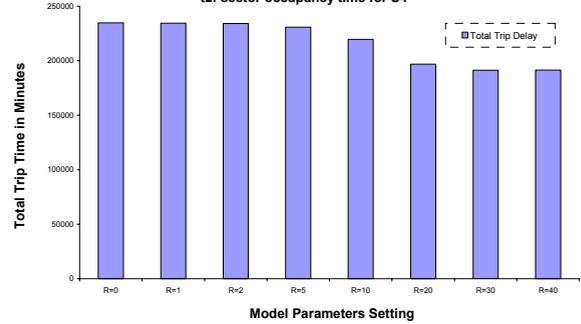


Figure 11: A Case of Beneficial Spatial MIT Restrictions

### 5 CONCLUSIONS

The authors have provided an explicit spatial MIT metering equation that relates delay penalty between two consecutive flights crossing a sector boundary or fix. The concept of recursive flight delays computation is an extension of the flight delay tracking discussed earlier in an ATIO paper (Wang, Wieland, and Wojcik, 2001). It is demonstrated that such a recursive MIT penalty function can be implemented in a discrete event simulation for the entire NAS and be used as a tool to quantify the tradeoffs of various MIT programs against different model parameter settings such as flight schedules, sector occupancy, capacity, weather conditions, and imposed ground or air delays. The model can also be used for evaluating different TFM programs and provide quantitative performance metrics to help understand the impacts of different potential actions.

It is also shown that MIT restrictions can be harmful if mis-applied. With the right model parameter settings, it is demonstrated that MIT restrictions can be a very powerful tool to reduce the severity of performance degradation resulting from bad weather or high traffic loads.

Future work would include the integration of this newly developed tool into other simulation and modeling tools at MITRE for analysts and operators to help with analysis or, perhaps in the future, real time applications.

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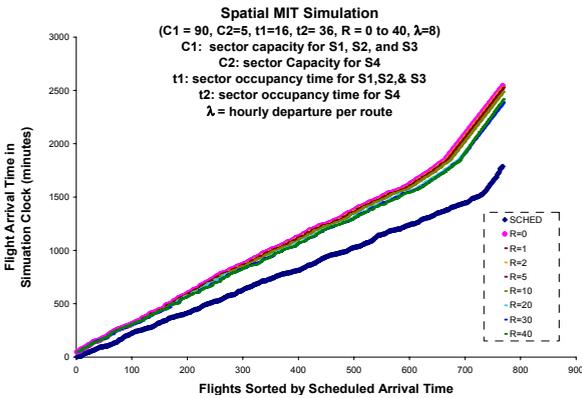


Figure 9: Flight Arrival Time with MIT Restrictions

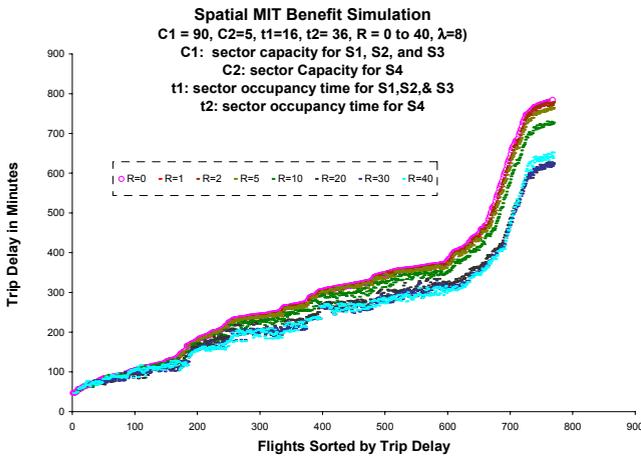


Figure 10: Flight Trip Delay with MIT Restrictions

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