MULTIMODAL COLLABORATIVE PASSENGER-CENTRIC DECISION MAKING TO MITIGATE THE IMPACT OF AIRSIDE PERTURBATIONS

A Thesis
Presented to
The Academic Faculty

by

Aude C. Marzuoli

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Aerospace Engineering

Georgia Institute of Technology
May 2015

MULTIMODAL COLLABORATIVE PASSENGER-CENTRIC DECISION MAKING TO MITIGATE THE IMPACT OF AIRSIDE PERTURBATIONS

Approved by:

Professor Eric Feron, Advisor
School of Aerospace Engineering
Georgia Institute of Technology

Professor Amy Pritchett
School of Aerospace Engineering
Georgia Institute of Technology

Professor John Paul Clarke
School of Aerospace Engineering
Georgia Institute of Technology

Dr Joseph Rios
Aviation Systems Division
National Aeronautics and Space Administration

Professor Alexandre Bayen
School of Civil Engineering
University of California at Berkeley

Date Approved: March 16, 2015

It's not about falling down, it's about getting back up.

ACKNOWLEDGEMENTS

I would like to begin with thanking my advisor, Pr Eric Feron, for hiring me four and a half years ago based on my martial arts skills. The "let's get a Master and why not a PhD while we are at it" road has been full of excitement, sudden changes and digressions. I had no idea that I would live in Atlanta, Toulouse, Brussels, Mountain View and Berkeley, all within such a small time frame, and keep working on both US and French projects, no matter the time difference. It all finally came together, thanks to careful monitoring and constant encouragement from my advisor. Eric, I promise I will not forget the many lessons learnt, including the importance of acting silly whenever possible and serious whenever necessary.

I would like to thank my committee members for providing guidance and support during this journey.

Thank you Pr Pritchett for your wise advice on a variety of topics, your ability to find interesting nuggets in my research, and your enthusiasm for teaching and learning. The teaching practicum has been one of the highlights of my PhD and really helped me grow as a person.

Thank you Pr Clarke for sharing your infinite knowledge of aviation, for all the insider stories, for teaching me flight dynamics and for always been in such a good mood.

Thank you Dr Rios for taking an interest in a student at a conference and welcoming her to NASA Ames. My summer at Ames was a wonderful experience, many research paths that stemmed from our discussions remain to be explored and I am extremely thankful.

Thank you Pr Bayen for encouraging me to give my very best, for welcoming me at Berkeley, for encouraging my interests and ambitions, for recommending me and for providing so much valuable advice for my future career.

I would also like to thank Pr Hansen for his insight on aviation problems, for his incredible sense of humor and for making a detour on his way to Philadelphia so he could preside over my PhD defense.

I would like to acknowledge my collaborators on various projects, without whom I could never have accomplished so much : Pablo Colomar, Mathieu Guerpillon, Paul van Erp, Alexis Ucko, Harold Nikoue in the US, and Dr Daniel Delahaye, Dr Christophe Hurter, Dr Isabelle Laplace, Dr Lynnette Dray, Roger Gardner, Gunnar Spies, Thomas Gunther in Europe.

To Maxime and Adan, a heartfelt thank you for mentoring me, for infinitely proofreading my first papers and turning a young student into a researcher, it meant a lot to me.

To Jim, thank you for making me feel like family, for helping me make life decisions and for cooking the best ribs I have ever tasted.

To my labmates and friends : Romain, Tim, Florian, Vlad, thank you for providing a warm and cheerful environment; Zarrin, thank you for your positive take on academic life and trading US-French adaptation tips; Scottie-Beth, Alexandra and Natalie, thank you for the well-deserved coffee pep talks that made difficult weeks much more bearable. Christabelle, thank you for your enthusiasm about aviation, for sharing your impressive knowledge of airplanes and operations, for being the proud representative of French women at NASA, and for tireless proofreading. All of you made my PhD a much better time than I could have imagined.

Finally, I would like to thank Emmanuel and my family for their love and their unconditional support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

Transportation networks constitute a critical infrastructure enabling the transfers of passengers and goods, with a significant impact on the economy at different scales. Transportation modes, including air, road or rail, are coupled and interdependent. The frequent occurrence of perturbations on one or several modes disrupts passengers' entire journeys directly and through ripple effects. Collaborative Decision Making has shown significant benefits at the airport level, both in the US and in Europe. This dissertation examines how it could be extended to the multimodal network level, discusses the supporting qualitative and quantitative evidence, and provides recommendations for implementation. A case study on the crisis management following the Asiana Crash at San Francisco International Airport in July 2013 is presented. The resulting propagation of disturbances on the transportation infrastructure in the United States is examined. The perturbation takes different forms and varies in scale and time frames: cancellations and delays snowball in the airspace, highway traffic near the airport is impacted by congestion in previously never congested locations, and transit passenger demand exhibit unusual traffic peaks in between airports in the Bay Area. The crash led to a large number of domestic and international flight diversions to many airports. Passenger reaccommodation varied greatly from airline to airline and airport to airport. To illustrate how Collaborative Decision Making within and across transportation modes could potentially improve responses to such

disturbances, first a passenger-centric reaccommodation scheme is developed to balance costs and delays, to best utilize neighboring diversion airports. Second, an analysis demonstrates that there was enough capacity at the neighboring airports, Oakland and San Jose, to accommodate most of the diverted flights and reoptimize the allocation of flight diversions to the Bay Area airports. Finally, recommendations are discussed for further multimodal network collaborative decision making.

CHAPTER 1

Introduction

In 2012, 2.9 billion passengers boarded an airplane, whether for business or leisure, across the world [55]. Yet, air transport is only a portion of the passenger door-to-door journey, which also relies on other modes of transportation, such as rail, road and water. Transportation modes are usually studied separately as if not interacting, although they are intrinsically coupled through passenger transfers. The failure of one mode disrupts the entire passenger journey. Over the past few years, many disruptions have highlighted the rigid structure of transport infrastructures and the potential for perturbations to snowball across multimodal infrastructures. In particular, the failures and inefficiencies of the air transportation system not only have a significant economic impact but they also stress the importance of putting the passenger at the core of the system [46] [47] [94] [95]. The objective of making each passenger or cargo's door-to-door journey seamless cannot be achieved without a better understanding of the multi-modal transportation network. The regular occurrence of significant perturbations that propagate through the system and sometimes even paralyze it highlights the need for further research on its resilience and agility and for adequate coordination at the network level. As the number of passengers keeps growing [55], congestion and snowball effects threaten the resilience of the whole multimodal transport infrastructure.

1.1 Propagation of Disturbances and Performance in the Air Transportation System

On the air transportation side, there has been extensive research on disturbance propagation in the airspace [2] [72] [75] [79] , the impact of airline scheduling of aircraft and crew [14] and the best recovery optimization schemes [56] [78].

In the coming decades, air traffic demand is expected to increase significantly [49]. The present airspace capacity limits, i.e. the maximum number of aircraft present in a given airspace at a given time, are predicted to be exceeded. Delays caused by congestion or weather perturbations are increasing on the ground and in the air. The cost of congestion in such a tightly interconnected network of airports and aircraft reached \$41 billion in the US in 2008 [83]. In 2012, 18.22 % of flights were delayed in the United States [2]. The role of Traffic Flow Management (TFM) is to manage demand against available airspace capacity. TFM is a distributed, hierarchical system within the National Airspace System (NAS). Significant effort has gone into trying to better understand delay propagation in the air transportation network over the past few years. Pyrgiotis et al. design an analytical queuing and network decomposition model that computes the delays due to local congestion at individual airports and captures the "ripple effect" causing the propagation of such delays [79]. AhmadBeygi et al. study the relationship between the scheduling of aircraft and crew members, and the operational performance of such schedules [14], in order to develop more robust airline planning tools. Propagated delays create significantly more impact than the original root delays themselves. A single delay can "snowball" through the entire network. The multi-airport system is defined as a system with a set of airports that serve the air traffic of a metropolitan area. Many of these airports have coordinated operations in terms of sharing regional airspace : some act as reliever airports in case of overshooting of capacity at other airports. Nayak [75] provides valuable insight on quantifying the interdependencies between airports in a multi-airport system and it investigates the delay propagation from the system to the rest of the National Airspace System (NAS) and vice-versa. Queuing delay and adverse weather are major causal factors of delay. They stress the need for proper regional level airport and airspace planning. Airlines try to increase aircraft utilization to maximize their revenue, and hence shorten time buffers between scheduled arrivals and departures [69]. Delay propagation to later departure flights is therefore more likely. The capacity of the network to absorb disruptions decreases when demand levels get closer to capacity limits. Thus large-scale delays in the system become more frequent. When a disruption occurs, airline schedule recovery tries to maintain operations and get back to schedule as quickly as possible while minimizing additional costs. The different mechanisms they rely on are aircraft swaps, flight cancellations, crew swaps, reserve crews and passenger rebooking [78]. Usually airlines react by solving the problem in a sequential manner. First, infeasibility of the aircraft schedule is examined, then crewing problems, ground problems and last, the impact on passengers.

Most of the traffic demand growth is expected to take place in in major metropolitan areas. Metropolitan areas with high demand are often served by a system of two or more airports whose arrival and departure operations are highly interdependent, referred to as a metroplex [9]. For instance, metroplexes in the US include North and South California, Houston, South Florida, New York Philadelphia, D.C., Boston, Chicago. Atkins [15] examined the San Francisco Bay Area metroplex (San Francisco, Oakland and San Jose airports), providing a definition and an initial framework to measure metroplex performance. Clarke et al. [80] [34] identified six types of interdependencies between traffic flows in a metroplex based on observations. Li et al. [65] studied the metroplex operational interdependencies, resulting from sharing limited common resources in airspace, such as share of common fixes, partial flight paths, airspace volumes and downtstream restrictions. DeLaurentis [42] evaluated a concept of flexible operations at a metroplex to optimize the use of common resources.

1.2 Network Science

The world transportation industry is a critical infrastructure with a significant impact on local, national and international economies. However, Guimera et al. [52] find that the cities with the most connections are not always the most central in the network. Most cities, or nodes, are peripheral, meaning that the majority of their connections are within their own community. The nodes that connect different communities are usually hubs, but not necessarily global hubs. From a network science perspective, much research has focused on examining the structure of each transportation mode [52] [77] [91] [41] and the associated patterns of delay propagation[37] [36] [67]. To the best of our knowledge, there is little work on network coupling or interdependencies and hardly any on transportation infrastructures. One of the most striking examples to date is the electrical blackout in Italy in September 2003: the shutdown of power stations directly led to the failure of nodes in the Internet communication network, which in turn caused further breakdown of power stations [25]. At the theoretical level, the robustness of interdependent random networks is beginning to be understood [84] but research on real-world applications is lacking. Interdependent infrastructure networks are complex cyberphysical systems, and may also be seen as highly optimized tolerant systems [27]. Understanding the observability and controllability of complex networks [66] is critical to ensure their robustness under perturbations.

The structure of the airport network has been extensively studied [77], mostly using airline flight frequency. Sridhar et al. were among the first to examine metrics of the US air transportation network [91]. DeLaurentis [41] described system-wide factors and issues that also matter in the overall system performance, such as the service network topology, economic policy or airline fleet mixture. Conway [37] and Holmes [36] advocate that network science offers a new perspective on air transportation. Because of the network structure, some local delays can have ripple effects on the entire NAS and cause major delays [67].

1.3 Collaborative Decision Making (CDM)

CDM has had two parallel and yet intertwined developments in the US and in Europe.

In 1991, the FAA's Air Traffic Management Office commissioned an analysis to measure the effects of the airlines flight-substitution process on the efficacy of ground-delay programs (GDPs) [92]. The FADE (FAA Airlines Data Exchange) project, as well as the initial operational implementation of CDM, was aimed at the development of new operational procedures and decision support tools for implementing and managing GDPs. However, it became clear that the CDM philosophy and principles can, and should be, applied to a much broader class of problems in air traffic management. The primary focus of CDM in the US initially was the modification and improvement of GDP procedures, known as GDP enhancements. The collaboration between government and industry was born out of the FAAs need for real-time operational information from the airlines and the airlines desire to gain more control over their operations during a GDP, especially in matters with economic consequences [19]. Prototype operations of GDP enhancement began in 1998 at San Francisco and Newark airports [30]. Burgain et al. [26] developed a Collaborative Virtual Queue (CVQ) which uses virtual queuing to keep aircraft away from runway queues and enable last-minute flight swapping, to improve taxi-out time robustness. Recently, Gupta et al. [53] built an integrated strategic and tactical system for improving surface operations by metering departure aircraft called SARDA-CDM. It consists in the augmentation of ground and local controller advisories through sharing of flight movement and related operations information between airport operators, flight operators and air traffic control at the airport. The goal is to enhance the efficiency of airport surface operations by exchanging information between air traffic control and airline operators, while minimizing adverse effects on stakeholders and passengers.

In Europe, over the past decade, a number of airports have taken major steps that aim at CDM between all stakeholders at airports. This process is initiated and guided by the Airport CDM program. The objectives of A-CDM are to reduce delays and improve system predictability, while optimizing the utilization of resources and reducing environmental impact. They are achieved by real-time information sharing between key stakeholders, including airports, airlines and Air Navigation Service Providers. Current CDM efforts focus primarily on airside operations, with landside CDM usually considered separately. A-CDM is one of the five priority measures in the Flight Efficiency Plan published by IATA, CANSO and EUROCONTROL. In Europe, A-CDM has been implemented successfully at several airports. Details about A-CDM in Europe can be found in the Airport CDM Implementation Manual [28]. Airports where A-CDM has been fully implemented now include Munich, Brussels, Paris-Charles de Gaulle, Frankfurt, London-Heathrow, Helsinki-Vantaa and most recently, Dusseldorf and Switzerland's primary hub, Zurich. Collectively, these airports welcome over 250 million passengers a year and their efforts have yielded significant benefits for airlines and passengers. The most cited benefits to Airlines and Passengers are better punctuality, with an average 3 minutes reduction in aircraft taxi time, and fuel savings for airlines, up to 20.8 million euros in 2013 [62].

There is little theoretical literature on Collaborative Decision Making and its impact. Ball et al. [19] developed and analysed two approaches to incorporate stochastic optimization models in a CDM-like setting. These models are able to create a traffic flow management plan for a set of flights whose flight plan intersect a volume of airspace undergoing a severe capacity reduction. In their scenarios, the ANSP allocates certain resources to the flight operators and the flight operators then optimize the use of resources they are given. One of the first efforts to evaluate the potential of CDM at the network level is undertaken by Bertsimas and Gupta [22]. They propose an Air Traffic Flow Management model with a CDM framework from an airport setting to an airspace context incorporating fairness and airline collaboration. Their empirical results of the proposed model on national-scale, real world datasets, show promising computational times and a proof of the strength of the formulation. Modrego et al. [70], from Eurocontrol, performed a study to measure the impact on the network if 42 of the most delay constrained airports in Europe were to implement CDM in a near future. Their results suggest that, if more airports were to implement A-CDM and provide the CFMU with accurate Target Take Off Times (TTOT) via DPI messages, the benefits could extend from the local airport environment to the network. They compute a potential sector capacity increase within the European area of up to 4%, that is between one and two aircraft per sector. Their analysis of A-CDM on delays points out a room for improvement between 33% and 50%.

Three needs led to the creation of CDM and are still at the heart of the concept today:

- The need for a shared global picture of predicted capacity and demand for various airspace resources, leading to common situational awareness and supported by appropriate information sharing
- The need for real-time models that predict the impact of potential control actions and user decisions, supported by data from all stakeholders

- The need for collaborative resource allocation tools, mechanisms and procedures.

1.4 Multimodal Transportation

Over the past few years, severe weather perturbations have paralyzed the transportation system. On the European side, the eruption of the islandic Eyjafjallajokull volcano in 2010 had the longest and biggest economic impact on aviation, with more than 100,000 flights canceled. The volcanic eruption had such an impact on aviation that it also had a series of knock-on effects on other modes of transportation. These can be explained by the rigidity and complex nature of transport networks, as well as by the lack of appropriate preparation. Bolic et al. [23] offer recommendations to better address such large disruptions, stressing the need for better information exchanges between all the stakeholders. Zhang [98] develops a framework to reduce passenger "disutility" due to delay and missed connections, to help airlines reduce operating cost and recover schedule more promptly, and to assist traffic flow managers to utilize and distribute scarce resources more efficiently and equitably. When there is a significant capacity shortfall, airlines with hub-and-spoke networks could incorporate ground transport modes into their operations. Real-time intermodalism includes the substitution of flights by surface vehicle trips and, when the hub is part of a regional airport system, the use of inter-airport ground transport to enable diversion of flights to alternate hubs. It recommends that the current CDM system be enhanced to realize a regional Ground Delay Program (GDP) by including regional transport agencies, regional airport authorities, airlines serving regional airports and others. These enhancements cannot be realized without collaboration between FAA, airlines, airports, passengers, nor without consensus on the importance of integrating underutilized regional airports into disruption recovery strategies. For the passengers, traveling across several modes of transportation to complete their journey can be difficult, especially when it comes to planning travel times. To improve the passenger's experience, an increasing number of advanced transport information systems (ATIS) provide services such as route planning, navigation, updates on disruptions, real time information alerts and replanning tools. The Strategic Research and Innovation Agenda (SRIA) in Europe is the new strategic roadmap for aviation research, development and innovation developed by ACARE. By 2050, "door-to-door integrated journey planning, payment and single ticketing & accountability, and automatic journey monitoring and disruption management for over 90% of journeys" are to be in place. In the US, the Obama administration has made high-speed rail a national priority, the first U.S. administration to do so ever. Joseph Sussman [43] argued that "The Northeast Corridor of the United States stretching from Boston, MA to Washington, DC is the most densely settled region in the richest country in the world, yet it has been plagued for decades with congestion of all types on its roads, in the air and on its rails." He calls for a multimodal approach to solve such problems.

1.5 Shifting the focus of transport operations towards the passenger

Recently, a shift towards passenger-centric metrics in air transportation, as opposed to flight-centric, has been promoted, highlighting the disproportionate impact of airside disruptions on passenger door-to-door journeys [39] [24] [93] [18]. However, flight delays alone do not accurately reflect the delays imposed upon passengers' full multi-modal itinerary. The growing interest to measure ATM performance calls for metrics that reflect the passenger's experience. Cook and al. [38] designed flight-centric and passenger-centric performance metrics, and compared them with existing flight-centric metrics. In [24], Bratu et al. calculate passenger delay using monthly data from a major airline operating a hub-and-spoke network. They show that disrupted passengers, whose journey was interrupted by a capacity reduction, are only 3% of all passengers, but they suffer 39% of the total passenger delay. Wang [93] estimates Air Transportation System-wide passenger trip delay using publicly accessible flight data on 1,030 routes between the 35 busiest airports in the US in 2006. High passenger trip delays are disproportionately generated by canceled flights and missed connections. Wang showed that 17% of routes, or 9 of the busiest 35 airports, cause 50% of total passenger trip delays. Congestion flight delay, load factor, flight cancellation time and cooperation policy between airlines are the most significant factors affecting total passenger trip delay.

1.6 Research Questions

The present research aims at the extension of Collaborative Decision Making to the Multimodal Network level. Qualitative evidence for this need has been uncovered through the MetaCDM project in Europe. Quantitative evidence is shown through a clinical study of the Asiana crash in San Francisco airport on July 6th, 2013 and the resulting large-scale multimodal perturbation that propagated on the airside and the landside is described. The objective is to provide the first quantitative case study of infrastructure failure leading to a multimodal disturbance on different time frames and scales across various transportation networks. The higher-level goal is to foster a better understanding of multimodal transportation to increase its resilience and facilitate the passenger door-to-door journey. This research can provide the first experimental basis upon which several system engineering methods could be applied to improve the entire passenger journey.

The present dissertation tackles the following research questions:

1. Can the coupling between transportation modes be analyzed and/or quantified?

2. How can Multimodal Collaborative Decision Making improve the performance of the Transportation System to support seamless door-to-door passenger travel?

3. How can Multimodal Collaborative Decision Making improve disruption management at the network level, from passenger-centric and flight-centric perspectives?

1.7 Outline

This dissertation is structured as follows. Chapter 2 discusses the evidence of the need for Collaborative Multimodal Transportation. Chapter 3 presents a case study on the Asiana crash and its multimodal impact. Chapter 4 develops two optimization schemes to analyze how the disruption could have been better handled, from a flight-centric and a passenger-centric perspectives. Chapter 5 provides recommendations for the elaboration and implementation of collaborative decision making at the multimodal network level. Finally, Chapter 6 draws the conclusions of this effort and suggests future research paths.

CHAPTER 2

Qualitative Evidence of the Need for Collaborative Multimodal Transportation

Crisis events impose huge costs on the air transport system and society and it is the passenger who bears the practical consequences. Collaborative Decision Making (CDM) has been very successful at enabling advanced air transportation concepts, such as ground delay programs and airport departure managers. Implementing Airport CDM (A-CDM) helps to mitigate the effects of delay upon Air Traffic Flow Management (ATFM) slot adherence and although it helps airports, airlines and ground handlers in optimising their resource allocation, landside efficiency is not within its current scope. To fully handle crisis events and include the passenger in the CDM process an extension of A-CDM to the landside is needed.

For Europe, a summary of all major disruptive events is included in the Eurocontrol Network Operations Reports (NOR) [44] and the CODA delay digest [45]. These reports review network activities and disruptive events across Europe by month and by season. The most common disruptive events noted in the NOR are weather, strikes, and disruptions caused by the implementation of new infrastructure. Other disruptive events include accidents, security alerts or attacks, IT systems failures, measures to prevent the spread of infectious diseases, and infrastructure upgrades. Their impacts can vary significantly, e.g. closure of airspace or airports, absent staff or significantly increased process times of passengers and operations.

Some specific examples from the past few years in the US and in Europe are described below.

In December 2014, a technical fault in the flight data system at Swanwick air traffic control center in England caused many cancellations at Heathrow and London city airport, delays at Gatwick, Stansted, Newcastle, Luton, Bristol, Edinburgh, Glasgow, Southampton and Manchester airports. It was reported that some flights from Tunisia landed at Charles de Gaulle airport in Paris instead of London. The previous year, problems with the internal telephone system had also caused delays [20].

On September 26th, 2014, a fire started by an employee in the telecommunication room of the Chicago En Route Center (ZAU) in Aurora, IL, led to the evacuation of the facility, which is one of the busiest in the United States. The ZAU facility was declared "ATC Zero" (meaning the FAA is unable to safely provide the published ATC services within the airspace managed by a specific facility). The airborne traffic already in ZAU airspace was transferred to controllers in other centers, and all other flights within ZAU were grounded. More than 5,000 flights were cancelled at Chicago's O'Hare and Midway airports during the following week. The facility only reopened two weeks later, causing a reorganization of traffic in this portion of airspace [35] [16] [54].

In September 2013, lightning struck at Baltimore-Washington airport (BWI), leading to its shutdown for three hours, therefore delaying and stranding thousands of passengers, and causing several flight diversions [11]. In August 2013, Sabre airline reservation system, which serves more than 300 airlines, experienced a system outage for more than two hours. As a consequence, the affected airlines' websites could not book or change reservations, and boarding passes had to be handwritten. The effect was mostly felt in Europe and in the Middle-East, where it was mid-morning, whereas it was night in the US. Virgin Australia had to cancel several flights, and many airlines reported subsequent delays. This issue occurred two weeks after United Airlines had encountered a similar collapse in their HP SHARES system. In July 2012, the Amadeus ALTEA airline reservation system was down for several hours, following power failures at Amazon's cloud services in Seattle. As a result, Qantas and Virgin Australia airlines had to cancel and delay many flights, while resorting to manual processing of passengers [10] [12]. More examples include snow storms paralyzing flights in Western Europe (December 2010); volcanic ash clouds grounding a vast portion of European traffic for a week (April 2010); a crash at Amsterdam Schipol (February 2009); a radar failure at Athens Airport (September 2012); strikes affecting French airports (April 2012); Hurricane Sandy leading to airport closures all over the East Coast of the United States (October 2012). Storms and hurricanes can be forecasted, but the uncertainty on their trajectory and magnitude still makes appropriate preparation difficult. However, no warning is available in case of a crash or an infrastructure failure. Such events are exacerbated by the rigidity and complex nature of transport networks, as well as by the lack of appropriate preparation.

Responsibilities in addressing massive flight disruptions to normal flight operations are shared by a number of stakeholders, including the FAA, airlines, airports, and passengers [21]. Airlines have individual management strategies for massive flight disruptions [64]. American Airlines set a policy for flight disruptions to return to the preplanned or normal operational schedule as soon as possible, without regard for the impact on revenue [88]. American Airlines considers crew scheduling to be a priority; therefore, it attempts to keep the reallocation of aircraft within specific aircraft types because crews are trained and certified by aircraft type. Since the enactment of the 3-Hour Tarmac Rule, American Airlines has developed tools for tracking aircraft delayed on the ground and has adopted a contingency plan for aircraft delayed on the tarmac known as "drop and go" where aircraft pull into a gate, drop passengers, and then leave the gate to allow other aircraft to use the gate to let passengers off the aircraft. Past striking examples leading to the enactment of the Tarmac rule include Detroit in 1999 : seven thousands passengers were stranded on the tarmac for up to ten hours during a snowstorm. Inside the planes, food ran out and in some cases water was not available. Several planes also had lavatories overflow. Northwest Airlines settled to compensate the passengers with $ 7.1 million.

United Airlines developed a Systems Operations Advisor (SOA) to provide real-time decision support to the operations center. It evaluates the impact to the network of flight delays and cancellations and provides recommendations for affected flights. The SOA provides options: delaying, canceling, or swapping a flight with a different aircraft [13]. Continental Airlines, now merged with United Airlines, chose pre-emptive decision making to cancel flights under disruptive weather forecast. The benefit to the passengers was advance notice of a flight cancellation before they leave home. The benefit to the airlines was easier schedule recovery and return to the preplanned flight operations. The negative to pre-emptive cancellations was the possibility that the weather does not appear in the region and flights could have operated normally or with a delay.

In the case of delayed or diverted flights, it is difficult to return to planned operations because the aircraft are not in the right position and are not available for future flights with that aircraft. In the case of cancellation, the aircraft can be reassigned to other flights in an attempt to return to planned operations. During such disruptive events, system-wide ripple effects prevent the use of the air transportation systems for several hours, and subsequent delays prevented passengers from reaching their destinations at least on the same day, even though multimodal passenger routing offer viable alternatives to minimize passenger disruptions.

2.1 Existing stakeholders initiatives

In Europe, a number of recent projects have aimed at enhancing, extending and further integrating airside and landside CDM to reduce passenger disruption (both during normal conditions and disruptive events). Two of the most important recent projects in the context of MetaCDM are the TAMS project [89], which looked at integrating landside and airside CDM, and the ASSET project, which looked at the efficiency of landside processes. TAMS is the first project that implemented, simulated and validated a whole Airport Operation Centre. This work can be taken as reference for what can be done to enhance collaboration with more information becoming available on the landside. The aim of ASSET is to develop and assess solutions for airport process improvements in terms of punctuality regarding passenger, baggage handling and aircraft turnaround processes in an integrated approach. The objective was to enable a higher punctuality and performance of the whole air transport network in Europe by improving predictability and punctuality of the off-block time of departures.

The MetaCDM (Multimodal Efficient Transportation in Airports Collaborative Decision Making) project for the European Commission considered first the air side, where CDM is most concerned about airline incurred delay management and is named airside CDM, and second the land side, named landside CDM, which focuses on the passenger delays experienced as soon as entering the airport until he or she enters the aircraft, especially during significant adverse events. The project aimed at identifying the opportunities to link airside and landside CDM in a unified concept [62].

The MetaCDM project investigated how information sharing, CDM and multimodality can improve passenger experience during disruptive events [63]. The most comprehensive set of recommendations for airports dealing with disruption is made by the Airport Cooperative Research Program [73]. This report discusses in a US context how airports can best develop, evaluate and update contingency plans for the occurrence of irregular operations (IROPS) as a result of disruptive events. Four types of IROPS impact situations are identified: surge, in which extra aircraft and passengers flow into an airport; capacity, in which the airport terminal becomes full of passengers or ramp space/gates become full of aircraft; after-hours, in which aircraft land and passengers need to deplane at hours when facilities are not functional; and extended stay, in which passengers and aircraft may be immobilized at the airport for an extended period of time. Bolic et al. [23] offer recommendations to better address such large disruptions, stressing the need for better information exchanges between all the stakeholders with, for instance, a central repository of all information related to a given crisis.

Resilience is a priority for major airports, which typically have dedicated crisis centres, recovery plans and a co-ordinated multi-stakeholder response to crisis events. Airlines may have their own crisis cells operating in close collaboration with those at the airport, and their own equipment and procedures for dealing with stranded passengers (for example, camp beds, and arrangements with hotel and bus companies for transport to overnight accommodation). At the highest level, governments also have oversight of airports that are classified as "national assets". Monitoring meetings take place between government, airports, civil aviation authorities and other bodies such as Air Navigation Service Providers (ANSPs) to review plans, threats and resilience, and potentially to intervene in significant disruptive events. One hazard is the potentially large number of agencies who may be involved in crisis response at larger airports, meaning that sometimes responsibilities and lines of command are not clear. For smaller airports the risks associated with disruptive events are typically lower, as are the corresponding resources. Resilience planning may be just one of several responsibilities for a particular manager, and training may be covered by just a formal annual exercise combined with desktop training. At all airports, contingency planning and risk management are ongoing activities, involving many stakeholders, and, particularly at large airports, plans are subject to regular review. Revisions may also be made based on lessons learned after disruptive events. For example, following the December 2010 Winter season, Heathrow adopted a three-tier Bronze, Silver, Gold framework as used by emergency services, representing operational control, tactical command and strategic command to be activated sequentially depending on the severity of the incident. Similarly, staff training needs to be a regular and continuing activity. Alert processes typically vary significantly depending on the type of incident. Information on current or projected disruption can come from ANSPs, airlines, government, security and blue light services, meteorological services, local authorities or web and media scanning. Contingency planning distinguishes between predictable and unpredictable crisis irregularities. A longer advance notice period means an event is typically easier to deal with.

Currently, CDM does not strongly interact with disruption management. CDM processes are typically not used in a crisis situation and airports switch to face-to-face and/or phone communication for the majority of interactions. For example, there is a dedicated crisis room at Paris Charles de Gaulle (CDG) airport where stakeholders may be gathered in the event of a crisis to ensure common situational awareness and improved decision processes. In general, the focus on face-to-face information means that communication in crisis situations can be delayed, particularly for bodies outside the immediate crisis response cell. Similarly, external information is mainly collected via phone calls to different stakeholders. As a result, passengers may not be able to access information about the situation because it is simply not available. This was the case during the December 2010 snow crisis for passengers stranded in Toulouse airport. Any scheme to increase information provision to passengers, therefore, may need to be accompanied by greater automation of crisis communications. Stakeholders also feel that there is not enough information available at a network level, given that disruption at one airport may have impacts at many others.

Airports consider that the main benefits of A-CDM in disrupted conditions are improved situational awareness and communication. However, typically in major crisis situations CDM techniques are used only minimally or not at all. In crisis situations at Paris CDG, stakeholders move to what is known as "Plateau CDM", with meetings in a designated crisis room. Information is still supplied via the airport's CDM website, including changes to schedules, and can act as an alert process if an unusually large number of delayed flights are displayed. An additional problem in data sharing is verifying that data. In crisis situations, stakeholders try to get information by whatever means possible, leading to data that is sometimes inadequate, incorrect or inconsistent. One case was discussed during the interview process of two different organisations at the same airport using meteorological data from different companies; one indicated it was safe to continue operations, the other did not, and the resulting confusion led to further disruption and costs for both companies. Whilst A-CDM focuses on airside performance monitoring, there are some technologies already used to facilitate landside performance monitoring, including Bluetooth, video and light barrier passenger detection in the airport. However, few decision support tools are used for landside processes. In general, the airports and airlines interviewed were interested in the idea of extending CDM concepts to the landside in principle. A number of non A-CDM airports, for instance regional platforms as opposed to hubs, have indicated that they would be interested in a "CDM-lite" approach enabling some of the benefits at a lower level of investment. These airports were concerned about the cost of a full implementation, and also that A-CDM benefits might be fewer for smaller airports due to their greater ability to respond to disruption. As discussed above, there is also interest in CDM-type sharing of information at a network level to give airports and airlines greater warning about problems elsewhere that may impact on their operations. As both A-CDM airports and airports considering taking the first steps toward A-CDM status were involved in the interview process, it was also possible to discuss the process of gaining A-CDM status. This highlights the processes, barriers and potential challenges that could be faced in adopting similar concepts. The interested airports highlighted better information sharing, visibility and image as reasons for their interest. Current A-CDM airports reported common situational awareness between stakeholders and an increase in operational predictability as being major benefits.

2.2 Taking into account the passengers' perspectives

Each stakeholder individually interacts with passengers and records its own performance. This performance of one stakeholder in providing a given service to passengers is usually only available to the stakeholder itself, and not shared with other stakeholders. Therefore, assessing the performance of the whole transportation system in providing an efficient and pleasant door-to-door journey to passengers is difficult. For example, the Airports Council International (ACI) was highlighted as an organization that supports airports in service quality management; however, it does not cover all indicators from a passenger perspective. One example is the provision of the predictability of average transfer time at an airport, which is not included in the ACI survey. This type of information in particular may be withheld by stakeholders due to business interests. Airports and airlines vary in the amount and type of support and facilities available for stranded passengers. The airlines interviewed had various methods to get information to passengers in the case of disruption, including email, phone calls and smartphone apps. The information supplied depends on what is available to the airline at the time. For example, one airline interviewed at Paris CDG only had access to CDG-related information, but could request information about disruption at other airports from its headquarters. This links into the point previously made about the speed of information exchange between stakeholders in crisis situations; if information is not available to the airline, they cannot share it with passengers.

The UK Civil Aviation Authority (CAA) [33] conducted an online survey of passengers to assess how passenger welfare could be improved during disruption, in the context of the severe snow perturbation in the UK in 2010. Considerable room for improvement was found; 74% of respondents were dissatisfied with the quality of information they were given, 75% were not informed of their rights, and 60% received no care or assistance from their airline. The accessibility of passenger information was highlighted as a particular problem. Facing inadequate information about whether their flight was operating, many passengers chose to travel to the airport in search of better information; and, once there, many passengers were reluctant to leave for similar reasons. The need for clarity on information about what costs incurred by passengers would be reimbursed by airlines (e.g. hotels, food or onward journeys) was noted. As the aviation system grows, more airports will be operating close to capacity, leading to decreased ability to recover from or mitigate disruption. However, progress on technologies will likely facilitate earlier warnings of disruptive events, better recovery from disruption, increased safety and increased systems robustness. SITA [86] reports that improving passenger experience is the number one driver of Information Technology investment by a majority (59%) of the world's airports. A rapid increase in mobile and social media applications is expected to deliver a more personalized customer experience, such as keeping passengers informed about flight status and wait times. 88% of airports plan to invest in mobile apps by the end of 2015.

As the number of passengers continues to rise at airports across the world, optimizing the use of the available real estate is a priority and passenger flow management will become more and more important; half of the airports see geolocation as a top priority for reducing passenger congestion. Within the next three years, new wayfinding services are set to become commonplace on mobile devices, allowing passengers to navigate easily through the airport. Just 10% of airports provide them today but this figure is set to jump to 70% by 2015. Airports are also investing in business intelligence solutions to deliver an improved passenger experience. Some 86% of airports see it as a priority for sharing information and collaborating with partners; 83% to ensure more accurate service information for passengers; and 76% to reduce flight delays due to ground operational issues [86]. With airports planning to invest in business intelligence, and using it to better collaborate with partners, it is clear that there is a strong desire among operators to work together with stakeholders, including airlines and ground handlers, to create a better passenger journey. While the growth of personal mobile devices is an opportunity for air transportation providers to decrease fixed asset costs, the delivery of relevant time-critical information has the potential to enhance the situational awareness of travellers and their opportunities to either actively participate in the decision making process regarding the planned travel and/or to replan the travel on their own.

Stakeholders also felt that there is not enough information available at a network level, given that disruption at one airport may have impacts at many others. One key example is during the severe winter weather which affected many Northern European airports in December 2010. During this period, CDG was operating close to maximum capacity. CDG was not aware of the closure of Heathrow until shortly beforehand and had to accommodate long-haul flights bound for Heathrow at short notice. Subsequently, CDG also had to close due to a lack of deicing fluids for passenger aircraft. As an airport with an A380-capable runway, Toulouse Blagnac had to accept long-haul flights bound for CDG on very short notice. Although Toulouse Airport was unaffected by snow, it suffered severe disruption because of the large numbers of stranded passengers from the diverted flights and a lack of aircraft parking space. Improving information sharing on a network level is therefore a desirable goal.

Because air passengers are customers of the whole transportation system and often turn to other modes of transport in case of airside disruptions, a multimodal perspective is needed. Multimodality is slowly becoming a reality, at least within the European transportation system. The principal difficulty is not whether it should be done or not - it is widely admitted that flights lasting less than one hour could be advantageously replaced by ground transportation, such as rail. Indeed, finding an economically viable path towards fully integrated multimodal transportation will require leveraging today's resources and investing the profits in system improvement until satisfaction is reached. Such a plan may last several years or decades to be executed and would be highly sensitive to political noise. However, industry today offers interesting leads towards an acceptable implementation plan. Some European airlines already offer origin-destination fares that are using rail transportation for some or all of the passenger journey. Even though the databases and schedules are shared, there is no common optimization between the rail and the airside. Even if there is a TGV (high speed train) station at CDG, passengers have to find their luggage and take it to the train, and the train may not be departing from the train station inside CDG.

The next chapter tackles a case study of the Asiana crash, a recent crisis event that led to ripple effects on the multimodal transportation network, and quantifies the resulting multimodal perturbations.

CHAPTER 3

Quantitative Evidence through a Case Study of the Asiana Crash

This chapter briefly presents the Asiana crash, details the ripple effects of the crash on the airspace and on other transportation modes, and finally examines the consequences for passengers.

3.1 Crash description

First let us briefly summarize the events leading to the Asiana crash at San Francisco airport. The layout of San Francisco International Airport (SFO) is displayed in Figure 1. It is the seventh busiest airport in the United States, with about 400,000 movements and 45 million passengers per year.

On July 6th, 2013, the weather was good and the winds were light. The instrument landing system vertical guidance (glide slope) on runway 28L was, as scheduled, out of service. At 11:28 a.m, Asiana Airlines Flight 214, a Boeing 777-200 ER aircraft, crashed just short of runway 28L's threshold at San Francisco International Airport. Of the 307 people aboard, 3 died, 181 others were injured. The crash resulted in a five hour total closure (and cancellation/redirection of all fights) of the runways at the

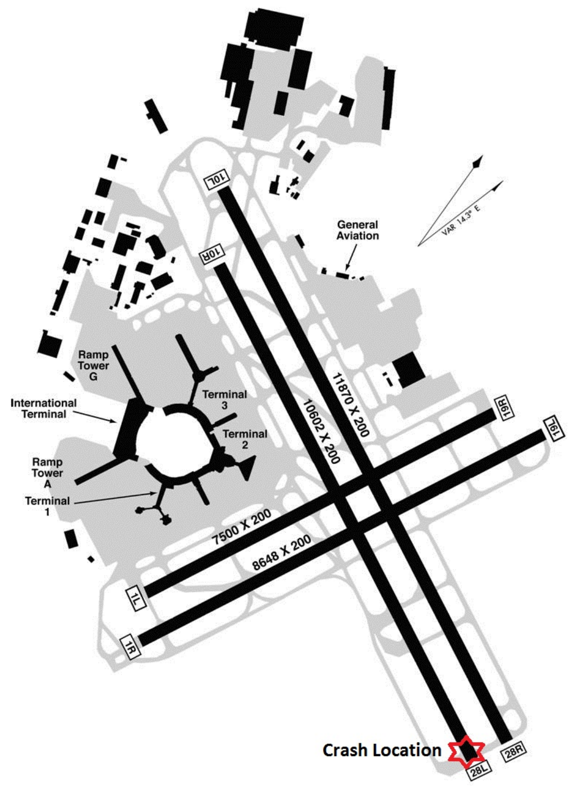


Figure 1: San Francisco Airport Layout.

airport. By 3:30 p.m. PDT, the two runways perpendicular to 28L were reopened; runway 10L/28R (parallel to the runway of the accident) remained closed for more than 24 hours. The accident runway, 10R/28L, reopened on July 12.

The National Transportation Safety Board provides the accident timeline, as illustrated in Figure 2.The accident investigation submission [74] states that "the probable cause of this accident was the flight crew's failure to monitor and maintain a minimum airspeed during a final approach, resulting in a deviation below the intended glide path and an impact with terrain. Contributing to this failure were (1) inconsistencies in the aircraft's automation logic, which led the crew to believe that the autothrottle was maintaining the airspeed set by the crew; and (2) autothrottle logic that unexpectedly disabled the aircraft's minimum airspeed protection." The significant contributing factors to the accident identified are : "(1) inadequate warning systems to alert the flight crew that the autothrottle had (i) stopped maintaining

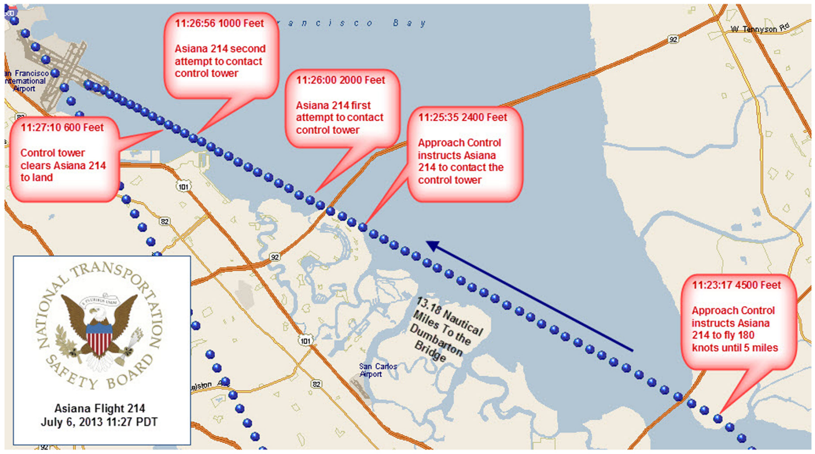


Figure 2: Asiana 214 Approach phase. The blue bullets represent the aircraft trajectories. The information in red describes the exchanges between the Asiana 214 flight and Air Traffic Control.

the set airspeed and (ii) stopped providing stall protection support; (2) a low speed alerting system that did not provide adequate time for recovery in an approach-to-landing configuration; (3) the flight crew's failure to execute a timely go-around when the conditions required it by the company's procedures and, instead, to continue an unstabilized approach; and (4) air traffic control instructions and procedures that led to an excessive pilot workload during a high-energy final approach."

3.2 Airside Analysis

The crash led to the closure of SFO and, even after the airport reopened, its capacity was reduced significantly. The crash led to cancellations, diversions and delays at SFO, and impacted the rest of the airspace with ripple effects. The work presented is based upon publicly available data from the Bureau of Transportation Statistics that are primarily used to evaluate airline on-time performance.

3.2.1 Impact of the Crash in San Francisco

3.2.1.1 Departures, Arrivals, Cancellations and Diversions at SFO

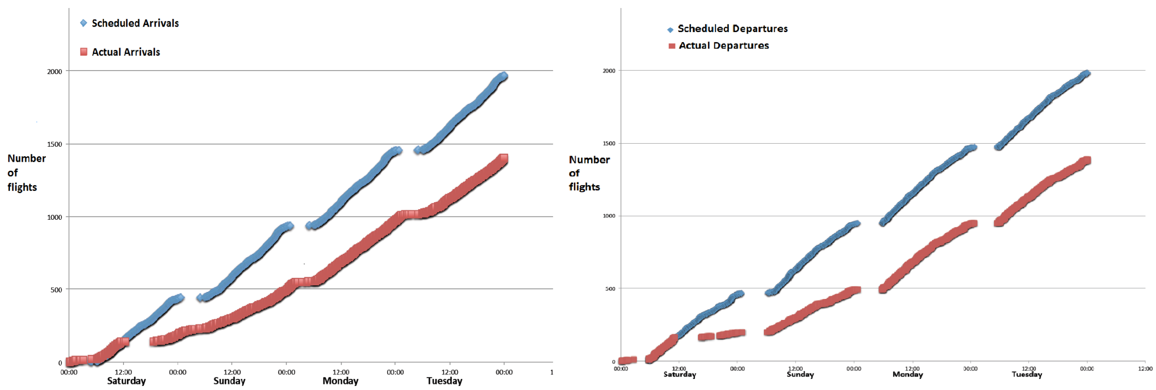


Figure 3: Scheduled vs Actual Arrivals and Departures at SFO airport, July 6th-9th 2013.

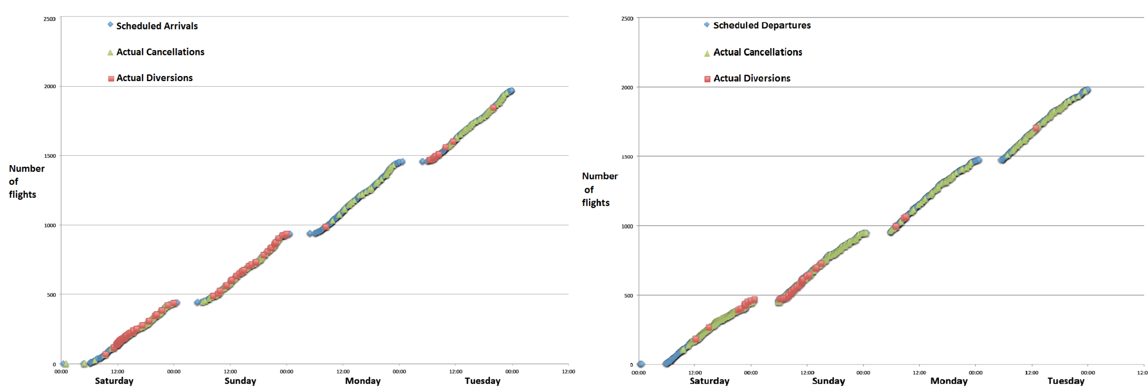


Figure 4: Temporal evolution of Cancellations and Diversions at SFO airport, July 6th-9th.

Figure 3 represents the difference between scheduled and actual operations at SFO from Saturday, July 6th 2013 to Tuesday, July 8th 2013. The divergence between scheduled and actual departures, as well as scheduled and actual departures begins immediately after the crash. The airport is closed until the two shorter runways, perpendicular to the crash runway, reopen in the afternoon. Departures and arrivals then resume at a slower pace than usual because of reduced runway capacity at the airport. Summing the results over four days, more than 660 flights scheduled to land at SFO airport had either been canceled or diverted, and more than 580 flights had been canceled or diverted at departure from SFO.

Figure 4 displays the temporal evolution of diversions and cancellations to or from SFO airport from Saturday July 6th 2013 to Tuesday July 9th. First, Figure 4 shows that diversions mostly occurred on Saturday as well as on Sunday. There are several departure diversions, meaning that flights that departed from SFO made a stop before reaching their final destination, mostly on Saturday evening and Sunday morning, when there are fewer arrival disruptions. The proportion of diversions is high : 17% of arrival flights to SFO were diverted on Saturday. After Sunday the number of diversions went back to normal, while cancellations remained considerable. Indeed, cancellations span the four days without any noticeable pattern regarding their timing. A closer look at the repartition of cancellations and diversions over the crash week-end in Tables 1 highlights the impact of the crash. More than half of the scheduled departures and almost half the scheduled arrivals were canceled on Saturday; these figures slowly decreased until Tuesday.

Day	Complete	Cancelled	Diverted
Sat	185	180	74
Sun	310	155	30
Mon	476	43	1
Tue	433	70	14

(a) Arrivals in SFO

Day	Complete	Cancelled	Diverted
Sat	198	231	11
Sun	293	174	30
Mon	456	62	2
Tue	439	74	1

(b) Departures from SFO

Table 1: Number of complete, canceled and diverted flights to and from SFO during the entire crash week-end.

Day	DEN	LAS	LAX	MSP	OAK	PHX	RNO	SJC	SLC	SMF	Sum
Sat	4	7	8	1	15	3	3	22	1	10	74
Sun	0	0	0	0	19	0	0	11	0	0	30
Mon	0	0	0	0	1	0	0	0	0	0	1
Tue	0	0	0	0	4	0	0	7	1	2	14

Table 2: Number of flights which were supposed to land at SFO airport and were diverted to other airports.

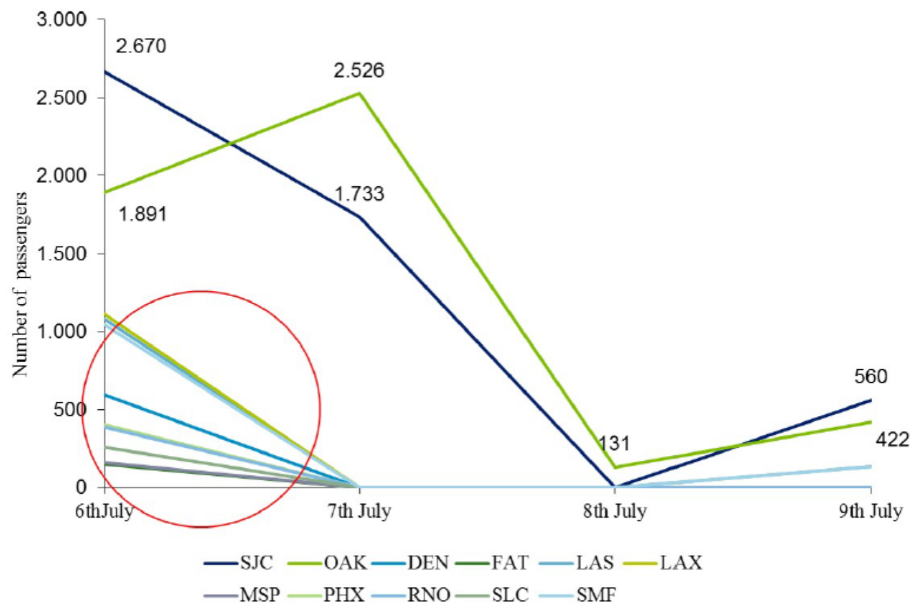


Figure 5: Estimated number of passengers diverted to different airports from July 6th to July 9th 2013. The red circle corresponds to the crash day during which there were the most diversions.

Operations were worse on Tuesday, July 9th than on Monday, July 8th. Moreover, due to the closure of the crash runway, runway capacity was still significantly reduced, leading to many cancellations. There are very few diversions after Sunday. This is to be expected since diversions are usually tactical operations. Upon further investigation of the departure diversions on Saturday evening and Sunday morning, these diversions impacted medium-haul flights only, with a short stop in SLC airport; they reached their final destination with little delay. The most likely explanation is that these flights were performed by fairly heavy aircraft. Because only the two shorter runways were opened until Sunday afternoon, they probably had to depart with less fuel than needed for their entire trip and their planned refueling at another

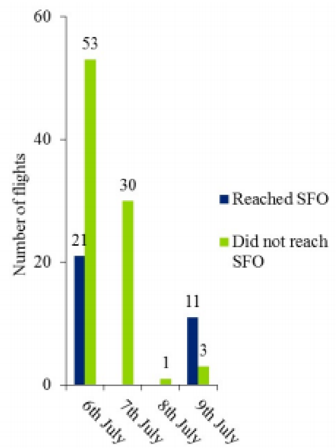


Figure 6: Among diverted domestic flights, number of flights that eventually left the diverted airport and reached SFO.

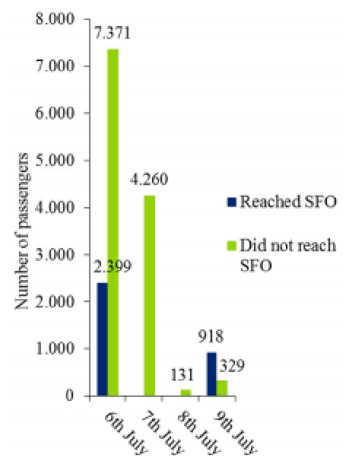


Figure 7: Among diverted domestic passengers, number of passengers whose flight eventually left the diverted airport and reached SFO.

airport appears in the data as a diversion.

The major carrier flights were diverted to a number of airports, as reported in the BTS data. The other Bay Area airports, Oakland (OAK) and San Jose (SJC) accommodated most flights, from Saturday to Tuesday. Nevertheless, several other airports, as far as Denver, Los Angeles and Las Vegas, received many diverted flights on the crash day. Figure 5 displays the estimated number of passengers who were diverted to different airports than SFO from July 6th to July 9th, based on the load factor reported by each airline for July 2013 to the BTS. Figure 5 shows that several

6th July					
Tail number	Sched. Dep.	Actual Dep.	Sched. Arrival	Actual Arrival	Total block delay
N33292	8:54	8:54	12:32	19:55	403
N846VA	9:35	9:21	12:35	18:01	380
N951SW	9:39	9:49	12:00	17:40	330
N528VA	10:00	9:57	12:45	18:33	391
N851VA	10:05	10:03	11:50	18:46	418
N37437	10:01	10:05	13:44	19:33	345
N229SW	10:19	10:20	11:55	19:45	469
N758SK	10:23	10:29	12:00	18:32	346
N962SW	9:51	10:40	12:00	18:41	312
N522VA	10:30	10:45	13:45	18:40	320
N139DL	10:55	10:52	13:05	9:21	1.178
N795SK	11:12	11:11	12:30	17:54	325
N431UA	11:21	11:21	14:00	21:04	424
N646DL	11:22	11:21	12:20	18:33	334
N701BR	11:30	11:27	12:52	19:34	405
N583NW	11:45	11:37	13:44	20:32	416
N36247	11:30	11:39	13:16	20:35	430
N402UA	12:30	12:28	15:17	21:53	358
N16732	11:32	12:44	13:43	19:49	294
N37422	12:55	12:52	16:05	22:08	366
N13718	13:19	13:19	15:22	19:45	263
				Average [min]	**405**
				Standard deviation	**189**

Figure 8: Average delay incurred for the diverted passengers whose flight eventually left the diverted airport and reached SFO.

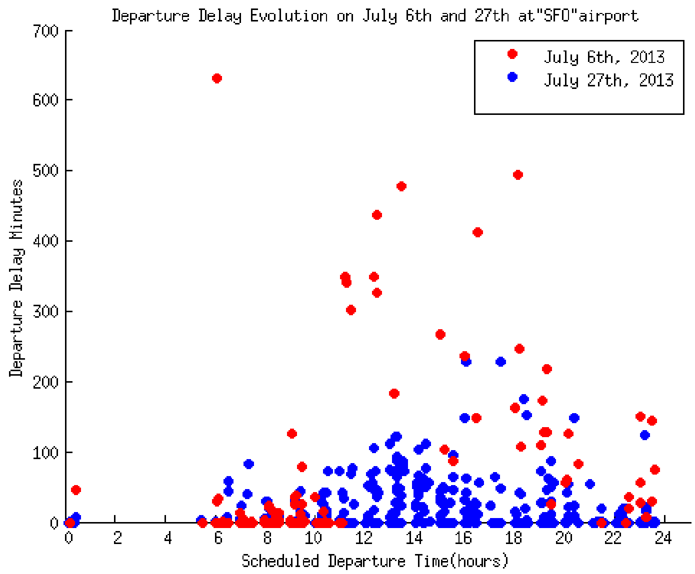
thousands of passengers were diverted to other airports from July 6th to July 9th. Figures 6 and 7 indicate the proportion of diverted flights and their passengers that eventually reached SFO at the end of the day, after taking off from the diverted airport. Figure 8 provides the delay suffered by the diverted passengers who reached SFO on the same flight they were diverted in. The average delay for these passengers was, on average, greater than 6 hours. For the diverted passengers whose flight could not land in SFO, this delay was of course much greater.

The BTS data does not provide indications regarding diversions of international flights but news reports [61] that several international flights were diverted to Seattle Tacoma (SEA) on Saturday, July 6th, coming from London, Dubai, Frankfurt, Paris and Zurich.

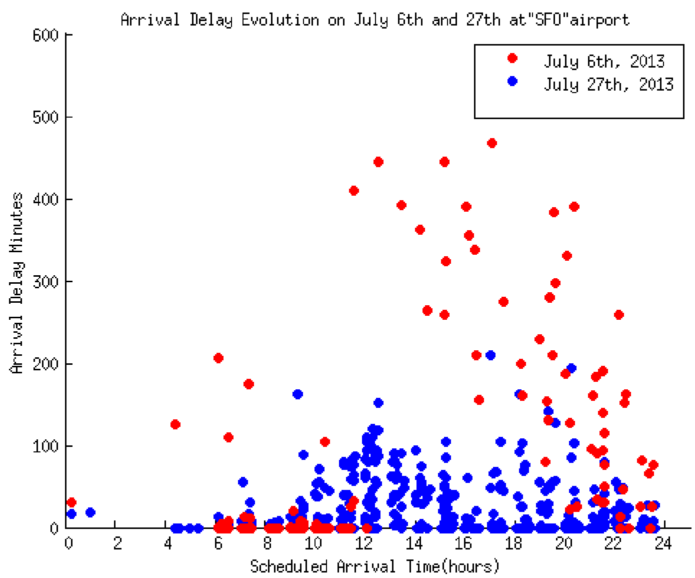
Many more issues arose when flights were diverted to airports in which their carrier does not operate. For instance, a SFO-bound United Airlines flight from Seattle was diverted to Oakland. Local news reporters [40] interviewed the 6th of July 2013 some of the flight passengers, who reported "United has no support here. They sent a dislocation team, but basically what they keep saying is: "You're dislocated." " The officials said they had to bring extra staff to accommodate passengers who were landing at the same time. Moreover, many passengers were diverted to airports where their airline operates at low frequency.

3.2.1.2 Delays at SFO airport

When it comes to operations at the airport itself, Figure 9 displays the delay minutes for each departing and arrival flight against their scheduled departure or arrival time at SFO airport during (i) the crash day and (ii) Saturday July 27th, which is used as a reference day. There were 879 scheduled flights at SFO on July 6th and 901 on July 27th, corresponding to domestic US carriers. On July 6th, there were a total of 411 cancellations and 85 diversions, whereas on July 27th, 8 flights were cancelled and none diverted. Immediately after the crash, departure and arrival delays rise significantly and are much higher than on July 27th, although the number of operations is considerably smaller. The delays go back to almost normal levels after 10 pm. Figure 10 presents the taxi-out and taxi-in times at SFO airport through the crash day and a normal Saturday. Contrary to departure and arrival delays, the taxi-out times were completely normal through the day. This means that the departure delay observed is primarily due to delay incurred at the gate. Taxi-in times were normal except around the crash time. Because of the number of emergency vehicles going to the crash runway, arrival flights on the ground may have been held to let them through.



(a) Departure Delay

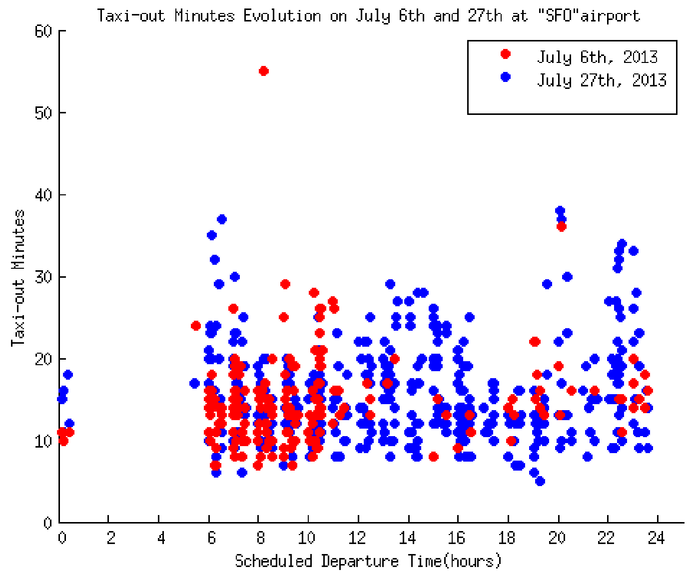


(b) Arrival Delay

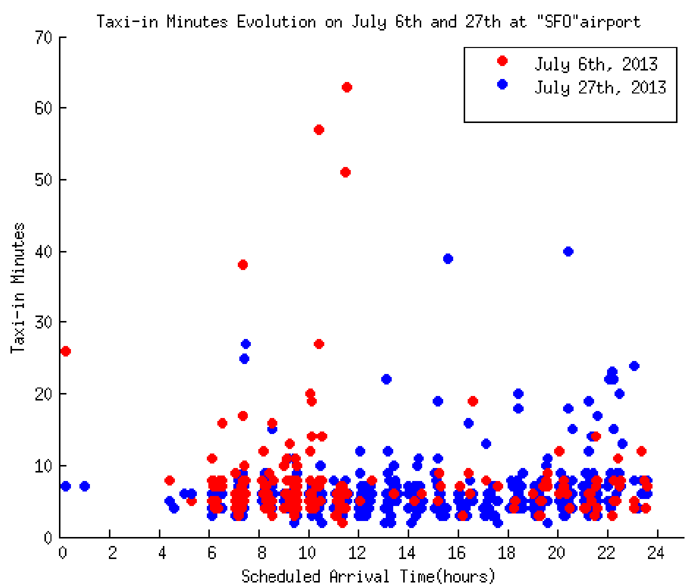
Figure 9: Delay comparison between the crash day and a normal Saturday at SFO.

3.2.2 Impact of the crash on the Air Transportation Network

Cancellations and delays due to the crash at SFO propagated through the airspace and the ripple effect lasted several days.



(a) Taxi-out time



(b) Taxi-in time

Figure 10: Taxi time comparison between the crash day and a normal Saturday at SFO.

3.2.2.1 Cancellations and their propagation

Figure 11 shows the number of departure and arrival cancellations at SFO for the entire month of July. The day of the crash, Saturday, is the worst in terms of cancellations, with more than 45% of the scheduled flights cancelled. Sunday July 7th

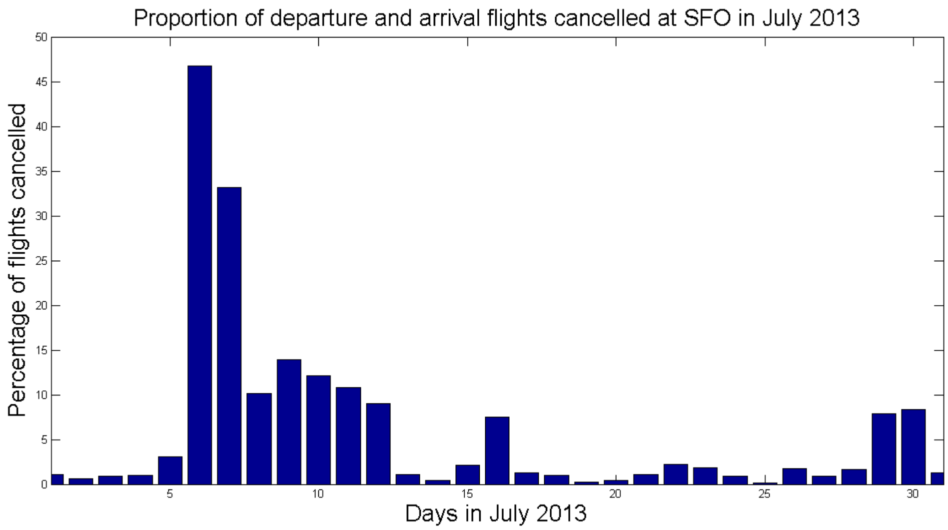
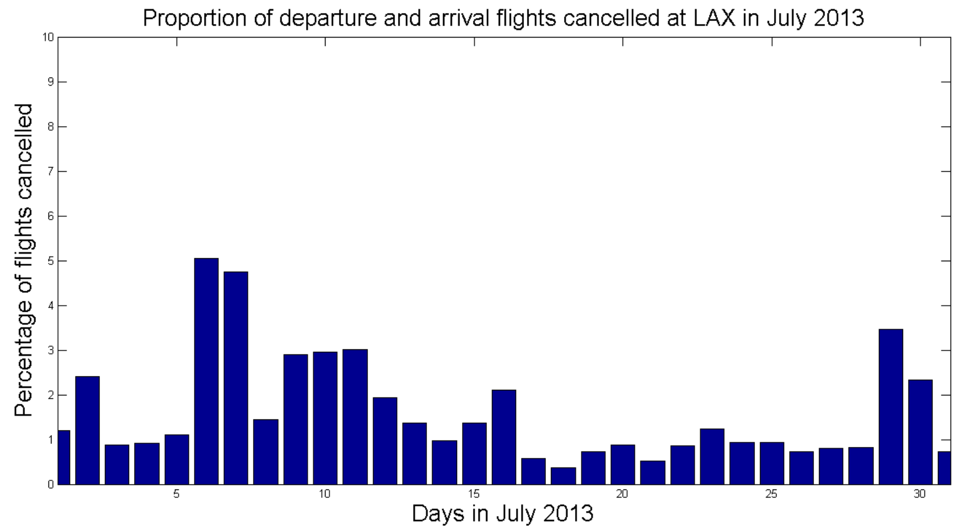


Figure 11: Proportion of cancelled flights among the total scheduled traffic departing or arriving at SFO airport for July 2013.

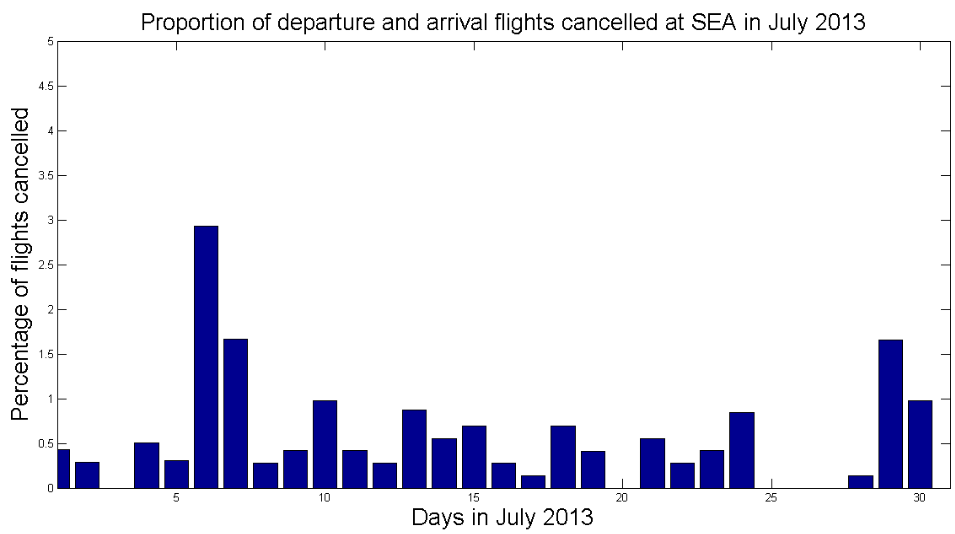
is the second worst. The recovery takes more than a week after the crash, with the week from July 8th to July 12th witnessing cancellations of more than 10% of the number of scheduled flights each day.

Figure 12 shows the number of departure and arrival cancellations are Los Angeles International Airport (LAX) and Seattle-Tacoma International Airport (SEA). Among the other top 30 airports in the US, LAX and SEA were most affected by cancellations due to the crash. On July 6th and 7th, the proportion of cancelled flights at LAX and SEA was highest for the month of July, with more than 5% of cancelled flights at LAX and 3% at SEA.

Cancellations can propagate through schedules. Indeed, a given aircraft is scheduled to fly several legs through a given day. Once one of these legs has been canceled, the airline tries to get back on schedule, but this schedule recovery is airline- and aircraft-specific. To analyze this propagation phenomenon, the tail numbers of all aircraft involved with flights canceled at departure or arrival to SFO airport from July 6th to July 9th were tracked. In the BTS data, some tail numbers are missing, making these aircraft impossible to track. Such flights are counted in Table 3 under



(a) LAX airport



(b) SEA airport

Figure 12: Proportion of cancelled flights among the total scheduled traffic departing or arriving at Los Angeles (LAX) and Seattle (SEA) airports for July 2013.

'missing aircraft id' and only one cancellation is computed. For the aircraft with available tail numbers, each aircraft's individual schedule is recovered. The number of legs each aircraft was supposed to fly is computed. Among these scheduled legs, the total number of cancellations is recorded. In Table 4, the number of cancellations encountered by any aircraft with available or missing tail numbers are summed. This Table provides the total number of cancellations directly attributable to the SFO crash over the crash week-end. The total number of cancellations regarding flights departing or arriving at one of the top 35 airports in the US is also computed for the crash week-end. The ratio between cancellations attributable to the crash and cancellations in the entire airspace is underestimated, because of the missing tail numbers. On the day of the crash, the propagation of cancellations due to the Asiana crash accounts for more than 85% of all cancellations in the airspace, more than 50% on Sunday and more than 25% on Monday and Tuesday. Over the four days, the Asiana crash led to more than 49% of all cancellations in the US.

Table 3: Flight cancellations propagation due to SFO airport.

Day	Missing aircraft id	Available aircraft id	For the available aircraft id, flights scheduled	For the available aircraft id, flights cancelled
July 6th	144	137	707	279
July 7th	62	119	708	269
July 8th	17	48	338	92
July 9th	11	59	452	139

Table 4: Cancellations in the airspace attributable to perturbations at SFO airport.

Day	Number of flights canceled departing or arriving at the top 35 airports in the US	Number of cancellations due to SFO perturbations	Percentage due to SFO perturbations
July 6th	488	423	86%
July 7th	609	331	54%
July 8th	456	109	24%
July 9th	510	150	30%

Figure 13 shows, for each aircraft with a tail number that encountered a cancellation to or from SFO airport, how much of its schedule was disrupted. Some aircraft were supposed to operate up to eight legs on the crash day. Some aircraft had a first flight cancelled early in their schedule and could not perform any of the remaining legs through the day, whereas others encountered cancellations but could still complete most of their scheduled legs. On Saturday July 6th and Sunday July 7th, most aircraft completed between one and two thirds of their scheduled legs. On Monday

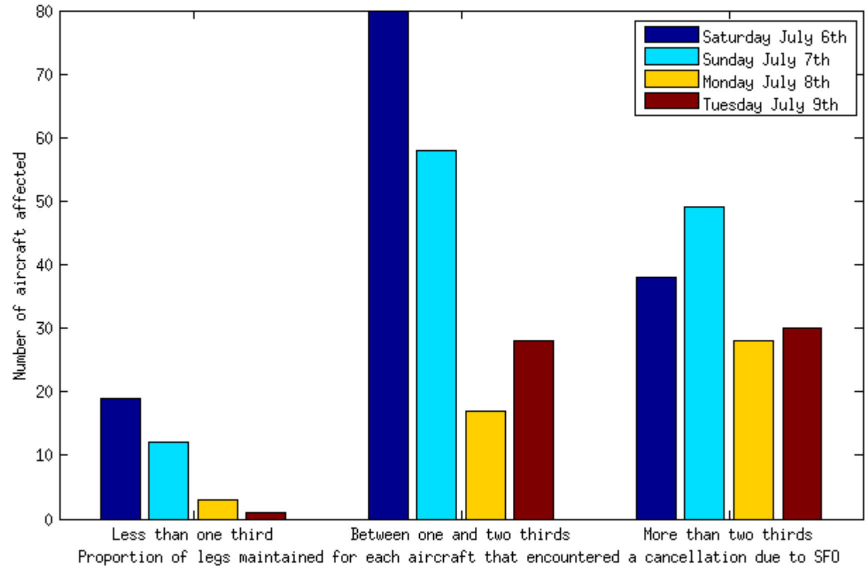


Figure 13: Number of flights maintained per aircraft encountering a cancellation due to SFO airport from Saturday July 6th to Tuesday July 9th.

July 8th and Tuesday July 9th, more than 50% of the aircraft that encountered a cancellation were then able to complete more than two thirds of their scheduled legs.

3.2.2.2 Delays and their propagation

To evaluate the impact of the crash on delays throughout the national airspace, the number of delayed aircraft at the top 35 passenger airports in the US is computed for July 2013. The results are displayed in Figure 14. Saturday, July 6th and Sunday, July 7th have some of the lowest total delay in the entire month because cancelled flights are not accounted for in the delays. Since a large proportion of flights were cancelled, even if many of the maintained flights were delayed, the effect of lower flight volume made the overall delay lower.

A visualization tool, inspired from the publicly available "misery map" from Flight Aware [50] was developed to display the proportion of delayed and on-time flights at the top passenger airports in the US over 4-hour periods. The tool also ranks these

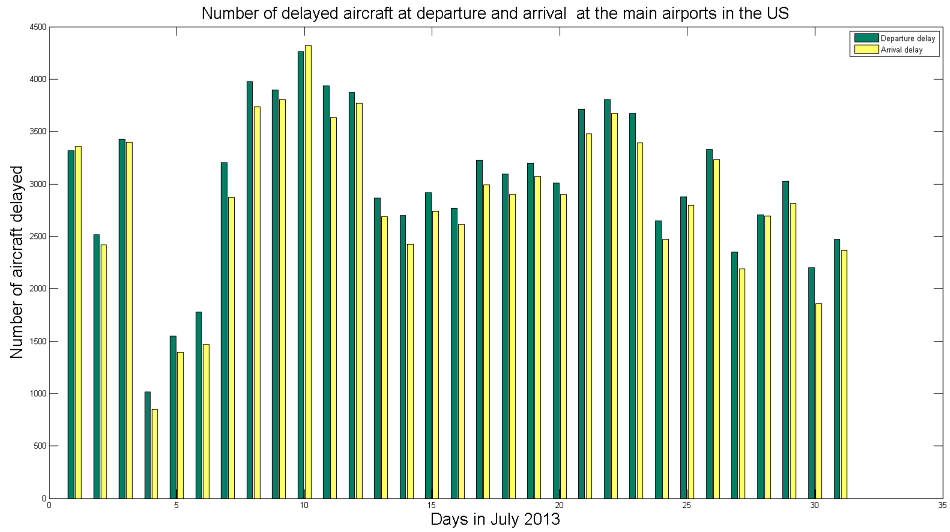


Figure 14: Delays at the top 35 airports for July 2013.

airports by number of cancellations. Figures 15 and 16 are screen shots of the visualization tool through July 6th and 7th. The time indicated is Pacific time. First, on July 6th, before the crash, Chicago O'Hare was the airport with the most cancellations and the highest proportion of delayed flights, because of a weather perturbation. Right after the crash, the number of cancellations at SFO increases significantly, leading to cancellations at LAX, PHX, SEA in particular. ATL cancellations increase too, but it is also due to the weather pattern observed that day. The proportion of delayed flights also increases throughout the entire airspace. On July 7th, the proportion of delayed flights is much higher than on the previous day at most of the busiest airports, particularly in the afternoon. This could also be an effect of the end of a holiday week-end. For instance, the number of cancellations is much higher in the New York Area airports and Boston than on the previous day.

3.2.3 Cost analysis

The overall passenger-centric cost of the crash is evaluated for the period ranging from Saturday, July 6 to Tuesday, July 9. This cost can be broken down into delay cost, cancellation cost and diversion cost.

3.2.3.1 Delay Cost

Time is a valuable economic resource that may be devoted to work or leisure activities. Because travel takes time, it imposes an opportunity cost equal to the individual value of time in work or leisure activity. Moreover, since travel may take place under undesirable circumstances, including long waits or rides aboard a crowded or uncomfortable vehicle, it may impose an additional cost on travelers. Travel time saved or lost as a result of investments or regulatory actions should be valued in benefit-cost analyses to reflect both the opportunity cost and discomfort, if any, people experience when traveling.

The Department of Transportation (DOT) provides recommended values for aviation passenger travel time [51] on all-purpose air carriers, of \$ 40.10 per hour and person.

First consider the delayed arrival flights to SFO. The capacity of all the delayed flights during the considered time period is retrieved. The BTS provides the average load factor for July 2013 for departure and arrival flights at SFO airport. This leads to computing an estimate of the total number of passengers delayed, the number of hours of delay and the associated costs.

$$Passengers\ per\ Flight = \ Load\ Factor\ \times\ Flight\ Capacity$$
$$Delay = \sum_{\substack{i=0\\ i}}^{n} Aircraft\ Delays_i\ \times\ Passengers\ per\ Aircraft_i$$
$$Cost\ per\ Day = \ Delay\ \times\ Hourly\ Value\ of\ travel$$

Because there were more canceled flights and fewer delayed flights on the crash day compared with Sunday, the delay cost is lower on Saturday. The overall delay cost for departures and arrivals reaches 14 million \$.

3.2.3.2 Cancellations

There have been several attempts to estimate the equivalence between cancellations and delay minutes. One solution, used in both academia and industry, is to assign a rough estimate to cancellation cost based on their knowledge and experience. Sridhar [90] states that one cancellation is equivalent to approximately 200-300 minutes of delay. In an unpublished study by Metron Aviation [96], the cost of a flight cancellation is estimated at 6,000 $. In this subsection, we draw a distinction between the airplane standpoint and the passengers standpoint.

Our working assumption is that one cancellation is equivalent to 250 minutes of delay. Given the number of cancellations per day, the equivalent delays and the total delays are computed by multiplying the number of total passengers and the delays. The same method is applied to departure flights, and the same trend observed. As for delayed flights, the number of passengers affected is a function of the load factor and the airplane capacity.

$Delay = Delay\ Equivalent\ \times\ Number\ of\ passengers\ per\ cancellation$

$Cost\ per\ Day =\ Delay\ \times\ Hourly\ Value\ of\ Travel$

The passenger cost of having his or her flight canceled can be estimated from aggregated statistics. In 2007, 11.4 million passengers were affected by flight cancellations, for a reported cost of \$ 3.2 million [85]. We compute the passenger cost per cancellation as the passenger cost recorded in 2007 divided by the number of passengers disrupted by a cancellation that same year, and it reaches \$ 281.

3.2.3.3 Diversions

Diversions are an expensive, chronic and disruptive element of flight operations, costing at least 300 million dollars annually to US carriers for domestic flights alone. A diversion is not a single, discrete event, but rather a set of cascading actions that cause severe disruptions to airline schedules, major costs, and significant passenger frustration. Diversion costs from the airline standpoint can range from 15,000 $ for a narrow-body domestic flight, to more than 100,000 $ for a wide-body international flight. Perry Flint, from the International Air Transport Association (IATA) [8], states that there is no average cost for diversions. The diversion cost depends on the size of the aircraft and the number of passengers on board, severity and operational consequences: delays, resulting missed connections, flight cancellations, cost of hotels/meals for passengers and crew.

Assume that the diversion cost depends on the diversion airport.

For the diverted flights that finally reached SFO, their arrival delay is computed and the same value of hourly travel time is used to estimate the cost from the passengers point of view.

$$Delay = \sum_{\substack{i=0 \\ i}}^{n} Aircraft\ Delays_i \ \times \ Passengers\ per\ Aircraft_i$$

3.2.3.4 Overall Cost

The overall passenger-centric cost of the crash is computed as the difference between the cost of the crash week-end and that of the previous "normal" week-end. The cancellations costs due to the crash is estimated at $ 22.1 million , or 56% of the total crash cost. The delay cost is estimated at $ 11.6 million , or 30% of the total cost. The diversions cost is the lowest, accounting for 14% of the total crash cost. Thanks to these observations, it is clear that the important cost of the crash is mainly due to the cancellations and the important delays during the week-end.

It should be noted that the overall cost calculated does not take into account the cost of passenger losses, passenger evacuation and hospitalization, emergency interventions on the crash scene, airport repairs and aircraft loss.

The total crash cost during the crash day is the highest compared to the other days. Indeed, this cost is equivalent to 37% of the total cost during all the week-end. Once again, the higher cost is due to cancellations and then due to delays. This is

Cost ($ million)	Crash week-end	Previous week-end	Difference
Delays to SFO	8.0	0.4	7.6
Delays from SFO	5.6	1.6	4.0
Cancellations to SFO	10.2	0.4	9.8
Cancellations from SFO	12.5	0.3	12.3
Diversions to SFO	4.9	0	4.9
Diversions from SFO	0.8	0.1	0.7
Total	42	2.8	39.2

Table 5: Cost evaluation for the crash week-end.

the basis for future work on evaluating the potential savings that could have been achieved if canceled flights to SFO had been transferred to other airports in the Bay Area.

This cost decomposition analysis suggests that the costs incurred to the air transportation system could have been strongly reduced if several delayed and/or cancelled flights arriving in SFO had been diverted to OAK or SJC, if additional gate and runway capacity were available.

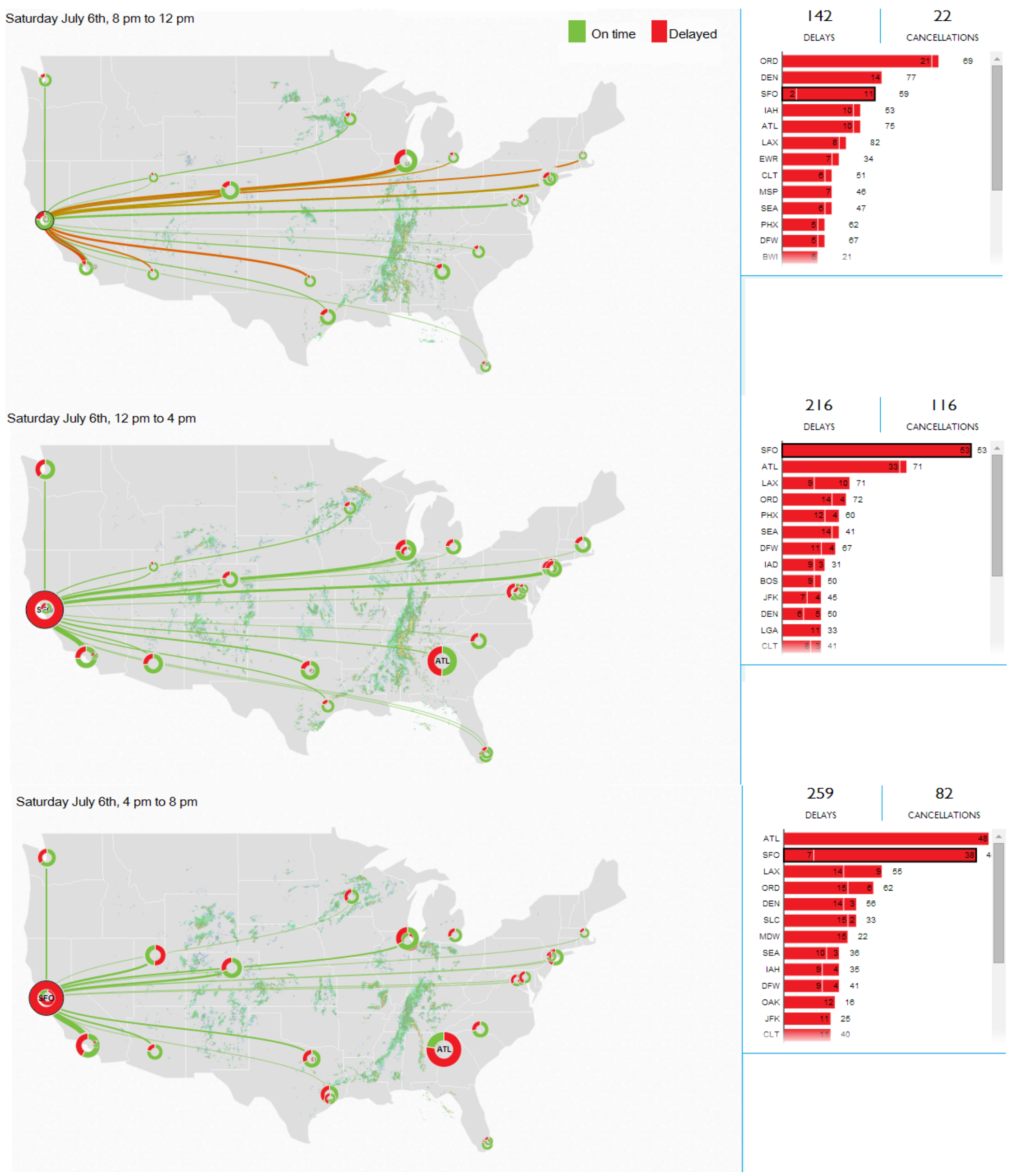


Figure 15: Proportion of delayed flights and number of cancellations at the top airports on July 6 2013.

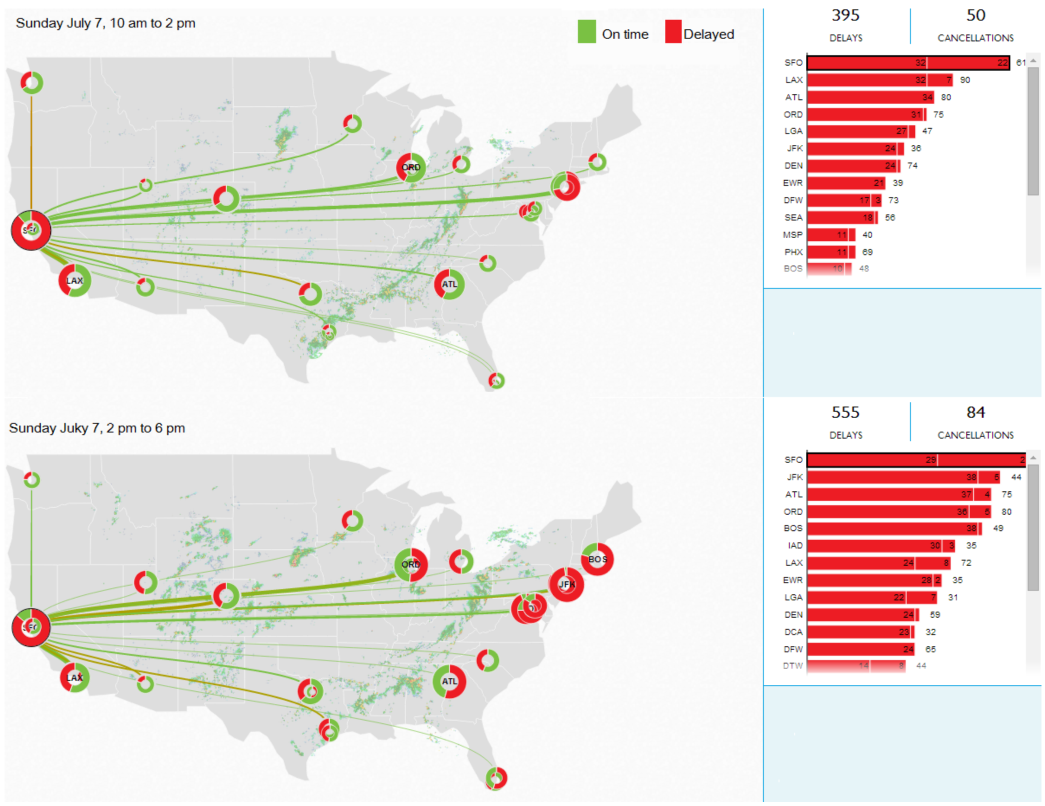


Figure 16: Proportion of delayed flights and number of cancellations at the top airports on July 7 2013.

3.3 Impact of the Crash on other Transportation Modes

3.3.1 Ground Transportation : Highway Traffic

The major data source for the road network in California is PeMS, which stands for Freeway Performance Measurement System [5]. Measurements from loop detectors on the major roads in California are recorded and stored in PeMS. The loop detectors measure the number of vehicles passing per time period (flow) and the fraction of time that the loop is occupied (occupancy). From these measurements, a number of traffic properties are estimated, for example the average speed of vehicles on a given road. However, the PeMS data presents two main limitations. First the traffic conditions on a road stretch between two detectors are not observed. Second, many loop detectors are out of order for periods of time. The second limitation has an compounding effect on the first limitation.

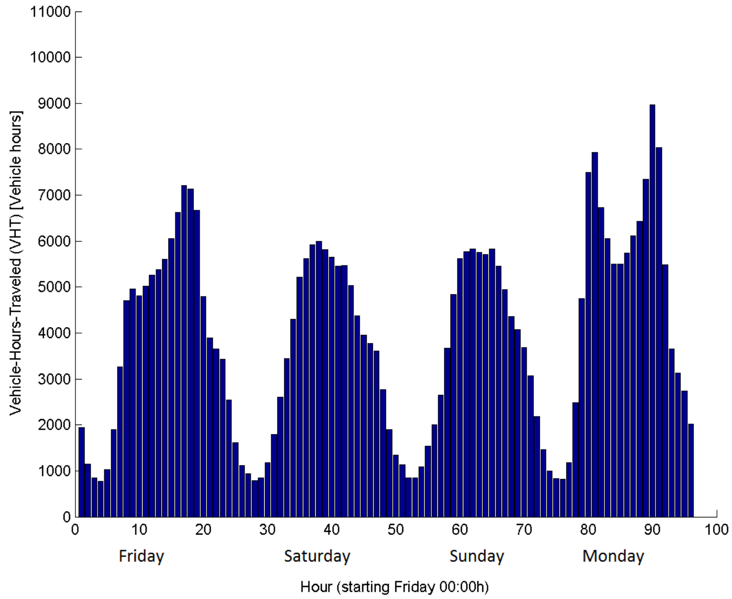
Choe [32] proposes a method to analyze road traffic conditions using PeMS. PeMS has been used in several studies to study congestion growth [31]. For the present study, the hourly Vehicle-Hours-Traveled (VHT) and Vehicle-Miles-Traveled (VMT) in an eight-mile radius [1] around SFO airport are studied from Friday, July 5th to Monday, July 8th, as displayed in Figure 17.

The variables used to understand road traffic are defined as follows. q is the flow in [veh/h], T is the time period in [h], L_s is the length of the considered road stretch in [mi], and v and v_r are the observed and reference speeds in [mph], respectively.

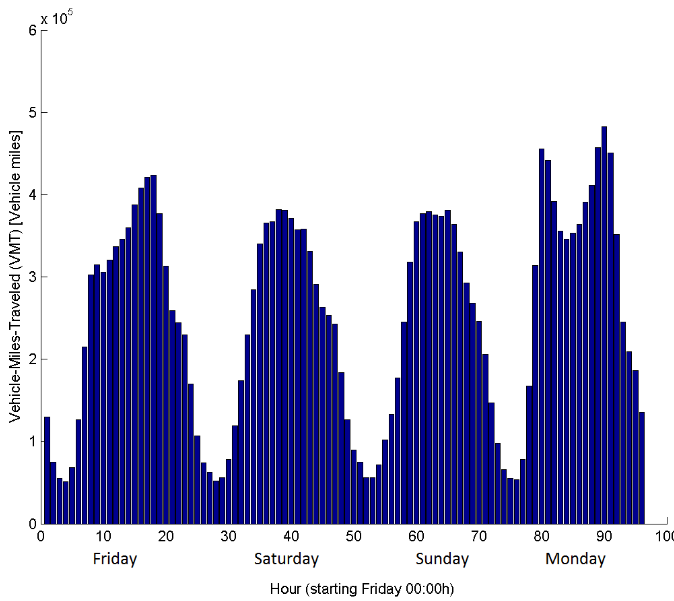
$$Delay = qTL_s \left(\frac{1}{v} - \frac{1}{v_r} \right) \tag{1}$$

$$VMT = qTL_s \tag{2}$$

[1] This data is not a direct output of PeMS. The VHT and VMT for the different PeMS roads stretches within this area are summed.



(a) Vehicle Hours Traveled



(b) Vehicle Miles Traveled

Figure 17: Road traffic performance data for the long weekend in which the ASIANA crash occurred.

$$VHT = qT\frac{L_s}{v} = kTL_s \tag{3}$$

$$Speed_{avg} = \frac{VMT}{VHT} \tag{4}$$

To better understand performance data based on certain traffic conditions, consider

Table 6: Performance variables for three one-mile road stretches with uniform traffic conditions during one hour (the reference speed for delays is 65 mph).

State	Flow[veh/h]	Speed[mph]	Delay[veh/h]	VMT[veh/mi]	VHT[veh/h]
1	6000	65	0	6000	92.31
2	7900	64	1.90	7900	123.44
3	7180	50	33.14	7180	143.60

an hypothetical road stretch of one mile during a period of one hour. For this space and time, assume uniform traffic conditions. Table 6 shows the resulting performance variables. This example only works for uniform traffic conditions, but gives a good indication of the contribution of traffic conditions types.

A traffic state is defined for a given flow rate and speed, for a specified time period and road stretch. State 3 in Table 6 is the only congested state. In the road stretches where this state is observed, the average speeds are lower and the delays higher than in the other road stretches. From this example, congestion leads to a large delay and low speed. Near capacity (synchronized) flow contributes mostly to a increase in VMT.

Table 7: Performance variables for six road stretches consisting of two one-mile road stretches with uniform traffic conditions during one hour (the delay reference speed is 65 mph).

States	Speed_{avg} [mph]	Delay [veh h]	VMT [veh mi]	VHT [veh h]
11	65	0	12000	184.62
22	64	3.80	15800	246.88
33	50	66.28	14360	287.20
12	64.43	1.90	13900	215.75
13	55.87	33.14	13180	235.91
23	56.47	35.04	15080	267.04

Now consider the example of a two mile road stretch during a one-hour period, with two equal length uniform traffic conditions. The corresponding performance data is depicted in Table 7. The VMT and VHT are both larger in state 22 than in state 13. It is not always the case when there is a combination of free-flow and congestion, yet it indicates that it is possible. It corresponds to light congestion and free-flow that is not close to capacity.

The traffic performance data around SFO displayed on Figure 17 do not indicate any clear effect of the crash on the aggregated traffic conditions for Saturday, July 6th. However, a more detailed analysis can be performed using the space-time contour plots described in [32]. We define "abnormal congestion" as congestion that does not occur on reference days and thus is not caused by regularly occurring bottlenecks. The road traffic conditions are compared with reference days, namely with the 26 Saturdays between April and September 2013. Using the method in described in [32], the congestion on on US101, I80 and I880 near SFO is recorded for each of the Saturdays. The congestion on the US101N near SFO stands out as abnormal. At all other locations and times where congestion was observed, congestion had also occurred at least once during the reference Saturdays. Therefore, the rest of this subsection focuses on the US101N to observe the traffic jam reported in the news [29]. When it comes to freeway traffic, under nominal conditions, week days exhibit morning and evening peaks, but week ends do not. Figure 17 shows that only the congestion pattern on Friday, July 5th is different. This is expected for a normal long-weekend, with no morning peak because of July 4th on Thursday. A pattern change on Saturday due to the ASIANA crash is not clear from these figures because the data is too aggregated.

The performance data (speed, delay, VMT, VHT) at a US101N road stretch near SFO are shown in Figures 18, 19, 20 and 21. From the speed and delay histograms in the 12 am - 1 pm period, the speed and delay on the crash day stand out as outliers. On the other Saturdays in 2013, the delay was never as large and the speed never as low as on the ASIANA crash day. From the VMT and VHT plots in Figures 20 and 21, no clear effect of the ASIANA crash is observed after 1 pm on the crash day. The breakdown occurred shortly after the ASIANA crash and directly next to SFO.

The present focus is on understanding the causes of the congestion and, if possible, understand the causality is between the crash and congestion. Therefore, an in-depth analysis is performed into this congestion to examine if it is caused by the crash. As a starting point, the following hypotheses about the potential causes of the congestion are formulated:

- Increase in demand caused by vehicles leaving the airport.
- Rubbernecking, a traffic breakdown is caused by users watching the crash and thereby changing their behavior.
- Effect caused by emergency vehicles trying to reach the airport.
- Accident on the highway.
- Lane or ramp closure.

In order to investigate whether external events other than the ASIANA crash, such as an accident, caused the congestion, we consider the California Highway Patrol (CHP) incidents feed on the US101N near SFO on the crash day. The CHP incidents feed provide the incidents reported on that specific road stretch and time period. The Abs PM correspond to the first off-ramps upstream and downstream of SFO, it indicates the location of the road stretch studied. Here all reported types, namely accident, hazard, breakdown, police, congestion, weather and other are included. Table 8 shows the CHP incidents reported on July 6th, 2013 on the US101N near SFO. The CHP incidents feed provides no indication for the cause behind the observed aberrant congestion. All reported incidents occurred either after the aberrant congestion and/or on different locations. PeMS also has a lane closure system, in which the historical lane closures are reported. On the ASIANA crash day, two lane closures were reported by the system, see Table 9. We assume that these combined indicate that the off-ramp to SFO was closed at 12:30pm.

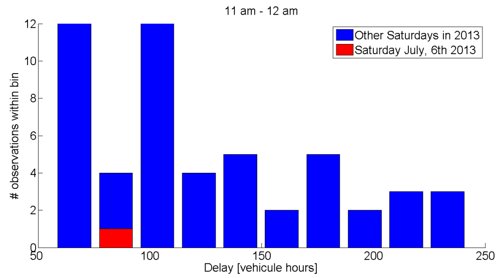
Table 8: CHP incidents feed on the US101N between PM 400-430 on July 6th, 2013 between 8am and 10pm. None of these CHP notations are related to the breakdown near SFO airport.

Time	Dur. [min]	Abs PM	Location	Description
15:26	18	425,5	San Francisco Us101 N / Us101 N Sierra Point Pkwy Ofr	1125-Traffic Hazard
12:18	27	404	Redwood City Us101 N / Willow	20002-Hit and Run No Injuries
12:41	19	414,7	Redwood City Us101 N / Us101 N Kehoe Ave Ofr	1179-Traffic Collision-1141 En route
19:25	6	418,5	Redwood City Us101 N / Us101 N Broadway Ofr	1125-Traffic Hazard

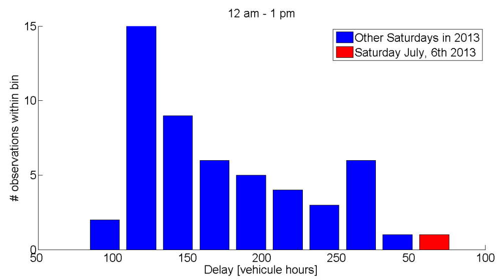
Table 9: Lane closures on the US101N between PM 400-430 on July 6th, 2013 between 8am and 10pm. The Abs PM correspond to the first off-ramps upstream and downstream of SFO. This can either mean that the two off-ramps were closed or that the one in-between (the SFO off-ramp) was closed. With additional information from news reports and tweets, the most likely meaning is that the off-ramp to SFO was closed. However it is unclear whether the off-ramps were closed for the entire period. The last update was at 13:54, which could correspond to the reopening of the off-ramps. The timing could also match an announcement of the reopening of the two shorter runways at SFO. Because the congestion observed is mostly between noon and 1 pm, therefore before 13:54.

Begin	End	Abs PM	Facility	Closure Lanes
12:30	16:30	420,134	Off Ramp	2
12:30	16:30	422,572	Off Ramp	2

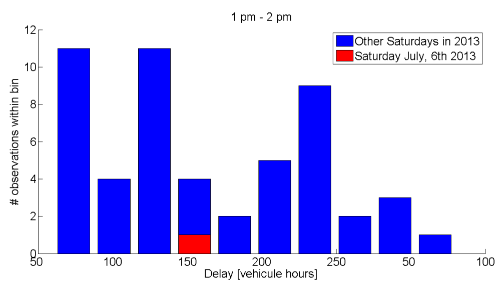
To study the congestion over time, the animation function available in PeMS [5] is edited to highlight the important moments. In Figure 22, screen shots of the animation tool are displayed to highlight the main events on the highway. At 11:26am, the ASIANA aircraft crashed just short of one of the SFO runways, see Figure 22a. At 11:53am, the first breakdown occurred at the on-ramp from Millbrae (PM 420.5), see Figure 22b, just upstream of the off-ramp to SFO. At the same time, conditions (lower speed) are deteriorating at the second upstream on-ramp (PM 419). However, a further breakdown first occurs at PM 420.5. Later, around 12:06pm, a further breakdown happens at PM 419, see Figure 22c. This creates the heavy congestion between PM 417-419, as previously observed. Around 12:49 pm the largest road stretch of the US101N is congested, as seen in Figure 22d with the red color. The congestion does not dissolve until 1:30pm, then the traffic conditions are restored to normal. In Figure 22e some lower speeds are spotted on the PM 419 on-ramp.



(a) Delay 11am-12am



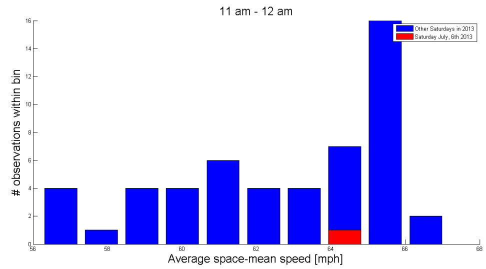
(b) Delay 12am-1pm



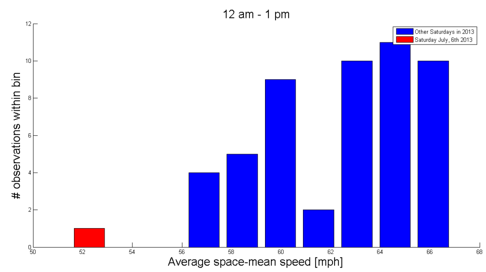
(c) Delay 1pm-2pm

Figure 18: Histograms of the delay on the US101-N PM 415-425 for the 26 Saturdays between April and September 2013.

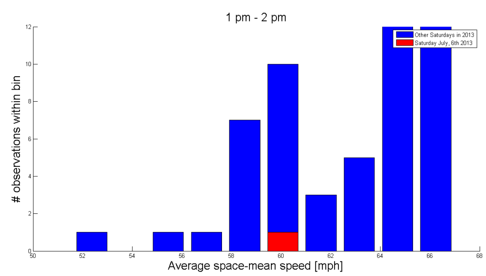
These observations suggest that the congestion was not likely to be caused by a large number of road vehicle departures from SFO (or inflow on the US101N) after the crash, because congestion occurs far upstream of the SFO to US101N on-ramp. The congestion observed on the US101N road stretches between PM 416.3 and 420.9. This range was selected such that the most upstream and downstream detectors show no sign of congestion. For further analysis, the road lay-out and individual loop detector stations on the mainline and ramps of the important road stretch are considered, as shown in Figure 23.



(a) Speed 11am-12am



(b) Speed 12am-1pm

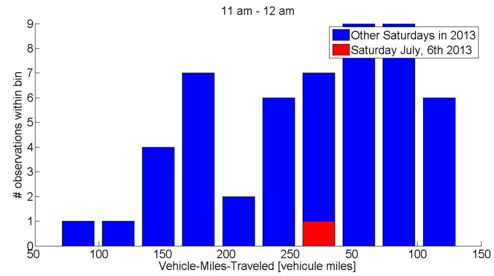


(c) Speed 1pm-2pm

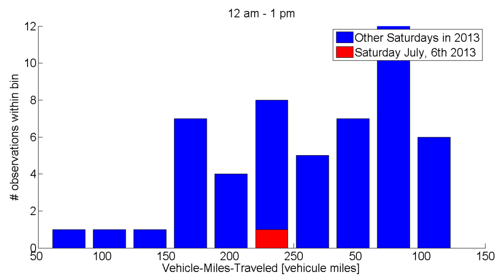
Figure 19: Histograms of the speed on the US101-N PM 415-425 for the 26 Saturdays between April and September 2013.

For the considered road stretch, fifteen mainline stations were available. Their locations are shown in Table 10. Besides these stations, traffic information is available on the Anza Boulevard on- and off-ramp and one of the two Broadway on-ramps, namely about the vehicles using the fly-over.

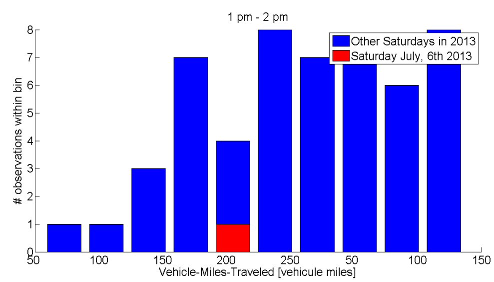
For all stations, the occupancy and flow is decomposed in 5-minute time-periods. For these time-periods, the average space-mean speed is also available at the mainline stations. Following [32], the present focus is on the occupancy over time on the different station locations. The first station is located downstream and the last upstream



(a) VMT 11am-12am



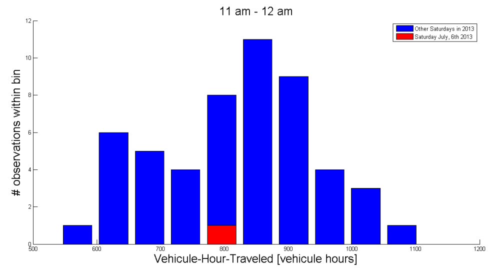
(b) VMT 12am-1pm



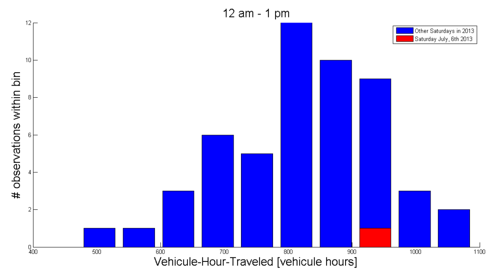
(c) VMT 1pm-2pm

Figure 20: Histograms of the VMT on the US101-N PM 415-425 for the 26 Saturdays between April and September 2013.

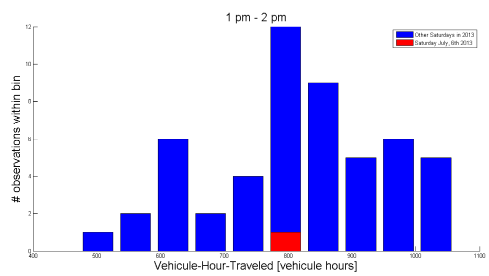
of the congestion on US101-N. At this location no congestion occurs, see Figure 24a. The occupancy upstream of the congestion remains stable between 0.070 and 0.075 (fraction of time a detector is occupied), while it varies more at the downstream station. However, the occupancy there remains under 0.100, indicating that there is no or very limited congestion. Between 12:00 pm and 12:30 pm, a break occurs, causing the occupancy to drop and oscillate around 0.065. This indicates that after this period, fewer vehicles use the US101-N at this location. At that point in time, the congestion may have been known to users and shortly after the authorities asked



(a) VHT 11am-12am



(b) VHT 12am-1pm

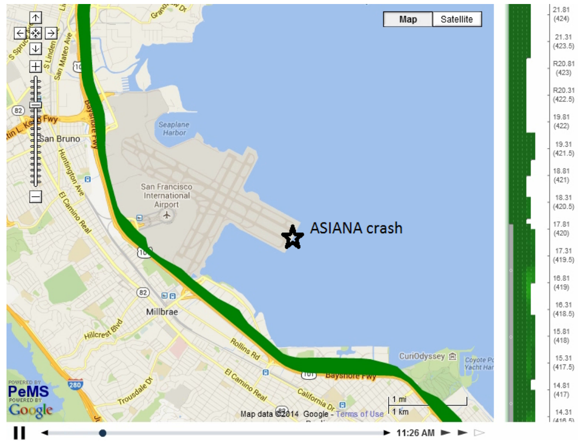


(c) VHT 1pm-2pm

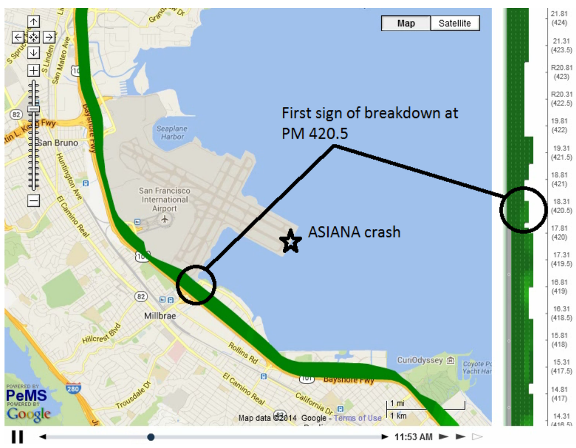
Figure 21: Histograms of the VHT on the US101-N PM 415-425 for the 26 Saturdays between April and September 2013.

people to use the I280 instead of the US101. The fact that congestion clear afterwards may suggest that people listened to the calls of the authorities.

A decomposition of the congestion pattern on US101 is provided in Figure 22, showing that two breakdowns occur. The first breakdown happens close to the Millbrae connection. The occupancy measured at the three detectors in the affected road stretch is shown in Figure 24b. The first peak indicates the breakdown timed at 11:53 am with the video-animation. Yet, this does not provide new insight regarding the potential causes of this breakdown.



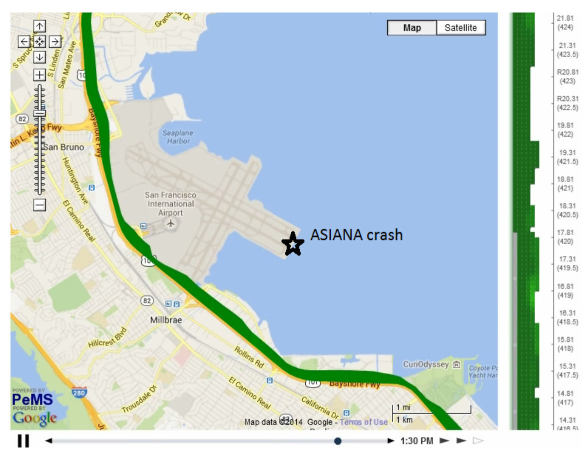
(a) 11:26am



(b) 11:53am

(c) 12:06pm

(d) 12:49pm



(e) 1:30pm

Figure 22: Traffic situation on the US101N at different times on July 6th, 2013. Two breakdowns can be observed: the first at 11:53 am, the second at 12:10 pm.

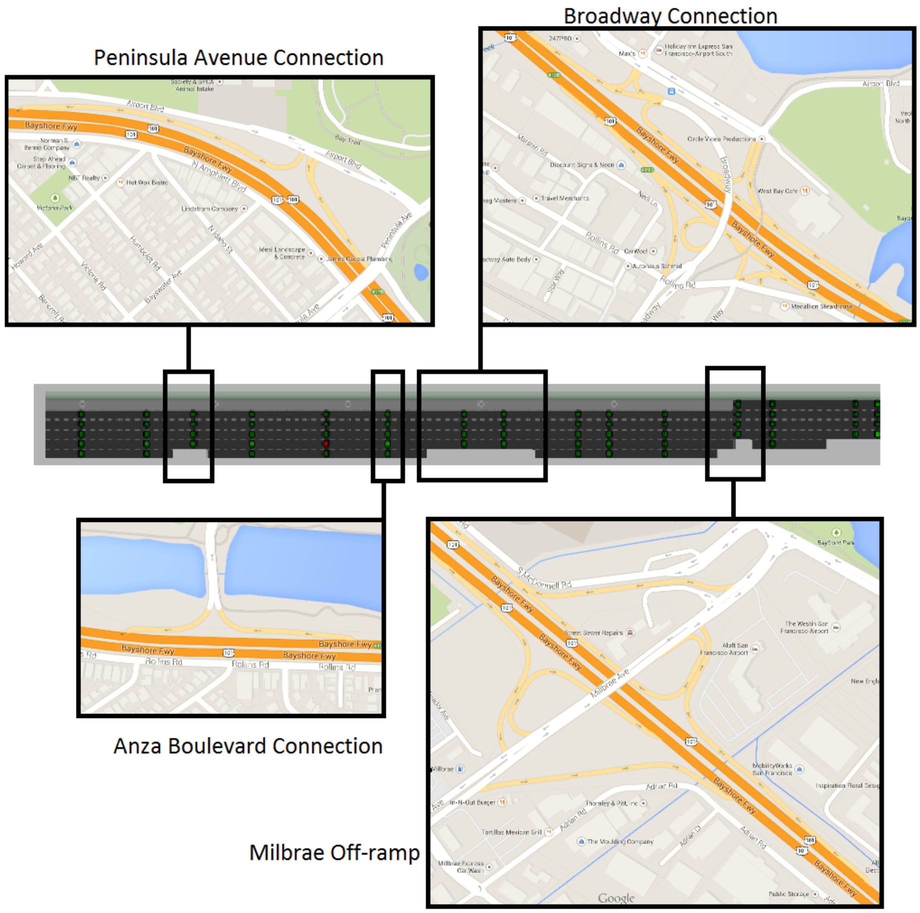


Figure 23: Lay-out of the US101N road stretch where congestion occurs near SFO after the ASIANA crash. The three connections, namely Peninsula Avenue, Anza Boulevard and Broadway, consist of both off and on-ramps, while the traffic coming from the Millbrae off-ramp stays on a secondary road until after the considered road stretch.

The second, more severe, breakdown occurs at the Broadway connection, where the causes may be better understood: the congestion resulting from the second breakdown is clearly observed by the seven detector stations shown in Figure 24c. This Figure shows that the congestion starts at the most downstream stations, as the PM 419.237 and PM 418.827 station first show a higher occupancy. A jump is observed during the 12:10-12:15 time-period. Although a decrease in speed is noted just before that in the video-animation, the breakdown in this period is displayed in 24c.

At the Broadway connection, only the detectors on the on-fly US101N on-ramp

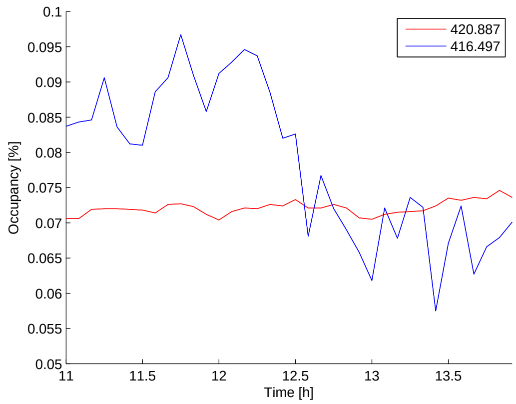
Table 10: The fifteen considered detector stations on mainline US101N. The Abs PM correspond to the locations of first off-ramps upstream and downstream of SFO.

Detector station number	Abs PM
1	420.887
2	420.767
3	420.307
4	420.117
5	419.717
6	419.407
7	419.237
8	418.827
9	418.607
10	418.187
11	417.847
12	417.437
13	417.117
14	416.857
15	416.497

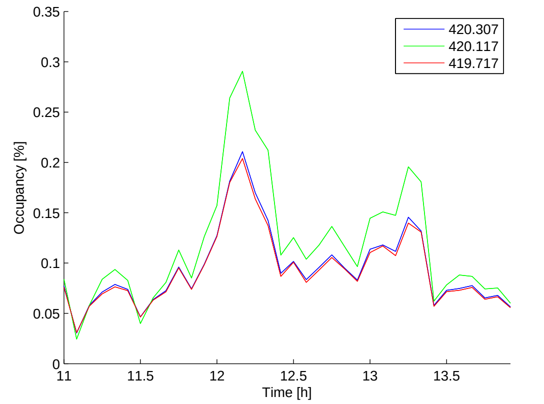
are working. Figure 24d shows the flow and occupancy over time on this on-ramp. A large, single-period peak in the flow is observed. This peak occurs within the same time-period as the breakdown, between 12:10-12:15. The increase in on-flow at Broadway thus coincides with the breakdown in the same location. It is the most likely cause of the breakdown. Although congestion may not have been purely caused by this increase in demand, it is at least one of the most contributing factors.

One probable explanation is that the congestion corresponds to 'extra' emergency vehicles dispatched to assist with the Asiana crash. From the Asiana crash investigation report, a transcript states that : "By 11:33,(...) all seven airport firefighting companies and paramedics were on scene. (...) One minute later, 56 ground ambulances arrived on scene. (...) At 13:01, the last patient was transported by ambulance." [68]. Additionally, a helicopter and two buses also helped transport patients to 12 area hospitals.

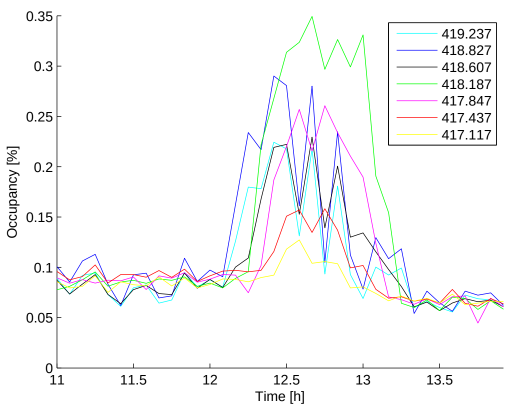
The ASIANA crash affected the ground traffic conditions. Although there were multiple breakdowns, we can only state that the congestion on the US101N near



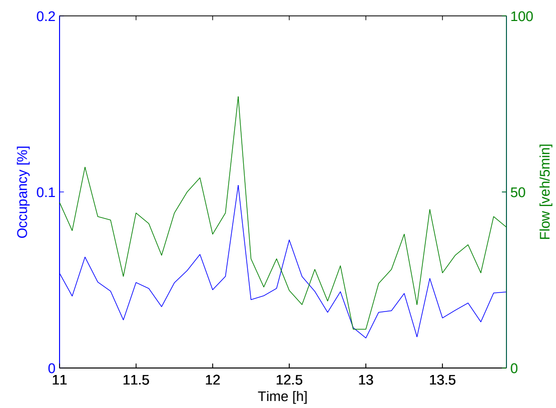
(a) Occupancy over time for the first (downstream) and fifteenth (upstream) considered stations



(b) Occupancy over time for the first breakdown



(c) Occupancy over time for the second breakdown



(d) Occupancy and flow over time on the Broadway on-ramp to the US101N.

Figure 24: Occupancy on US101 highlighting the two breakdowns after the crash.

SFO was a direct consequence of the crash. The (visible) smoke, the disturbance due to emergency vehicles and the ramp closures are the most likely causes. However, further details about the coupling between the airside and the highway system remains difficult to quantify.

Figure 25: BART network.

3.3.2 Ground Transportation : Public Transit with the BART

The BART, or Bay Area Rapid Transit, is one key element of the transit transport in the San Francisco Bay. It links SFO to OAK as well as SJC via the Caltrain connection, see Figure 25. Its importance for multimodality in the Bay Area was argued by Monteiro and Hansen [71]. The BART data obtained provides the origin-destination matrix of passengers for 15 minutes periods on Saturday, June 29th and Saturday, July 6th.

The comparison between June 29th and July 6th for departing and arriving passengers at the SFO BART station, displayed in Figure 26 shows that the total number of passengers using this transit station was smaller on the crash day, with up to 100 fewer passengers at peak hours. Because the airport was closed for part of the day and many flights were cancelled, we can hypothesize that simply fewer passengers used this transit station.

Next, passenger traffic at the OAK BART station is studied. The results are displayed in Figure 27 for passenger traffic between SFO and OAK, between OAK airport and SFO airport. In both directions between the two airports, there is a significant increase of passengers soon after the crash. Between SFO to OAK, there is very little traffic on both Saturday, June 29th and Saturday, July 6th, with fewer than 10 passengers per hour. On the crash day, between 2 pm and 3 pm, up to 160 passengers choose to travel from SFO to OAK. The reason behind this is still unclear : these passengers could be trying to reach air travellers diverted to OAK airport, or airline employees could be suddenly needed to accommodate the incoming air traffic at the airport. The Oakland to San Francisco passenger traffic is also an outlier on the crash day, but the number of additional passengers is not as high. One hypothesis is that it might be due to passengers diverted to OAK who had to go back to SFO for subsequent travel. Both abnormal patterns persist throughout the day.

3.3.3 The Asiana Crash and Social Media

The social network Twitter constitutes another network coupled with the infrastructure network. To provide a more complete analysis of the propagation of the information generated by the crash would constitute another research project and buying data from Twitter or other data analysis companies. This subsection aims at highlighting another dimension of disturbance propagation on infrastructure networks: the communication network that includes phone communications, any information available on the internet, e-mails exchanges, social media relays etc. Indeed, infrastructure networks constitute cyber-physical systems and the communication channels are critical in disruptive situations. From a network science perspective, social media has been widely studied over the past few years. Such research aims at understanding how information propagates, via "infection" mechanisms, revealing that the vast majority of users passively access information but very few actually relay it [97] [81].

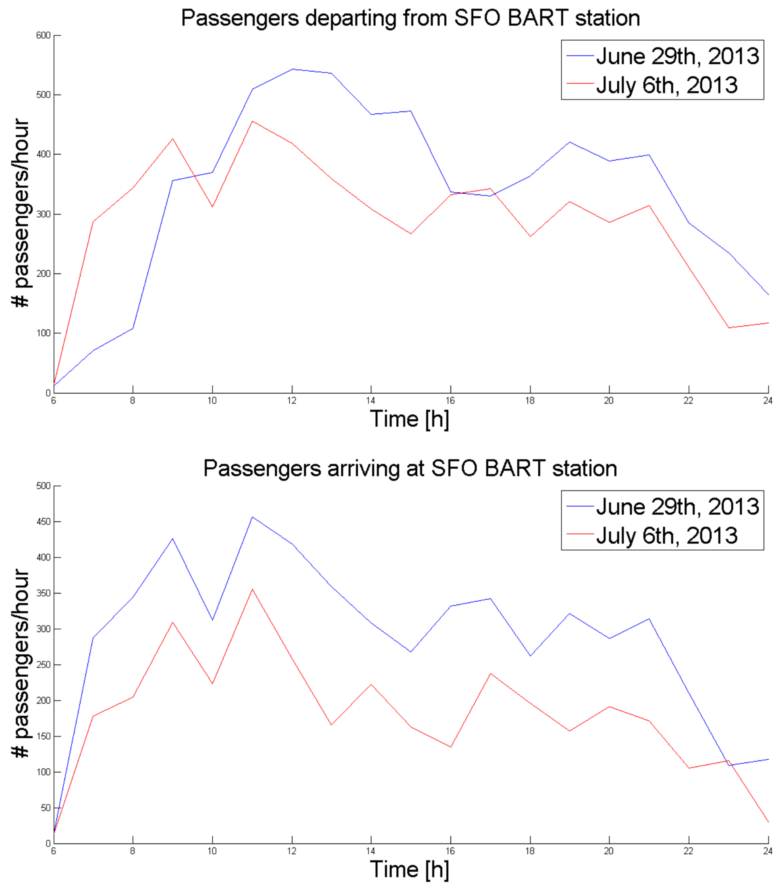


Figure 26: Departing and arriving passengers at SFO via BART.

Authorities, airlines and airports often use it as a fast means of conveying time-sensitive information. It provides passengers an access to real-time information from other passengers when stakeholders might be dealing with disruptive situations and delaying the provision of information to passengers. Twitter activity records can be accessed with an R interface for instance, but only up to 9 days back or 1500 tweets, which is not far back enough for this paper, whose analysis started in November 2013. Several websites provide different tools to access older data, but the amount of accessible data is limited and each website only provides a variety of aggregated information. However, a short analysis of several hashtags and account names, and their corresponding tweet frequency provides information about the timing of information provision, the reactivity of several stakeholders and the spreading of information on

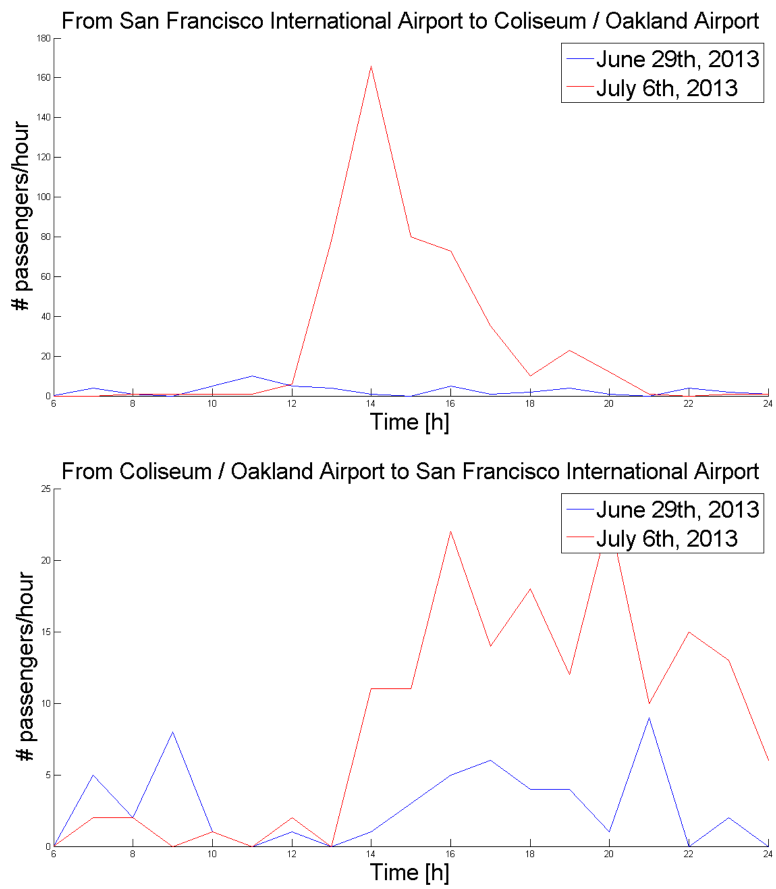


Figure 27: Number of passengers on July 6th on between San Francisco and Oakland airports.

Figure 28: CHP tweet to avoid US101 and use I280.

the communication network.

When it comes to timing, tweets provide a means to access the following specific information. Such information was otherwise very unlikely to resurface with usual internet searches because the large news coverage flooded the internet with similar summaries of events but little precision on the timing of events. Regarding the response of emergency vehicles, the San Francisco Fire Department spokeswoman stated that: "Within 18 minutes of receiving word of the crash, five ambulances and more than a dozen other rescue vehicles were at the scene or en route, in addition to airport fire crews and crews from San Mateo County and other agencies already on the scene" [76]. Because of the congestion growth on the highway, the California Highway Patrol, at 12:39, was advising road users to avoid I-280 which was congested, as seen in Figure 28. San Francisco airport informed passengers at 9:13 pm on the crash day that the restaurants in the airport would exceptionally remain open to accommodate passengers whose flights were disrupted or canceled and who were staying overnight in the airport.

To highlight how unusual the Twitter activity became in the Bay area, the frequency of tweets of several accounts or with specific hashtags is examined. The official Twitter account of San Francisco Airport, @FlySFO, twitted more during July 2013 than on any other month in 2012 and 2013, see Figure 29. Moreover, zooming in on July 2013, there is a peak of tweets, replies and retweets on the crash day and the following week.

The crash was such a widely covered event by the media, that a twitter account was opened by a journalist on the day following the crash, @SFOcrash. This account tweeted only July 2013, May and June 2014, as seen in Figure 30. Zooming in on July 2013, the plot only starts on July 7th, and shows that the account tweets correspond mostly to the week following the crash. While the number of tweets shows that the crash constitutes an outlier in the behavior of certain accounts, it does not provide an estimate of the impact of these tweets. The number of retweets gives some idea of information spread on the social network, yet it does not indicate how many users accessed or read that information and how it was used. According to tweetreach.com,

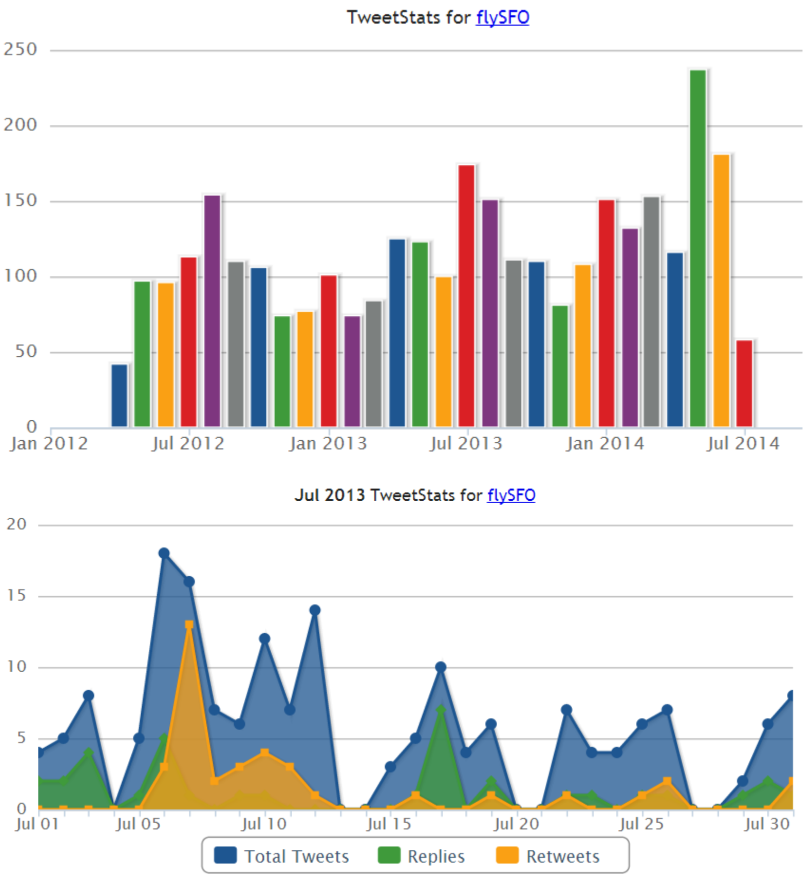


Figure 29: Tweet frequency of the official San Francisco Airport account @FlySFO for the past two years, and for July 2013. (www.tweetstat.com)

@FlySFO has an estimated reach of 106,388 people.

Twitter proved particularly useful to access information on diversions and their management depending on the airports the diverted flights landed at. It also provides a passenger-centric view of the disruption, which is rarely taken into account while analyzing the air transportation performance under disruptive situations. Most stakeholders only have access to a partial view of the disruptive situation and, in most cases, for only one mode of transport. Following the Asiana crash, if the main stakeholders had had access to real-time data feeds of reliable traffic data via collaborative decision making, it is likely that the recovery process could have been improved. Social Media provides pieces of information suggesting that the treatment of passengers varied greatly, depending on which airport they were diverted to, which airline they

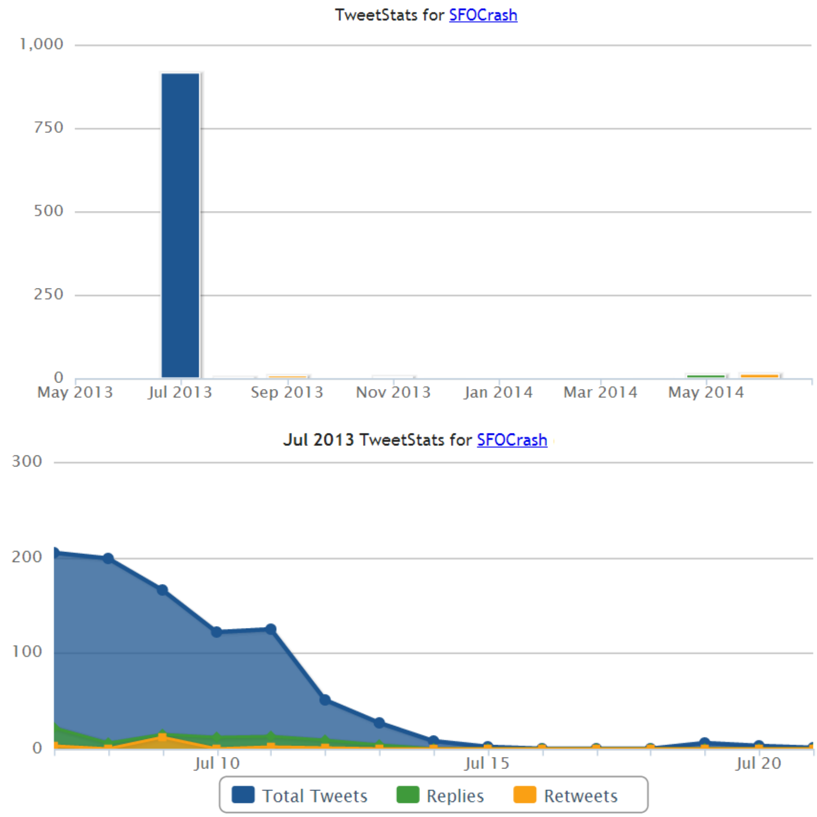


Figure 30: Tweet frequency of the official San Francisco Airport account @FlySFO for the past two years, and for July 2013. (www.tweetstat.com)

were traveling with, and whether they were domestic or international passengers.

9,770 domestic passengers were diverted the 6th of July, 4,260 on the 7th and approximately 1,470 on the 8th and 9th of July. Only 21% of these passengers could reach their final destination SFO with the same flight. The news showed how the disruption left most of the diverted passengers unattended and uninformed, waiting for the airline representatives to figure out how to reaccomodate them urgently. Twitter quickly started to be the most updated channel of information for passengers.

As seen previously, most of the flights were diverted to either SJC, OAK, or to the closests hubs to SFO (SEA, LAX, PHX). Most problems arose when flights were diverted to airports in which they do not operate. In the case of a United Airlines flight from Seattle, diverted to Oakland, Willit News [40] interviewed passengers on July 6th, 2013 : "We were dumped here," the man said, "United has no support here. They sent a dislocation team, but basically what they keep saying is: "You're dislocated." " The officials said they had to bring extra staff to accommodate all those passengers that were landing at the same time.

Many passengers were diverted to airports where their airline operates at low frequency. For instance, at the Virgin America counter of Seattle Tacoma International Airport on the 6th of July, Seattle Times [61] describes how customer-service representative Jody Devereaux collected travelers' names and phone numbers so the airline could rebook or cancel flights without the people standing line. "Just to cause them less stress," Devereaux said. She advised travelers that the quickest option to get home would be to rebook through another carrier and obtain a refund, as "the soonest flights on Virgin America will be Monday or Tuesday". Although being notified that waiting times could reach the two days, passengers argued they had no extra money to purchase new flights and be refunded later.

CBS news reports [7] how in Sacramento, located less than 100 miles from SFO, people waited for hours uninformed, queueing around help desks waiting for airline representatives to inform about the rerouting options. CBS News interviewed passengers who said : "We were not even aware of what had happened until someone on the flight was able to turn on the cell phone.", "Our carrier had no information whatsoever. Basically we were booted off the plane and with no direction whatsoever." Such witness accounts support the fact that airlines had no systematic rerouting scheme for such disruptive situation.

ABC Eyewitness News [6] focuses on the situation in LAX, explaining that, as Asiana Crash happened on a Saturday of a holiday week-end, planes were fully booked, and thus the rerouting of passengers was impossible. "Sunday's flights between LAX and SFO are heavily booked due to the combination of holiday weekend and peak summer travel. It is expected the airlines will need one or two days to catch up on the backlog of canceled flights.", adding also that "The route between LAX and

SFO is very busy, served by seven airlines including American, Delta, United, United Express, Virgin, US Airways and Southwest. But Saturday night's cancellations are making a big disruption for travelers on this holiday weekend. Some travelers will spend the night in L.A." Even for the LAX-SFO route, served by seven airlines, quick reaccomodation of passengers was unlikely, and therefore passengers may have to wait for two days to board a new flight.

The few pieces of information that airlines delivered, added to the highly booked situation of the holiday week-end, created additional disruptions in the diverted airports. At that point, a few number of airlines decided to implement first inter-modal operational measures, placing buses and taxis to reroute their passengers. However this solution was implemented in a non-collaborative, case-to-case fashion and resulted in wide discrepancies in the treatment of passengers affected by the same situation.

Figure 31: Tweets reporting inter-modal rerouting.

For instance, ABC Eyewitness News reported some inter-modal rerouting measures that some airlines took for LAX diverted passengers. Quoting from [6] , "Airlines that canceled flights between LAX and SFO are making arrangements for passengers, including rebooking flights, adding special flights if aircraft are available, busing passengers to SFO, putting up passengers in airport-area hotels and asking passengers to return to LAX on Sunday." Additionally, they explained how although the inter-modal rerouting saved passengers from spending the night in the diverted airports, many of them were disappointed for the disorganized and discentralized way in which they were assigned to the modes.

For instance, during the 6th of July Salt Lake City International Airport (SLC) absorbed most of the international flights, instead of San Jose or Oakland. SLC was the closest airport with an international custom able to process this international flights diverted, as OAK and SJC had no such facilities ready. Some international flights could not be diverted to international hubs such as Seattle or Phoenix, due to low fuel reserves for instance. Therefore, some of them were forced to land in Sacramento, which is not equipped in terms of customs, see Figure 32, forcing the custom officers to move to the aircraft to proceed with the security checks. Other customs issues were also reported in Oakland, see Figure 33.

Figure 32: Tweet reporting customs issues in Sacramento.

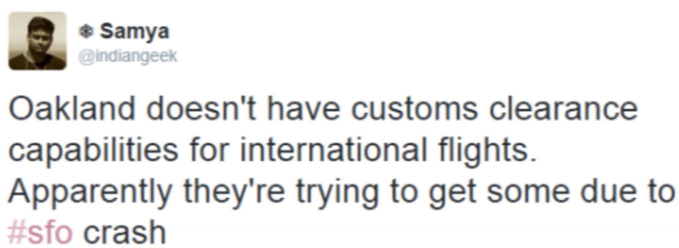


Figure 33: Tweet reporting customs issues in Oakland.

Therefore, after analysing how airlines started to implement first insights of inter-modalism in the rerouting of diverted passengers, the scope of the research was narrowed to try to develop a cost-effective model that may serve as first start for a decision-making support tool to determine the inter-modal rerouting passengers. The work presented in this master thesis explains the state of the art in inter-modal operations in the airline industry, analyses the operational isues of inter-modal rerouting, and offers two mathematical models to optimise the cost of reroutings in a passenger-centric way. The first model is an airport-pairs optimisation model, and has been implemented on a real set of data corresonding to the Asiana Crash period of study. The second optimisation model expands the first model to a whole network level, and its implementation has not been performed, reason why will be proposed as possible further research in this topic.

The LAX Airport Operations Center stated on July 6th, "Three international flights that diverted to LAX and deplaned their passengers have all left LAX and busing their passengers to SFO. Airlines that cancelled flights between LAX and SFO are making arrangements for their passengers, including: re-booking passengers on future flights, adding special flights if aircraft are available, busing passengers to SFO, putting up passengers in airport-area hotels, asking passengers to return to LAX tomorrow, etc. Tomorrows (Sundays) flights between LAX and SFO are heavily booked due to the combination of holiday weekend and peak summer travel, so it is expected the airlines will require one to two days to catch up on the backlog of cancelled flights " [7]. "Transportation to San Francisco for passengers diverted to Sacramento depends on the airline. Delta Airlines arranged taxi and shuttle services for passengers to get to San Francisco after their planes were forced to land in Sacramento. US Airways passengers were loaded on to shuttle buses at SMF to be taken to San Francisco. (...) United Airlines did not have a definitive plan in place to help passengers who were diverted to SMF. SMF has a Customs area at the airport, but has limited space " [4]. "Additional staff was brought in to help accommodate the more than 1,000 passengers that were diverted to Sacramento International Airport after the plane crash in San Francisco. Officials say they had to bring in extra staff to accommodate all those passengers that were landing at the same time. It was a mad rush as staff scrambled to get everyone to where they needed to go" [3]. Many more issues arose when flights were diverted to airports in which their carrier does not operate. For instance, a SFO-bound United Airlines flight from Seattle was diverted to Oakland. Local news reporters [40] interviewed passengers, who reported that

"United has no support here. They sent a dislocation team, but basically what they keep saying is: "You're dislocated." " The officials said they had to bring extra staff to accommodate passengers who were landing at the same time. Moreover, many passengers were diverted to airports where their airline operates at low frequency.

Regarding how airports handled flight diversions, the following statement was released by San Jose airport [1] : " SJC handled 25 flight diversions including two international flights while SFO was closed to all operations. Airport Operations staff handled the majority of duties directly associated with the diversions - the complex logistics of locating arriving aircraft at the terminal or at remote locations, and closing taxiways to allow for aircraft parking (...) Thirteen of the diverted flights were accommodated at the terminals; the remaining eight deplaned at the North Cargo Area where more than 500 passengers were bused from the airfield to the terminal. (...) In addition to Airport staff, many airport contractors assisted with the additional traffic Saturday including First Alarm, Shuttleport and Taxi San Jose (which saw a 100 percent increase in business). The Airport's federal partners, such as the FAA and Customs and Border Patrol also provided valuable support (who held over to clear passengers from the diverted international flights). (...) The airlines serving SFO continued with "planned" diversions throughout Sunday (15 flights) and Monday (5 flights). The advance notice makes the planned diversions much easier to handle from an operational perspective and provides better service to airline customers."

Much information has been extracted from Tweets that would have otherwise been very unlikely to resurface with usual internet searches, because the large news coverage added to the internet with similar summaries of events contain little event timing resolution.

3.3.4 Network Coupling

Transportation networks are intrinsically tied or coupled. In the present study, we consider the air, road and rail transit networks, plus the internet through Twitter's information envelope and contents. It must be noted that these networks exhibit interdependencies with other networks, such as the power and communication networks for instance. Networks are usually studied separately. To the best of the authors' knowledge, this paper constitutes the first study of interdependencies between transportation networks.

When studied individually, networks may appear to have a fairly robust structure towards random failures. However, when their coupling with other networks is taken into account, their sensitivity is higher than when studied independently. Figure 34, taken from [82], shows an example of such snowball effect on interdependent networks : the initial failure on the green network leads to the failure of another green node. Because these green nodes are themselves coupled with blue nodes, blue nodes begin to fail, triggering cascading failures on the blue network. Because the structure of each network is different and the dynamics on each do not have the same temporal and spatial characteristics, the propagation on each is studied separately.

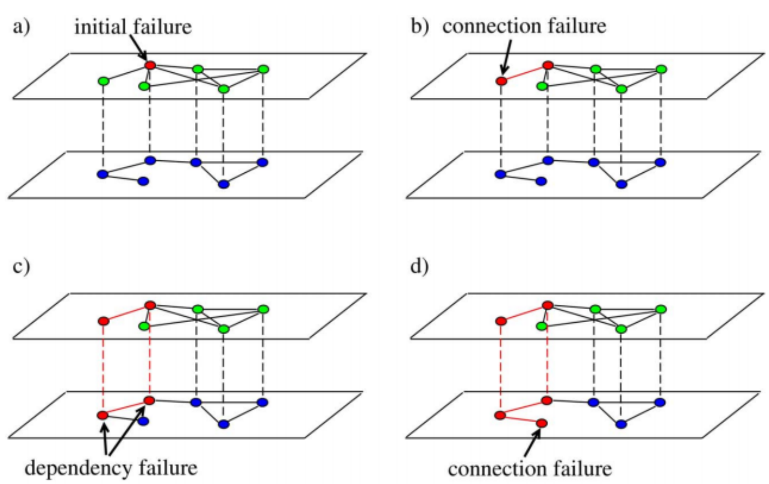


Figure 34: Propagation of Disturbances in Coupled Networks.

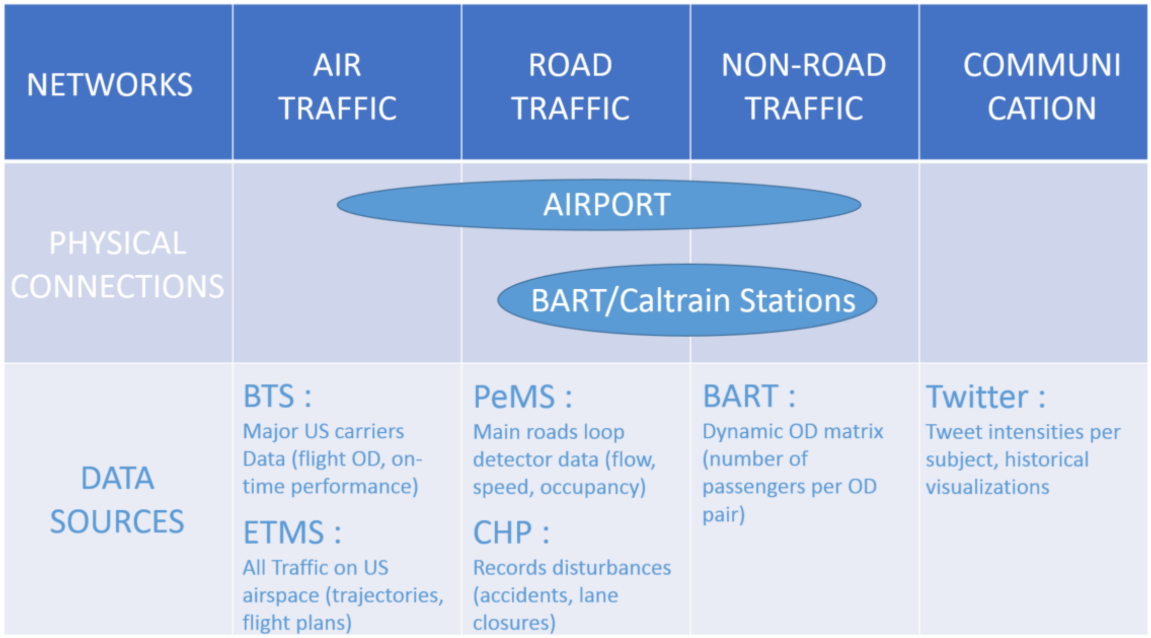


Figure 35: Data sources available for each network studied.

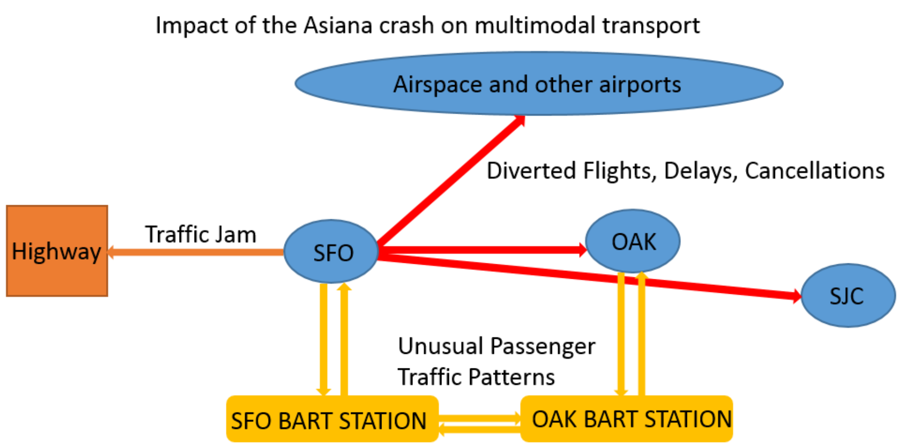


Figure 36: Flow chart of most significant repercussions of July 6, 2014 on the multimodal network.

A timeline summarizing the impact of the Asiana crash on the different transportation modes is provided in Figure 37, highlighting the varying time scales for each mode.

The Asiana crash is a powerful example of node failure leading to ripple effects on several networks. An airport is a node for the air transportation network, the road network because of easy highway access and the transit network, with a BART

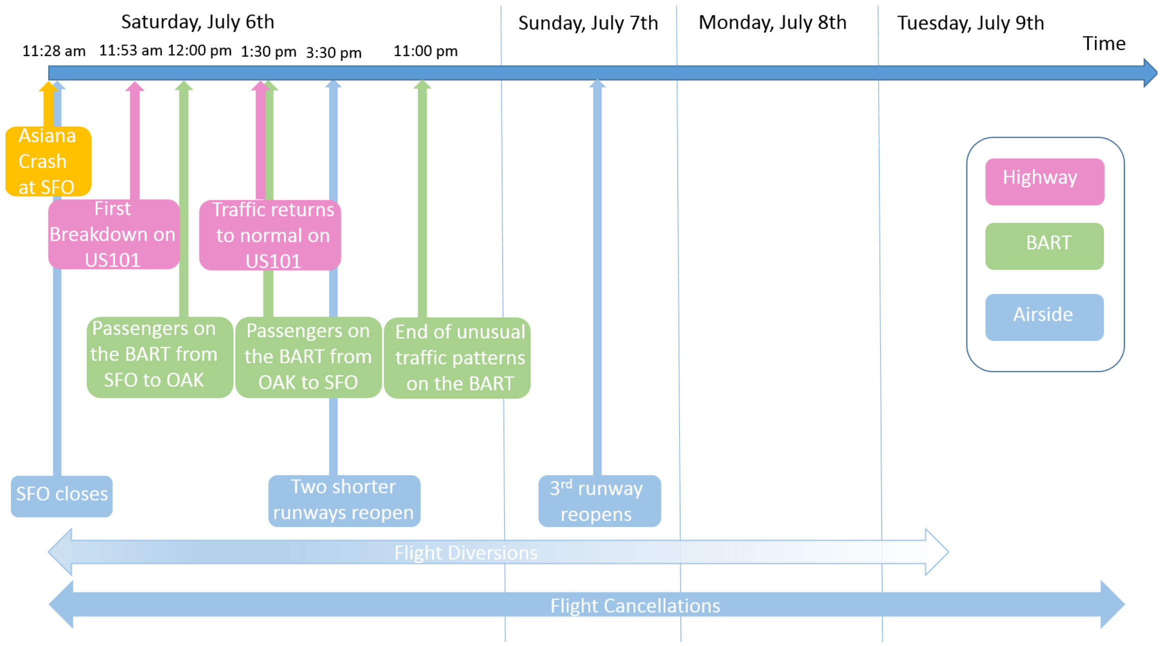


Figure 37: Timeline of events following the Asiana crash.

station in the Bay Area. Figure 35 provides an overview of the data sources that supported the analysis. Figure 36 provides a summary of the impact of the crash on the multimodal transportation network. When it comes to interdependencies between transportation networks, the data analysis shows its existence but the underlying mechanism and its properties remain to be studied. Passengers constitute, of course, the transfer flows at the multimodal nodes between networks. A combination of data analytics and queuing models may provide more insight on such coupling mechanisms.

3.4 Conclusion

This chapter examined the repercussions of the Asiana crash on the multimodal transportation network. Cancellations, diversions and delays lasted more than four days and impacted the entire airspace. Highway traffic near SFO was perturbed for more than an hour. Passenger traffic on the BART exhibited unusual patterns during the whole crash day. The next chapter provides insight on how multimodal CDM could have mitigated the ripple effects of the crash, both for passengers and for flights.

CHAPTER 4

Analysis of Opportunities to improve Disruption Management for Passengers and Aircraft after the Asiana Crash

This chapter tackles mitigation strategies following the Asiana Crash, both for passengers and for flights. First, flight diversions are introduced, from an airline and an Air Traffic Management perspective. Flight diversions are rare events, but they are harder to recover from than cancellations for instance. The Asiana crash was a striking examples of massive flight diversions because of an unexpected airport closure. Second, a passenger-centric optimization is proposed to reaccommodate, via bus or aircraft, passengers diverted to airports within reasonable drive distance of San Francisco. Third, a flight-centric optimization model examines how remaining capacity at Bay Area airports may have played a role in diversions of SFO-bound flights to far away airports.

4.1 Diversions

At the Flight Diversion Forum in 2011 [17], the FAA official J. Babbitt explained that "Thunderstorms are responsible for the majority of aircraft diversions each year. (..) Diversion flights are a rare occurrence. But when this does happen, we need to make the information available to help airlines, controllers and airport operators decide the optimal airport for a diversion."

Airline policy Most airlines indicated on their websites how diversions are handled and what the consequences may be for passengers. Even when passengers have a non-refundable ticket, airlines usually are supposed to refund ancillary fees. Delta Airlines stipulates in its contract that "in the event of flight cancellation, diversion, delays of greater than 90 minutes, or delays that will cause a passenger to miss connections, Delta will (at passengers request) cancel the remaining ticket and refund the unused portion of the ticket."

US Airways indicates on its website that "When a flight is diverted to an alternate airport and cancelled, the pilots or flight attendants will advise the customers of the reason for the diversion. The customers may need to remain onboard. In accordance with the US Airways Contingency Plan for Lengthy Tarmac Delays, US Airways may provide a limited beverage service. In the cases when the customers must deplane, all carry-on baggage and personal property must be removed from the cabin. (..) Some irregular operations may require landing at alternate airports, with bus service to the final destination. It is acceptable to allow a customer to leave directly from an alternate airport without requiring him/her to travel to the final destination. (..) When a flight (aircraft) is diverted to a city served by US Airways or codeshare partner, and canceled, the customer service representatives in that city will reaccommodate customers on either the next available US Airways flight or the next available flight via another carrier.(..) When a flight (aircraft) is diverted and then canceled in a city not served by US Airways or a codeshare partner, the customer service manager in US Airways' Operations Control Center will make arrangements with other carriers and/or hotel accommodations. Once the flight attendants receive word from the flight deck, they will communicate to the customers the reason for the diversion (if they are permitted to disclose), estimated time of departure and/or accommodations. If the flight is canceled, subject to availability, passengers will be reaccommodated via another airline. The flight attendants and flight crew will be the US Airways representatives for the customers. (..) When alternate transportation is unavailable until the following day and overnight accommodations are required, the flight attendants and flight crew will communicate to the passengers which expenses US Airways will pay. The following is a list of what US Airways will pay for providing the cancellation is due to anything other than weather:

- Hotel room (US Airways will not cover room service, alcohol or movies)
- Ground transportation (if not provided by the hotel)
- Passengers without baggage will be reimbursed upon presentation of receipts for reasonable incidentals such as toiletries needed until they are reunited with their baggage."

American Airlines states on its website that : "In extreme circumstances, it is possible that a flight will cancel while on the ground in the city to which it was diverted. When this happens, we will attempt to reroute you on the next American Airlines or American Eagle flight with available seats, or in some circumstances on another airline or some other alternative means of transportation. If we are unable to reroute you, reasonable overnight accommodations will be provided by American Airlines or American Eagle, subject to availability."

The FAA diversion recovery plan provides details on the chain of command in such events: " A diversion is a flight that is required to land at other than its original destination for reasons beyond the control of the pilot/company, e.g., periods of significant weather. Diversion recovery is an initiative orchestrated by the ATCSCC (Air Traffic Control System Command Center) and system users to minimize the impact of system disruption. Diversion recovery will be utilized during and after periods of significant weather or other phenomena that has adversely impacted the system resulting in flight diversions. The goal of the diversion recovery initiative is to ensure that flights which have already been penalized by having to divert to another airport, do not receive additional penalties or delays. Flights identified for diversion recovery must receive priority handling over other flights from their point of departure.

Diversion flights are identified by having "DVRSN" in the Remarks section of the flight plan, or the user inputs the information into the Diversion Recovery Tool (DRT).

The ATCSCC must:

- Implement diversion recovery.
- Transmit an advisory to inform both field facilities and users that a diversion recovery initiative has been implemented and the DRT has been activated.
- Adjust the initiative as necessary to meet changing conditions.
- Transmit an advisory when the DRT has been deactivated.

The ARTCCs (Air Route Traffic Control Center) must:

- Implement diversion recovery as directed by the ATCSCC.
- Notify the ATCSCC if they do not intend to use the DRT. In such cases, the ATCSCC must send the Center a general message with the information, every 60 minutes until diversion recovery is no longer in effect.

- Provide expeditious handling in returning to the system those flights identified by the ATCSCC/DRT as diversion flights.

- Forward user diversion recovery requests to towers and TRACONs.

Towers and TRACONs must:

- Provide expeditious handling in returning to the system those flights identified by the ARTCC/DRT as diversion flights.

- Notify the overlying ARTCC TMU if they will utilize the DRT."

IATA diversions management A representative of IATA summarized the criteria for selecting airports where diverted flights land [58]. The diversion decision criteria are as follows: Safety of Flight, Airspace or Airport Restrictions , Overflight authorization, Landing authorization, Immigration, Customs, Airport Services, Crew considerations, Service recovery options, Schedule recovery options. More precisely, the Safety of Flight includes choosing the emergency airport (nearest available and nearest suitable), evaluating the fuel remaining and getting the alternate approved. The primary objectives are to safely land and support the aircraft. The diversion airport is selected based on the following criteria:

- Approved Alternate

- Weather at diversion airport

- Airport services company, maintenance, fuel

- Aircraft servicing - tow bar, air stairs, main deck loader, ground power, air conditioning, parking

- Passenger handling facilities, Customs and Immigration, food, accommodations

- Other scheduled service

It should be best prepared to handle the aircraft, service the customer, return the flight to original destination. The crew aspects are also taken into account, such as on-duty times, the legal to finish limitations, the accommodations, the replacement crew availability and the crew pairing disruptions. Regarding service recovery, passenger disruption is examined regarding the delay to final destination, the 3 hour tarmac rules and the Customs and Immigration requirements, onward connections, company re-schedule options, and re-booking schedule options.

Cost of Diversions Jenkins et al. [57] describe disruptions as follows : "Diversions are an expensive, chronic, and disruptive element of flight operations, costing at least $300MM annually for US carriers for domestic flights alone. (..) A diversion is not a single, discrete event but rather a set of cascading actions that cause severe disruptions to airline schedules, major costs, and significant passenger frustration and ill will. Diversion costs can range from $15,000 for a narrow-body domestic flight, to over $100,000 for a wide-body international flight."

4.2 Passenger Multimodal Rerouting from airports where the diverted flights landed

This section studies how multimodal rerouting of passengers could have helped in the recovery process.

Hansen and Zhang [98] conducted a research on charter companies response to service inter-modal service requests. To get a general idea about how promptly charter companies could respond to service requests, they also conducted a telephone survey for ten randomly picked charter companies for six regions in the US: San Francisco, Los Angeles, New York, Chicago, Miami and Texas. All of the regions are supposed to have a charter companies offer comparable, if not bigger in some cases, to San

Francisco. They constructed a scenario motivating an urgent request for a motor coach service at an airport, and asked for a motor coach that could accommodate at least 30 passengers and their personal belongings and be available for at least 6 hours. Their results are shown in Figure 38.

	San Francisco SFO	Los Angeles LAX	New York JFK	Chicago ORD	Miami MIA	Texas DFW
Not available	3	2	3	5	4	4
1-1,5 hours	2	3	4	2	3	2
3 - 4 hours	4	5	3	3	3	4
Total	9	10	10	10	10	10

Figure 38: Intermodal Service Times reported by Hansen and Zhang

The airports from which a complete inter-modal substitution is feasible are :

- Sacramento International Airport (SMF), 100 miles from SFO;
- Reno Tahoe International Airport (RNO), 230 miles from SFO;
- Los Angeles International Airport (LAX), 390 miles from SFO;
- McCarran International Airport (LAS),565 miles from SFO.

The Department of Transportation proposes an approach to measure the hourly values of travel time for aviation passengers. These values are used by the Federal Aviation Administration (FAA), and are not to be updated for changes in price levels.

4.2.1 Model Formulation

4.2.1.1 Nomenclature used in the model

Input sets Let us define the input sets as follows:

- $\mathcal{A} = a_1, a_2, ..., a_4$ be the set of diverted airports (RNO, SMF, LAS, LAX),
- $\mathcal{F} = f_1, f_2, ..., f_n$ be the set of departure flights from the diverted airports to the Bay Area (SFO, OAK, SJC),

- $\Gamma = t_1, t_2, ..., t_T$ the set of discrete time periods,
- $\mathcal{P} = p_1, p_2, ..., p_P$ the set of diverted passengers,
- $A = g_1, g_2, ..., g_{MaxAircraft}$ the set of aircraft available for charter in the diverted airport,
- $B = b_1, b_2, ..., a_{MaxBuses}$ the set of available buses for inter-modal substitution in the diverted airport.

Input time and delay variables:

- ADT_f^a : Actual departure time of flight f from diverted airport a
- $ADivAT_p^a$: Actual arrival time of passenger p at the diverted airport a.
- BDT_{OAK}, BDT_{SJC}, BDT_a : Bus driving time from OAK to SFO, from SJC to SFO and from the diverted airport a to SFO.
- $FlightTime_a$: Flight time from diverted airport a to SFO.

Input capacity variables:

- $Seats_f^a$ is the number of seats left on maintained flight f
- $CapAircraft_g$ is the passenger capacity of chartered flight g
- $CapBus$ is the passenger capacity of any bus

Input cost coefficients:

- $CostCharter$: Cost of chartering a new aircraft [\$ / $hour \cdot passenger$].
- $CostBV$: Cost of bus reaccommodation [\$ / $passenger$].
- $CostP$: Passenger delay cost per time unit [\$ / $hour \cdot passenger$].

Other input coefficients:

- $Beta_{Wait}$: Weight coefficient for passenger waiting time.
- $Beta_{Transp}$: Weight coefficient for passenger reaccommodation time.
- $MinloadBus$: Minimum passenger load (percentage) to allow a bus to depart.
- $MinloadCharter$: Minimum passenger load (percentage) to allow an aircraft to depart.
- $TimeFactor$: Conversion factor used to convert time periods into minutes. 15 minutes time intervals are chosen.
- $MaxBuses_a$: Maximum number of buses available at diverted airport a.
- $MaxAircraft_a$: Maximum number of aircraft available to be chartered at diverted airport a.

Input binary variables: $OAK_f^a = 1$ if the destination of departure flight f from diverted airport a is OAK, $OAK_f^a = 0$ otherwise. $SJC_f^a = 1$ if the destination of departure flight f from diverted airport a is SJC, $SJC_f^a = 0$ otherwise.

Output binary variables:

The first type of output binary variables are $Squeeze_{p,f,a}^t$, $Subst_{p,b,a}^t$ and $Charter_{p,g,a}^t$. These three variables assign passengers to one of the three possible rerouting options: $Squeeze_{p,f,a}^t = 1$ if passenger p is squeezed into flight f departing from diverted airport a in time interval t; $Subst_{p,b,a}^t = 1$ if passenger p is rerouted with motor coach b from diverted airport a in time interval t; $Charter_{p,g,a}^t = 1$ if passenger p is rerouted with chartered flight g from diverted airport a in time interval t.

The second type of output binary variables are $DTBus_{b,a}^t$ and $DTCharter_{g,a}^t$, indicating when a bus or an chartered aircraft leaves diverted airport a. $DTBus_{b,a}^t = 1$ if bus b departs in time period t; $DTCharter_{g,a}^t = 1$ if chartered aircraft g departs in time period t.

4.2.1.2 Model Input Data

The input data for the mathematical programming is the following:

- Set of diverted passengers to the airport of study.
- Set of departure flights $\mathcal{F}$ from the diverted airport to SFO, OAK or SJC.
- Number of passengers booked and capacity of each flight f.
- Scheduled and actual departure and arrival times of each flight f.
- Bus driving times between the diverted airport and SFO.

Airlines' operations are difficult to optimize as a whole due to the interaction of many factors and feasibility constraints of different resources. Four main constraints affect the feasibility of airline planning and disruption management : aircraft maintenance checks, pilot work rules, fleet assignment and passenger accommodation. Therefore, the following assumptions are made to ensure an admissible problem complexity : connecting passengers will connect to their final destination from the Bay Area; there are only a limited number of aircraft available to be chartered; when the rerouting is done through the alternative airports in the Bay Area, only 80% of the passengers will be rerouted to SFO; the model does not take into account aircraft maintenance checks and pilot work rules, nor that pilots and crew are eligible to continue their scheduled tasks for 135 maximum hours of service; it is assumed there is enough capacity for the chartered flights to land in the Bay Area.

4.2.1.3 Objective function

The objective of the mathematical model is to minimize the cost of reaccommodation of diverted passengers. The input data is the actual schedule on July 6th, 2013 (e.g. what flights were diverted, which flights were cancelled and which ones could reach SFO), and the model computes the cost-effective rerouting back to SFO. The reaccommodation takes into account the following costs: passengers delay cost while remaining at the diverted airport, the cost of squeezing passengers into remaining seats on flights to the Bay Area, the cost of chartering an aircraft to ferry back diverted passengers, the cost of transporting passengers with motor-coaches, either from the diverted airport, or just within the Bay Area. At the end of the chosen time horizon, no diverted passengers must remain in the diverted airport. The optimization minimizes the value of the following objective function:

$$\sum_t [\ CSqueeze^t + CSubst^t + CCharter^t] \tag{5}$$

Cost of squeezing passengers into departure flights

$$\begin{aligned} CSqueeze^t \ &= \sum_a \sum_p \sum_f \ Squeeze^t_{(p,f,a)} \ [(ADT^a_f - ADivAT^a_p)\ CostP\ \beta_{wait} \\ &\quad + CostBV\ (SJC^a_f + OAK^a_f) + FlightTime_a \beta_{transp}\ CostP \\ &\quad + (BDT_{OAK} \cdot OAK^a_f + BDT_{SJC} \cdot SJC^a_f)\beta_{transp}\ CostP] \end{aligned} \tag{6}$$

The first term computes the passengers waiting time before being reaccommodated, translated to economic terms with the passenger value of time ($CostP$) and weighted with the variable $BetaWait$. The second term adds the operational costs of using motor-coaches, in case a passenger is reaccommodated with remaining seats on flights to Bay Area airports. The third term evaluates the economic value of the ground transportation times, weighted by the variable $BetaTransp$.

Cost of reaccommodation via ground transportation substitution

$$\begin{aligned} CSubst^t \ &= \sum_a \sum_p \sum_b \ Subst^t_{(p,b,a)}\ [\ (t \cdot TimeFactor - ADivAT^a_p)\ CostP\ \beta_{wait} \\ &\quad +\ (\ BDT_a \beta_{wait} CostP\ )\ +\ CostBV\ ] \end{aligned} \tag{7}$$

The first term of the equation computes the cost of passengers waiting time. The time of arrival to the diverted airport $DivAT_p$ is substracted from the departure time of the motor coach. The second term computes the cost of passenger transportation time, by multiplying the bus driving time BDT_{Div} by the passenger value of time $CostP$, weighted by $Beta_{transp}$. The third term computes the cost per passenger of contracting the motor coach service $CostBV$.

Cost of chartering an aircraft

$$\begin{aligned} CCharter^t \ = \ & \sum_a \sum_p \sum_g \ Charter^t_{(p,g,a)} \ [\ (t \cdot TimeFactor - ADivAT^a_p) CostP \ \beta_{wait} \\ & + \ (\ FlightTime_a \ \beta_{transp} \ CostP \ ) \ + \ CostCharter \ ] \end{aligned} \tag{8}$$

The first term computes the cost of passengers waiting time. The time of arrival to the diverted airport $DivAT_p$ is substracted from the departure time of aircraft a. The second term computes the cost of passenger transportation time, by multiplying the flight transportation time $FlightTime_{DivAirp}$ by the passenger value of time $CostP$, weighted by $Beta_{transp}$. The third term computes the cost per passenger of chartering an aircraft $CostCharter$. Additionally, it has been assumed in this particular rerouting option there is a limited amount of aircraft available to charter.

4.2.1.4 Constraints

Constraints of squeezing passengers into scheduled flights The number of passengers squeezed into flight f in time period $t+1$, should be less or equal to the number of remaining seats:

$$\sum_t \sum_p Squeeze^t_{(p,f,a)} \ \leq Seats^a_f \quad \forall f, \forall a \tag{9}$$

A passenger at diverted airport a can not be squeezed into flight f, if the flight has already departed:

$$(t \ \cdot TimeFactor - \ ADT^a_f \ ) \ \times Squeeze^t_{(p,f,a)} \ \leq 0 \qquad \forall t, \forall f, \forall a, \forall p \tag{10}$$

Constraints of the complete inter-modal substitution option The number of diverted passengers in airport a assigned to each motor coach must be less or equal to the motor-coach capacity, at every time slot:

$$\sum_p Subst^t_{(p,b,a)} \leq CapBus \; \forall b, \forall a, \; \forall t \tag{11}$$

The bus b and the passengers leaving with this bus leave at the same time:

$$DTBus^t_{b,a} \geq Subst^t_{(p,b,a)} \; \forall p, \; \forall b, \; \forall a, \; \forall t \tag{12}$$

The motor coach b contracted for inter-modal substitution can only depart if it is filled up to a minimum bus load.

$$\begin{aligned} If \; DTBus^t_{b,a} \geq 1, \\ then \; \sum_p Subst^t_{(p,b,a)} \geq MinloadBus \cdot CapBus \; \forall p, \; \forall b, \; \forall a, \; \forall t \end{aligned} \tag{13}$$

The motor coach b can only depart once from airport a:

$$\sum_t DTBus^t_{b,a} \; \leq \; 1 \qquad \forall b, \forall a, \; \forall t \tag{14}$$

Constraints corresponding to chartering a new aircraft to fly to one of the Bay Area airports

The number of passengers assigned to a new chartered aircraft g must be less than the aircraft remaining capacity, at every time slot:

$$\sum_p Charter^t_{(p,g,a)} \leq CapAircraft_g \forall g, \forall a, \; \forall t \tag{15}$$

The chartered aircraft g and the passengers leaving with this aircraft leave at the same time:

$$DTCharter^t_{g,a} \geq Charter^t_{(p,g,a)} \; \forall p, \; \forall g, \; \forall a, \; \forall t \tag{16}$$

A chartered aircraft g can only depart if it is filled up to a minimum aircraft load.

$$\begin{aligned} If \;\; DTCharter^t_{g,a} \geq 1, \\ then \; \sum_p Charter^t_{(p,g,a)} \geq MinloadAc \cdot CapAc \; \forall p, \; \forall g, \; \forall a, \; \forall t \end{aligned} \tag{17}$$

This conditional constraint is transformed into a pair of linear constraints with auxiliary variables.

A chartered aircraft g can only depart once:

$$\sum_t DTCharter^t_{g,a} \ \leq \ 1 \qquad \forall g, \forall a \tag{18}$$

Passenger conservation constraints

Each passenger must be assigned to one of three rerouting options during the time horizon considered.

$$\sum_t \left[\sum_f Squeeze^t_{(p,f,a)} + \sum_b Subst^t_{(p,b,a)} + \sum_g Charter^t_{(p,g,a)} \right] \ = 1 \qquad \forall p, \forall a \tag{19}$$

Passengers can only be assigned to a rerouting option 30 minutes after landing in the diverted airport:

$$\forall a, \forall p, \forall t, \forall f, \forall b, \forall g$$

$$[t \cdot TimeFactor - (30 + ActualDivAT_{p,a})](Squeezed^t_{(p,f,a)} + Subst^t_{(p,b,a)} + Charter^t_{(p,g,a)}) \ \geq 0 \tag{20}$$

4.2.2 Optimization Results

4.2.2.1 Baseline for study - reaccommodation of passengers under a unimodal scenario (flying only)

The best case real-life scenario for most diverted passengers is to be rebooked on flights to the Bay Area (SFO, OAK, SJC) that were not cancelled, on July 6th (crash day) and the following days, regardless of their original carrier. From passenger tweets, we do know that some airlines provided shuttles to the Bay Area in a few diverted airports, but most of them did not. Moreover, if we consider that a passenger can only be reaccommodated on later flights operated by his or her original carrier, passengers who landed in airports where the carrier does not operate would not have been rebooked. Figure 39 shows how long it would have taken for all passengers to be rebooked depending on the airport they were diverted to :

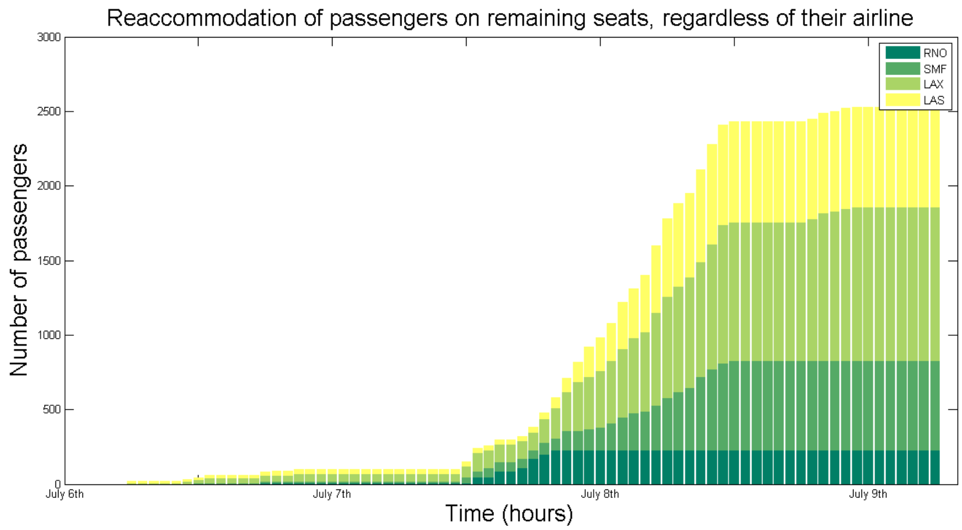


Figure 39: Reaccommodation of diverted passengers on remaining seats in flights that reached the Bay Area, regardless of their original carrier.

- RNO welcomed about 230 passengers, who would have been rebooked by Monday morning, July 8th,
- SMF welcomed about 600 passengers, who would have been rebooked by Monday evening , July 8th,
- LAX welcomed about 1030 passengers, who would have been rebooked by Tuesday morning, July 9th,
- LAS welcomed about 670 passengers, who would have been rebooked by Tuesday morning, July 9th.

Moreover, less than 300 passengers would have reached the Bay Area before Monday, July 8th at noon, that is more than 48 hours after the crash. This means most passengers' expenses probably included two hotel nights, and two full days of meals. This cost incurred is not included in the optimization model proposed, but adds to the benefits of multimodal rerouting.

4.2.2.2 Study of different scenarios involving various numbers of aircraft available for chartering

The input coefficients are set to the following values :

- $Beta_{Wait} = 0.5$
- $Beta_{Transp} = 1 - Beta_{Wait}$
- $MinloadBus = 0.75$
- $MinloadCharter = 0.9$

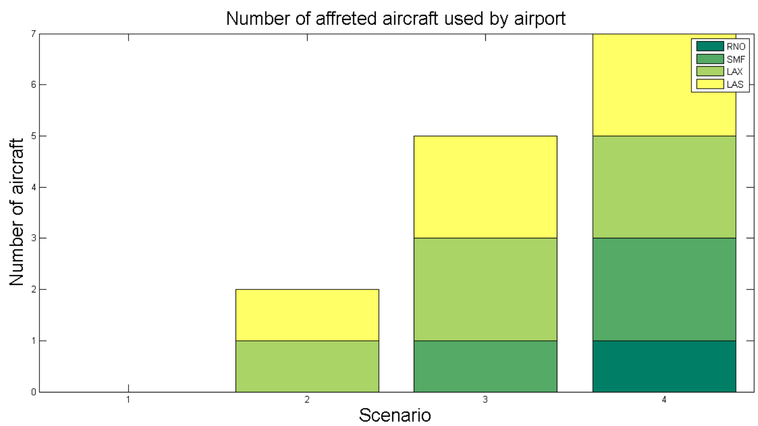


Figure 40: Number of chartered aircraft available and used in each scenario.

To understand the role of available multimodal substitution, four scenarios are studied. In each of them, the number of buses available in each airport remains the same, to ensure that all diverted passengers can be rerouted by bus. However, the number of aircraft available for chartering varies from zero aircraft in scenario 1, to one aircraft in RNO, two in SMF, two in LAX and 2 in LAS. The details for each scenario are shown in Figure 40. The maximum number of chartered aircraft was chosen small, because first, capacity at OAK and SJC would have been limited, even in the evening of the crash, and second, few aircraft might have been available at the diverted airports, except the diverted aircraft themselves.

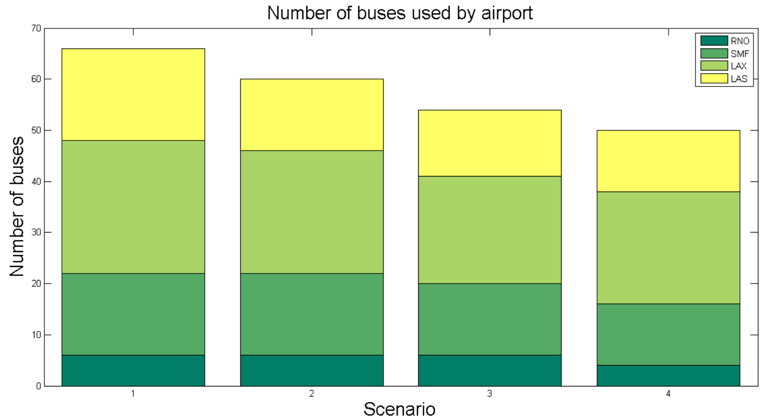


Figure 41: Number of buses used in each scenario.

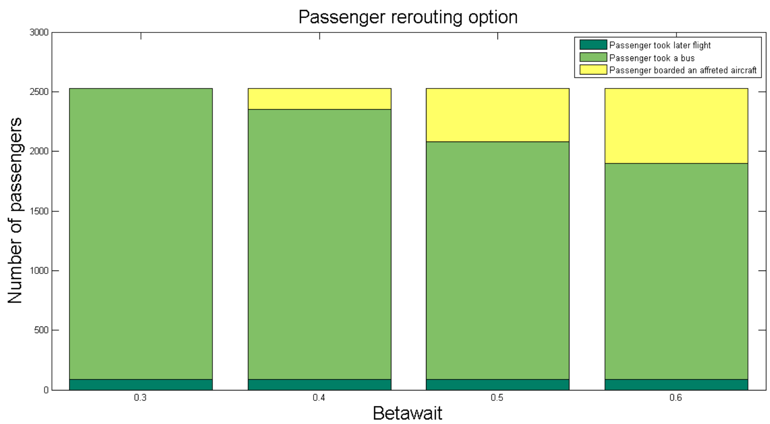


Figure 42: Rerouting assignment of passengers in each scenario.

Solving the optimization problem described above for the four scenarios described, the results show different trends. First, Figure 41 indicates the number of buses used to reroute passengers to the Bay Area. As the number of aircraft available for chartering increases, the number of buses used decreases. Even though chartering an aircraft is more costly than using a bus, the fact that aircraft have a larger passenger capacity and that flying provides a much shorter travel time make flying the most cost-effective option overall. This is confirmed by examining the rerouting option provided to each passenger in Figure 42, showing that chartering a total of five aircraft in scenario 4 largely changes the proportion of passengers accommodated on new flights.

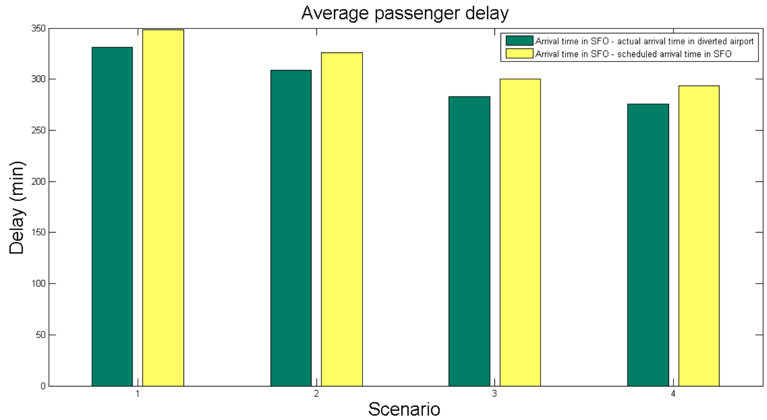


Figure 43: Average passenger delay in each scenario.

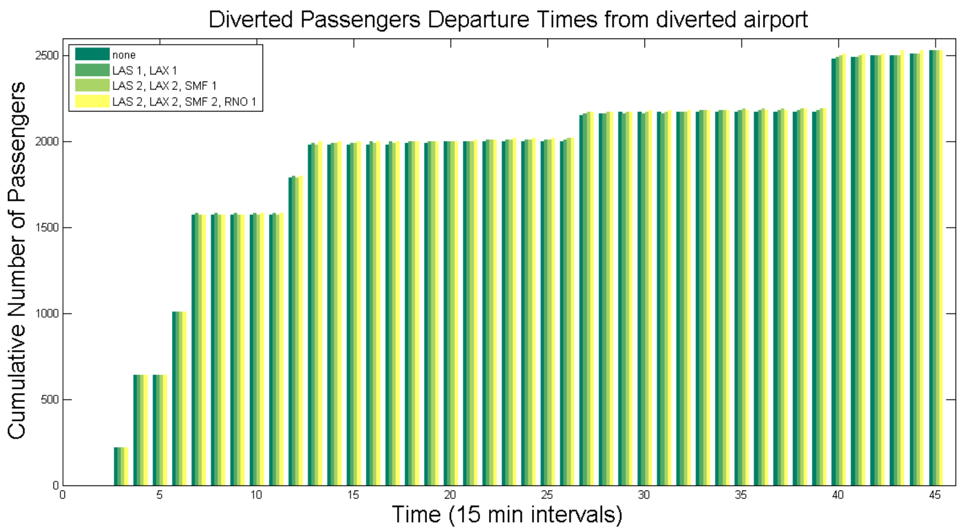


Figure 44: Cumulative Number of Passengers by departure time from the diverted airport, for each scenario.

The goal of this multimodal optimization problem is to ensure that passengers reach the Bay Area faster than they would have if they had waited to fill remaining seats on later flights operated out of the diverted airports to the Bay Area. Figure 43 presents the average passenger delay, that is either the average difference between the arrival time of a passenger in SFO and his/her scheduled arrival time in SFO or the average difference between the arrival time of a passenger in SFO and his/her actual arrival time in the diverted airport. The average passenger delay is less than six hours, which is small considering the bus travel time from the diverted airports

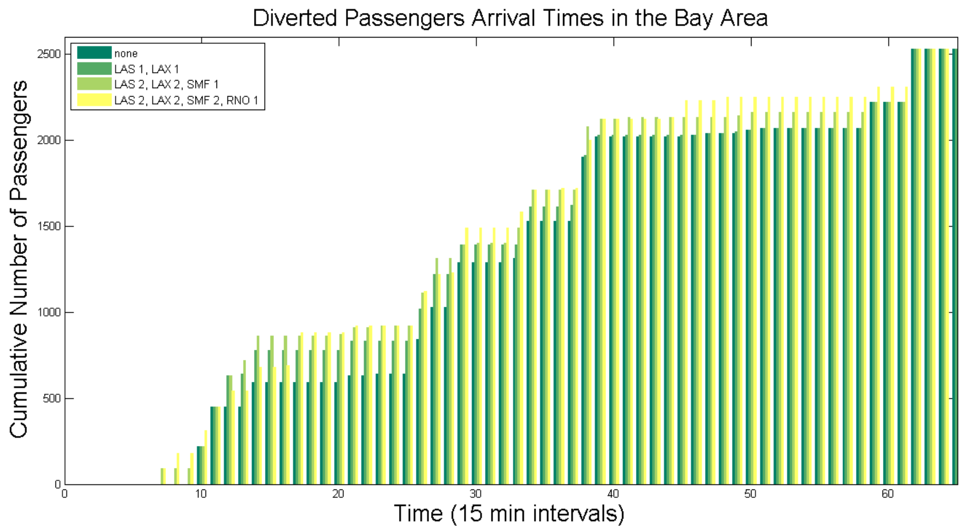


Figure 45: Cumulative Number of Passengers by arrival time in the Bay Area, for each scenario.

further away from SFO. It also highlights that chartering aircraft reduces the average delay suffered by about an hour. Figures 44 and 45 show that, across all scenarios, the differences in passenger departure times is very small. Moreover all passengers have left the diverted airports before midnight. However, the more chartered aircraft available, the earlier passengers arrive in the Bay Area on average. It should be noted that, because of bus travel time, some passengers reach the Bay Area at about 2 am on Sunday. For these small portion of passengers, a bus departure early the next day might be preferable and should be considered in future work.

4.2.2.3 Sensitivity analysis on β_{wait}

We want to understand the weighting in the objective function depending on whether we attach more importance to the delay suffered by passengers or the cost incurred by reaccommodating them on aircraft or buses. Therefore scenario 4 from the previous example, with one chartered aircraft available in RNO, two in SMF, two in LAX and 2 in LAS, is tested for $\beta_{wait} = 0.3$, $\beta_{wait} = 0.4$, $\beta_{wait} = 0.5$, $\beta_{wait} = 0.6$, $\beta_{wait} = 0.7$.

First, Figure 46 shows that the objective value decreases as β_{wait} increases. This

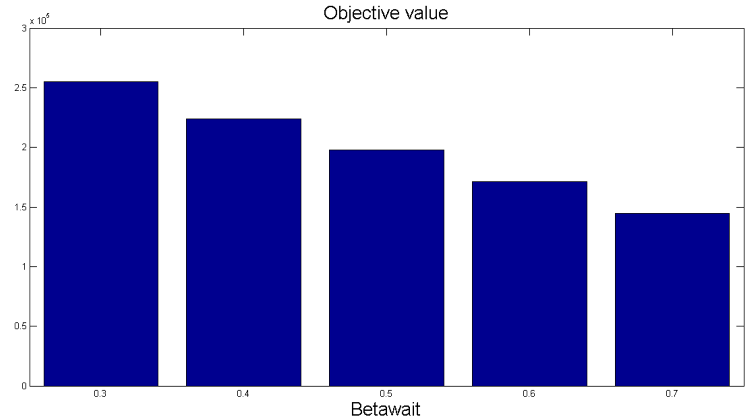


Figure 46: Objective value for each value of β_{wait}.

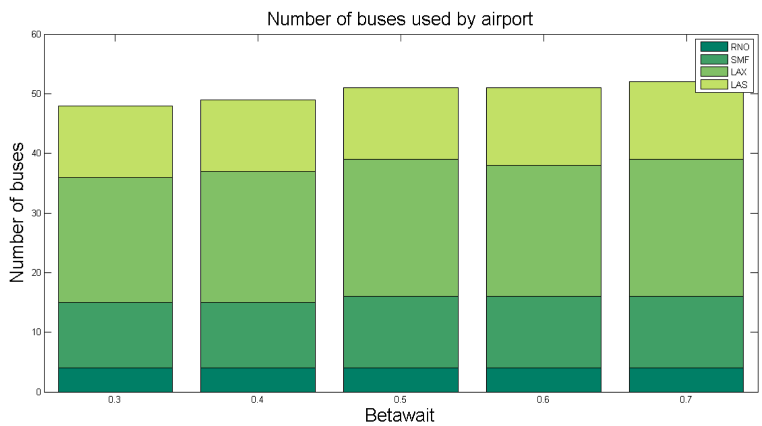


Figure 47: Number of buses used for each value of β_{wait}.

is intuitive since the optimization model forces all passengers to be rerouted. Second, in Figure 47, the number of buses used by airport increases with β_{wait}, while the number of chartered aircraft used remains constant and the number of passengers reaccommodated on buses remains the same. This means that the load in each bus decreases, the optimization is no longer trying to fill buses to their maximum capacity but only to fill them to their minimum capacity before letting them depart. Finally, Figure 48 indicates that the influence of β_{wait} on passenger delay is limited.

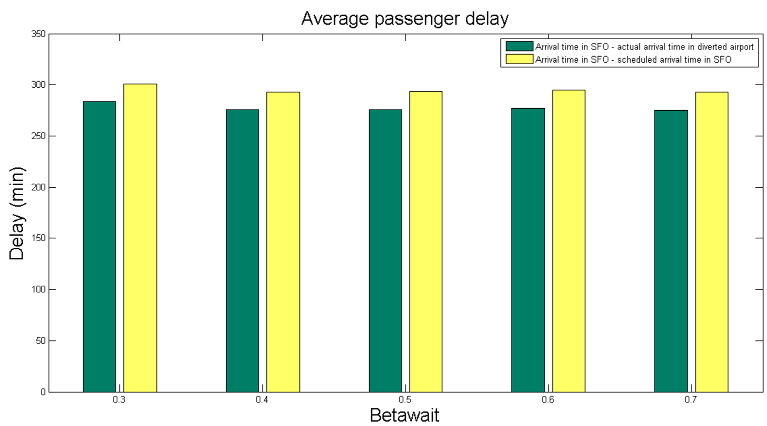


Figure 48: Average Passenger Delay for each value of β_{wait}.

4.3 Metroplex Flight Assignment

In the previous section, we studied how to better reaccommodate diverted passengers. However, instead of better reaccommodating passengers diverted to far away airports, we wonder if it could have been possible to land more diverted flights in the Bay Area, under metroplex operations, with real-time shared information between all stakeholders and collaborative decision making. In a metroplex environment, neighboring airports could dynamically act as reliever airports to SFO. Therefore, we first examine the situation, the remaining capacities at OAK and SJC, the domestic and international diverted flights, and then propose a reoptimization scheme.

Trajectories of diverted flights arriving in the Bay Area in the hours following the crash are displayed in Figure 50, and show the unusual number of holding patterns and reroutings in the air, so that the flights can land at SJC or OAK.

4.3.1 Inputs

Consider the time period from 11:30 am (local time at SFO) to 4:30 pm. The horizon is broken down into 15-minutes time bins, denoted by t in $\mathbf{T}$. Let each diverted flight f be in the set $\mathbf{F}$. Let the two other main airports in the Bay Area, OAK and SJC, be denoted by a in $\mathbf{A}$.

For each flight $f \in \mathbf{F}$, its scheduled arrival time at SFO is denoted by $arrSFO_f$, where $arrSFO_f = t$ corresponds to time bin t. The flight estimated arrival time (ETA) to the potential arrival airports at the time of the crash is denoted $timetoapt_{f,a}$, corresponding to the arrival time bin. Assume that all flights stay $gate\_time$ time bins at their gate, where $gate\_time$ enforces constraints on the minimum turnaround time and the maximum time at the gate allowed by the airports.

Each flight en-route is assumed to arrive to SFO at the ETA of the TZ table in the ETMS data, at the latest location message before the crash, to avoid taking into account any change of destination airport and by consequent an irrelevant ETA to SFO. This ETA is not available for flight that took off after the crash (it is unclear if the ETA in the data is for an arrival at SFO or elsewhere), in this case the ETA to SFO is determined using the earliest TZ data available, corresponding to the first point after take-off. The result is similar to the scheduled arrival time plus any actual departure delay. From the ETA to SFO, an approximation of $timetoapt_{f,a}$ can be obtained. The particularity of a metroplex is to have several airport close to each other. For the bay area SFO, OAK, SJC are close enough to have an approach path extremely restricted to avoid any hazard due to the neighboring airports traffic. The incoming flux fix for OAK and SFO are only few miles apart and therefore the ETA to OAK would be less than 5 minutes apart from the ETA for SFO. Knowing the precision of the ETA used for this study is 15 minutes, the two ETA can be estimated equal. While for SJC the incoming flux fix is about 30 miles south of the SFO incoming fixes. The estimated time to go from one fix to the other is about 10 to 15 minutes. Therefore depending of the origin of the flight, its ETA would be its ETA to SFO with an additional 15 minutes if the flight is arriving from the North, or with 15 minutes less when arriving from the South, or its original ETA when arriving from the East or West.

For each metroplex airport, SJC and OAK, the remaining runway capacity at each time bin is computed, while taking into account the actual (not the scheduled) arrival and departures (including international flights from ETMS), except the diversions from SFO on that day. The corresponding variable is $rwycapa_{a,t}$. Moreover, the remaining gate capacity at each time bin is calculated by taking into account actual arrival and departures (including international flights), and referred to as $gatecapa_{a,t}$. For domestic flights, the BTS data provides the gate arrival time. For international flights, the gate arrival time is extrapolated from the runway arrival time.

4.3.2 Problem Objective

The objective is to minimize the arrival delay of the diverted flights in the Bay Area. The goal is, under disruption, to land aircraft safely as close as possible to their original destination, that is SFO. The model optimizes the arrival times of each diverted flight and provides the following information. For each flight f, its runway arrival time is denoted by $arr_{f,t,a}$, its gate occupancy time is indicated by $gateocc_{f,t,a}$. The objective function can be formulated as follows:

$$\sum_{f\in\mathbf{F}}\sum_{t\in\mathbf{T}}\sum_{a\in\mathbf{A}} t\cdot arr_{f,t,a} - \sum_{f\in\mathbf{F}} arrSFO_f \tag{21}$$

4.3.3 Constraints

Flight Constraints The landing time at the actual arrival airport is bounded above and below. A flight f cannot land at the arrival airport before it has at least flown there. A flight usually only has a 45 minutes fuel reserve, therefore $reservetime = 2$ time bins, so it has to land before this time elapses.

$$\forall f, \sum_{a\in\mathbf{A}} \sum_{t_e=timetoapt_{f,a}}^{timetoapt_{f,a}+reservetime} arr_{f,t_e,a} = 1 \tag{22}$$

A flight can only land once and at one airport:

$$\forall f \in \mathbf{F}, \sum_{a\in\mathbf{A}}\sum_{t\in\mathbf{T}} arr_{f,t,a} = 1 \tag{23}$$

A flight cannot arrive a gate earlier than 15 minutes after landing and not later than 45 min.

$$\begin{gathered}\forall f \in \mathbf{F}, \forall a \in \mathbf{A}, \forall t \in \mathbf{T},\ if\ arr_{f,t,a} = 1 \\ Then\ \forall t_e \in [t+2, t+gate\_time], gateocc_{f,t_e,a} = 1 \\ and\ gateocc_{f,t+1,a} + gateocc_{f,t+gate\_time+1,a} = 1\end{gathered} \tag{24}$$

A flight remains $gate\_time$ bins time at one gate in one airport.

$$\forall f \in \mathbf{F}, \sum_{a\in\mathbf{A}}\sum_{t\in\mathbf{T}} gateocc_{f,t,a} = gate\_time \tag{25}$$

Airport Constraints The number of landing flights must be below the remaining runway capacity:

$$\forall t \in \mathbf{T}, \forall a \in \mathbf{A}, \sum_{f \in \mathbf{F}} arr_{f,t,a} \leq rwycapa_{a,t} \tag{26}$$

The number of flights parked at the gate must be less than the remaining gate capacity:

$$\forall t \in \mathbf{T}, \forall a \in \mathbf{A}, \sum_{f \in \mathbf{F}} gateocc_{f,t,a} \leq gatecapa_{a,t} \tag{27}$$

4.3.4 Results

Each one of the 90 diverted flights initially scheduled to land at SFO between 11:30 am and 4:30 pm could have landed in the Bay area, if there had been enough information sharing regarding the remaining capacities at SJC and OAK. Even in the worse case scenario where each flight occupies its gate for two hours, OAK and SJC could accommodate the incoming traffic, while keeping airborne flight delay relatively low and within safety limits.

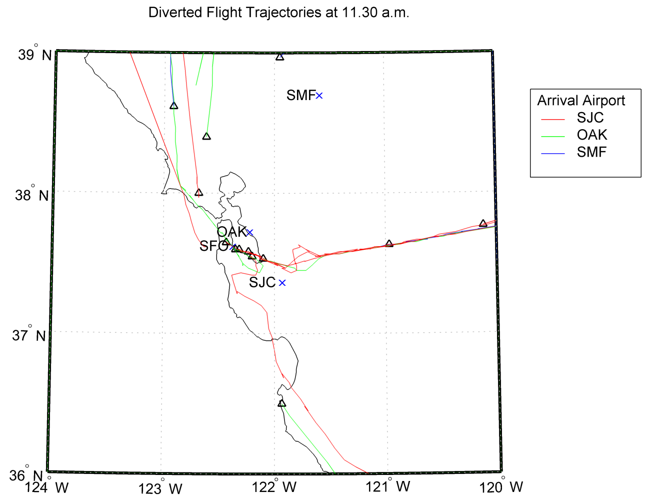
Gate occupancy time (minutes)	60	90	120
Diverted flight delay (minutes)	9.3	10.3	15

Table 11: Resulting delay per flight for each optimization scenario.

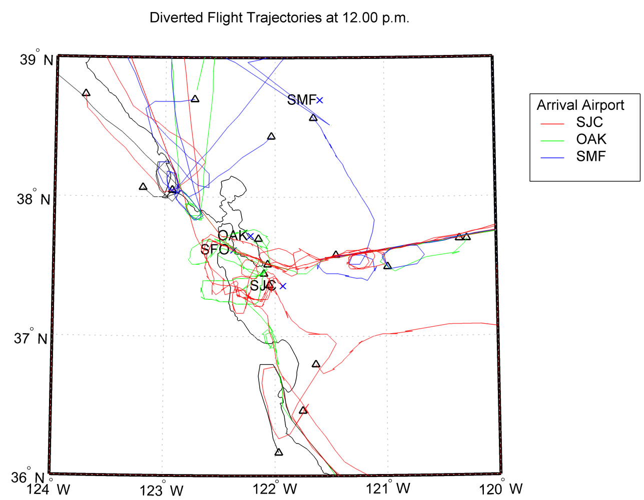
Figure 52 shows the runway capacity is stressed right after the crash, between 11:30 am and 11:45 am. However, even at its peak, the runway occupancy remains below 90% of capacity. The second peak is visible for the scenario with 120 minutes of gate time, and shows a short saturation of gate occupancy at both SJC and OAK, which leads to a temporary and manageable increase in airborne holding. The gate occupancy level reaches its limit for two scenarios and for the last scenario, the peak occupancy reached is 90%. However, the point here is that most diversions, if not all, with some uncertainty margin, could have landed in the Bay Area.

The repartition of diverted flights at SJC and OAK is similar, and balance each other, as illustrated in Figure 53. The larger the gate time enforced, the more balanced the repartition is. A noticeable fact is that no flights lands between 12:30 pm and 12:45 pm because all gates are full in the next time interval. Since the limit in gate occupancy lasts more than 30 minutes in the second and third scenarios, the taxi-in time margins are not enough to mitigate the peak, and therefore airborne holding time is used to delay aircraft. However, as shown in Figure 55, the airborne holding times are below 15 minutes and well below safety limits and reserve times. Because of the objective function that minimizes arrival delay, the aircraft land as soon as possible, favoring taxi-in delay over airborne holding. Figure 55 illustrates when the taxi-in modulations are not sufficient. The larger the gate occupancy, the more airborne holding time is allocated, but it remains low. Also it should be noted that a few flights arrive a few minutes earlier at OAK or SJC than their scheduled time at SFO, but this comes from the fact that their flight time slightly diminishes, for the flights coming from the East for instance.

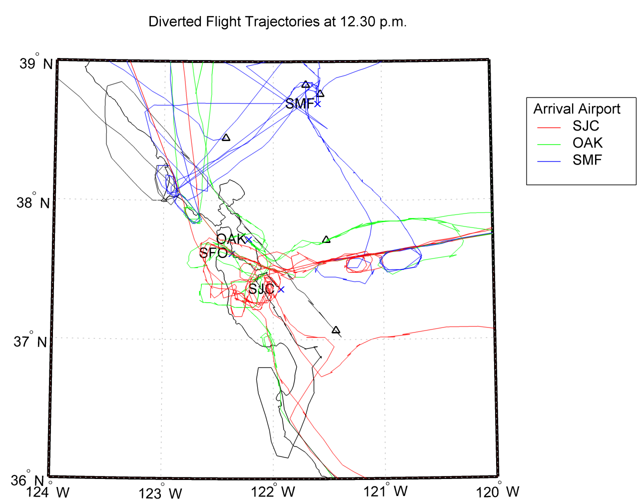
Overall, the optimization performed demonstrates that, assuming better information sharing throughout the system between airports, carriers, regarding estimated arrival times and remaining capacities, most diverted flights could have landed in the Bay Area, even with uncertainty present. However, it is understandable that safety was a priority and that grounding flights wherever possible when the situation was unclear was the best solution. With future concepts of operations, it is expected that disruption management will be handled better and avoid the diversions of thousands of passengers to far-away airports, causing many issues related to reaccommodation, customs, carrier support to name a few.



(a)



(b)



(c)

Figure 49: Trajectories of diverted flights in the Bay Area following the Asiana crash at SFO from 11:30 to 12:30.

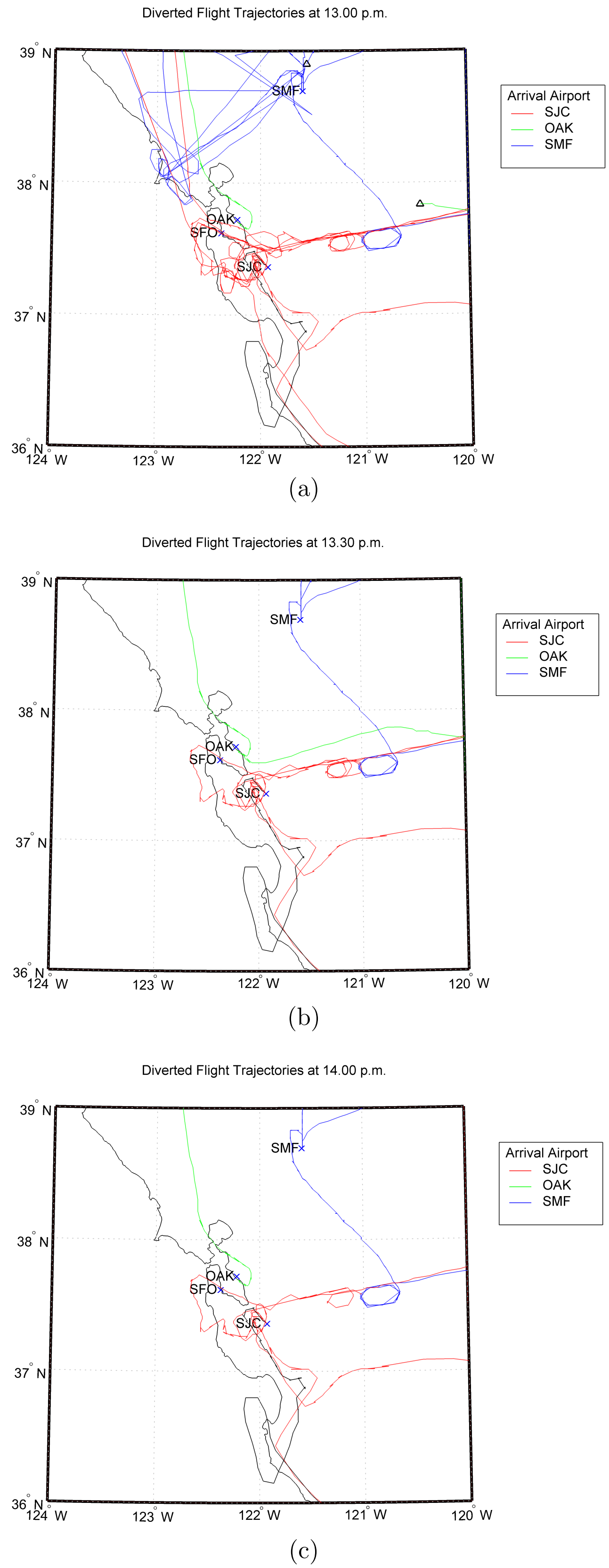
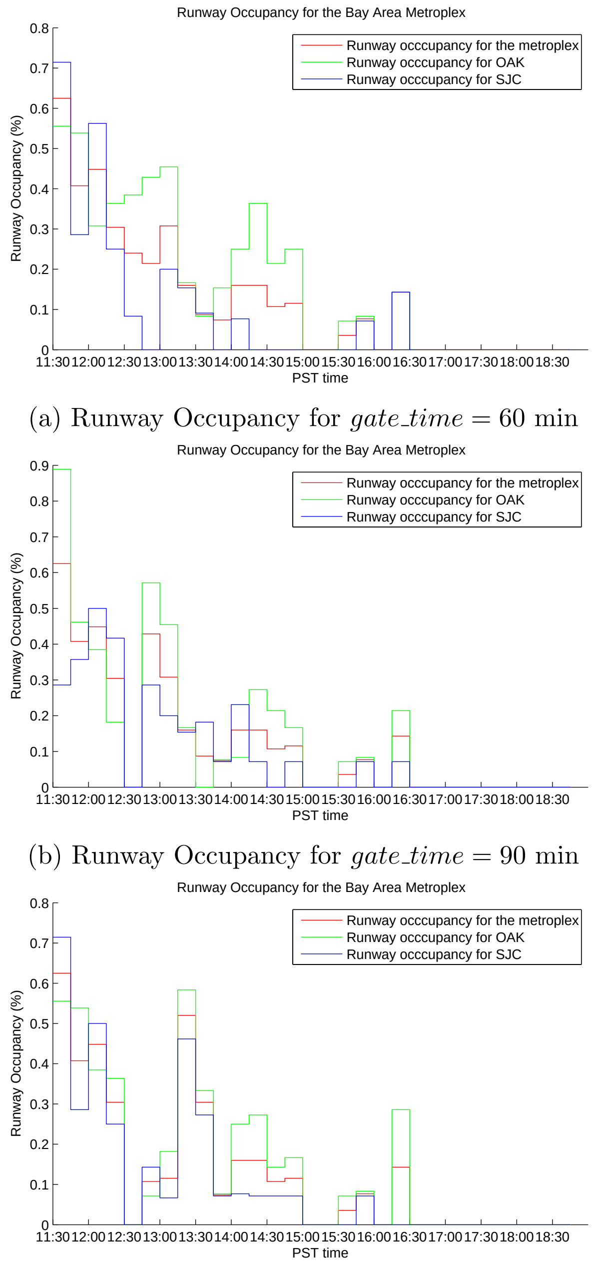


Figure 50: Trajectories of diverted flights in the Bay Area following the Asiana crash at SFO from 13:00 to 14:00.

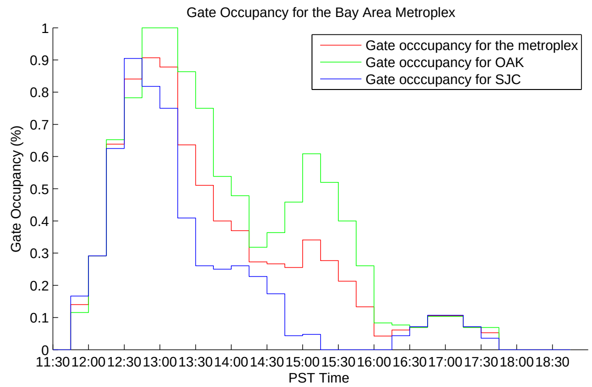


(a) Runway Occupancy for $gate\_time = 60$ min

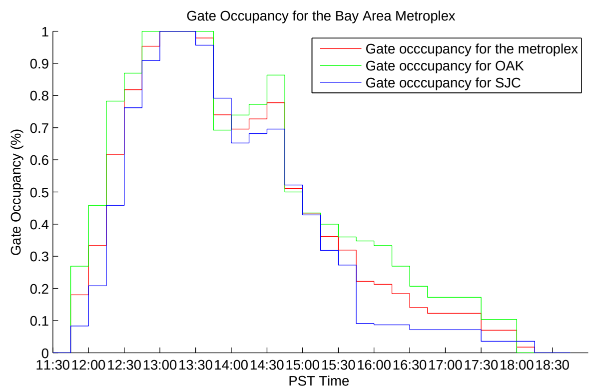
(b) Runway Occupancy for $gate\_time = 90$ min

(c) Runway Occupancy for $gate\_time = 120$ min

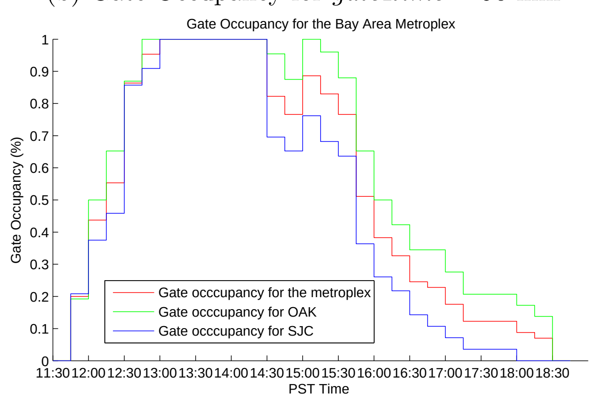
Figure 51: Runway Occupancy at SJC and OAK for each scenario.



(a) Gate Occupancy for $gate\_time = 60$ min

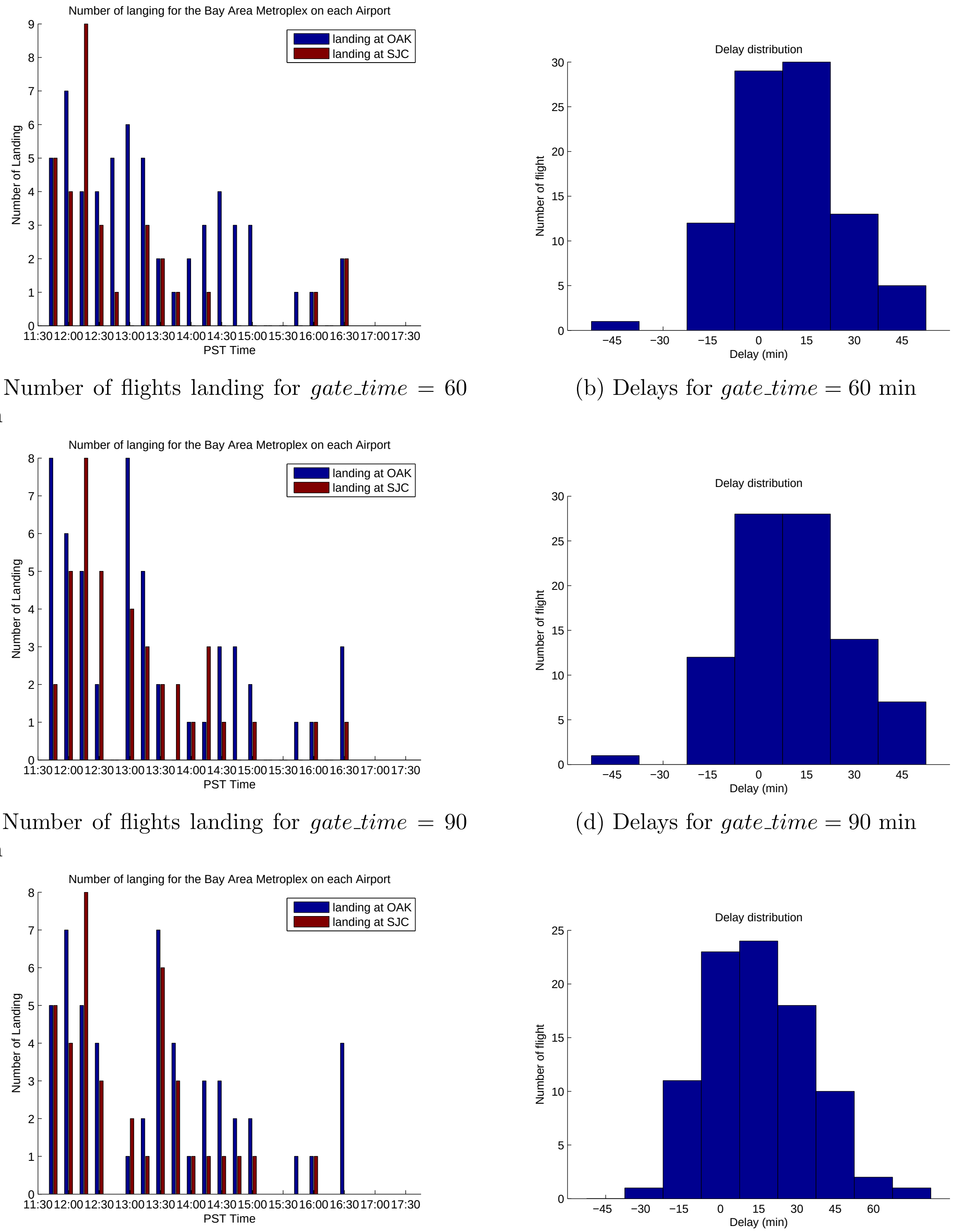


(b) Gate Occupancy for $gate\_time = 90$ min



(c) Gate Occupancy when $gate\_time = 120$ min

Figure 52: Gate Occupancy at SJC and OAK for each scenario.



(a) Number of flights landing for $gate\_time = 60$ min

(b) Delays for $gate\_time = 60$ min

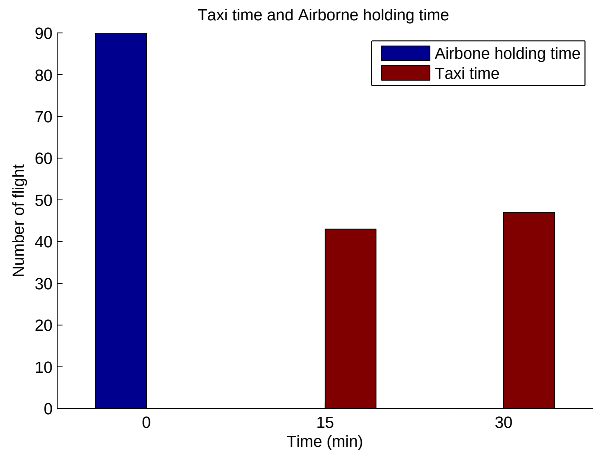
(c) Number of flights landing for $gate\_time = 90$ min

(d) Delays for $gate\_time = 90$ min

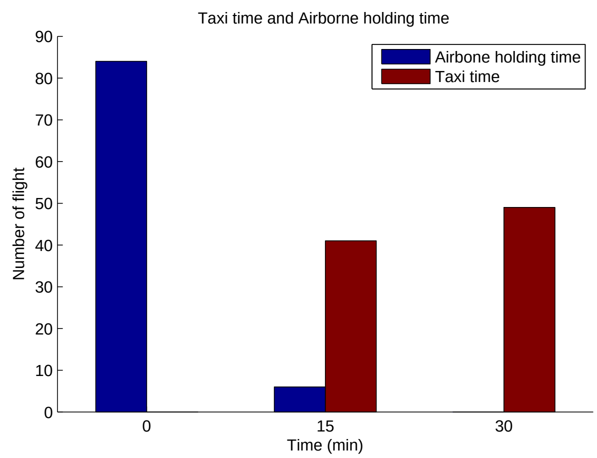
(e) Number of flights landing for $gate\_time = 120$ min

(f) Delays for $gate\_time = 120$ min

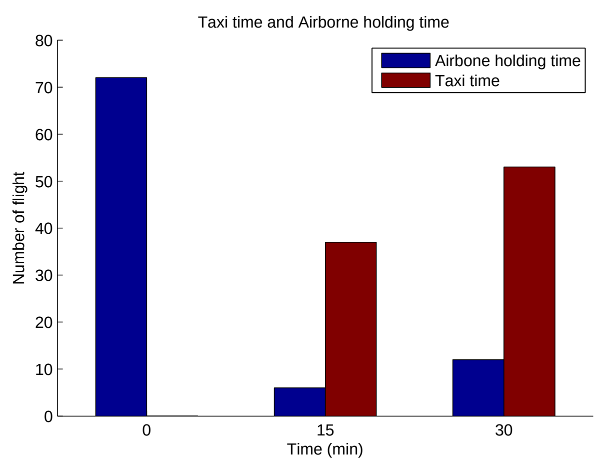
Figure 53: Number of flights landing at SJC and OAK, and associated delays for each scenario.



(a) Average Taxi vs airborne holding time for $gate\_time = 60$ min

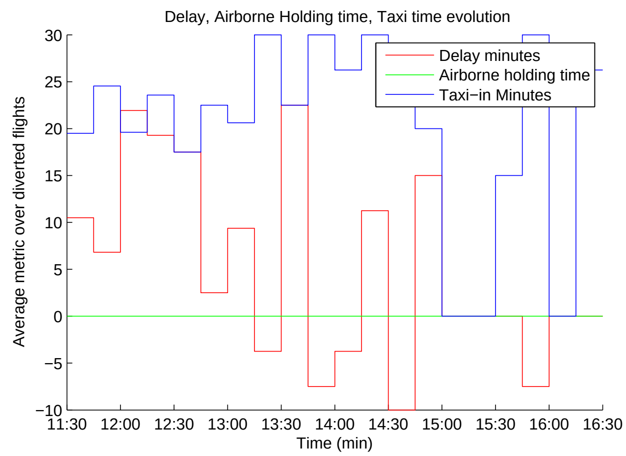


(b) Average Taxi vs airborne holding time for $gate\_time = 90$ min

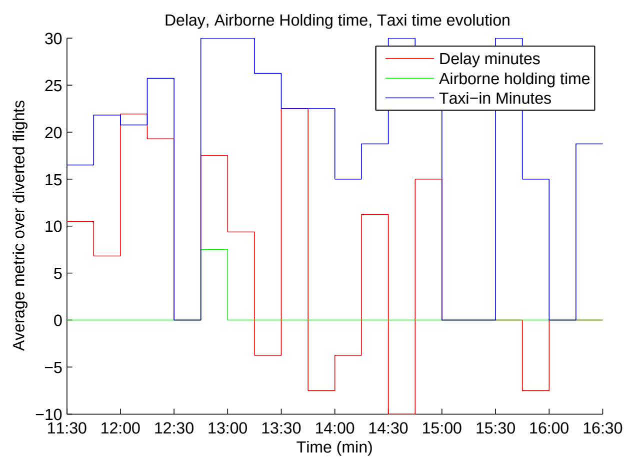


(c) Average Taxi vs airborne holding time for $gate\_time = 120$ min

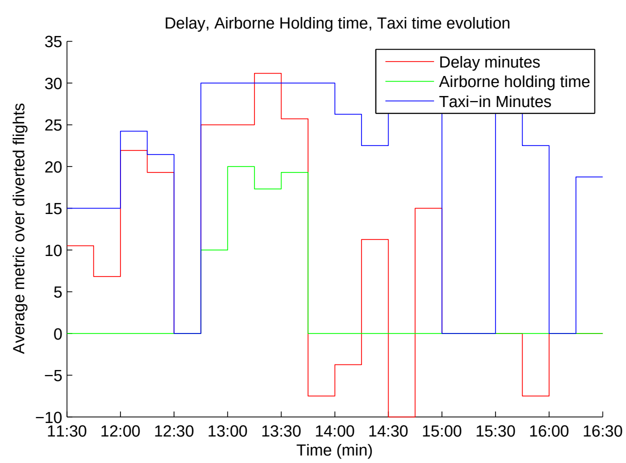
Figure 54: Trade-offs between Airborne holding at SJC and OAK for each scenario.



(a) Delay, taxi and airborne holding time evolution for $gate\_time = 60$ min



(b) Delay, taxi and airborne holding time evolution for $gate\_time = 90$ min



(c) Delay, taxi and airborne holding time evolution for $gate\_time = 120$ min

Figure 55: Average Flight Delay, Airborne Holding and Taxi-in Times at SJC and OAK for each scenario.

4.4 Conclusion

This chapter presented two optimization models showing that, in hindsight, disruption management after the Asiana crash would have been improved if multimodal CDM had been in place. For the diverted passengers and for the airlines whose flights landed in airports they do not usually operate at, multimodal passenger rerouting to the Bay area would have enabled recovery within less than 24 hours. Instead, many passengers had to wait up to several days to reach their final destination, sometimes by their own means of transport. From a flight-centric perspective, there was enough capacity at SJC and OAK airports to accommodate most of the diversions. The key issue was appropriate information sharing between the right stakeholders, both Air Traffic Control and Airlines, which ensures better decision-making, under time pressure. The next chapter provides recommendations based on the evidence assembled supporting the need for multimodal CDM and the Asiana crash case study.

CHAPTER 5

Recommendations for the Development of Collaborative Decision Making at the Multimodal Network level

5.1 Stakeholders and Action Plans

5.1.1 Passengers

The pivotal role of the passenger, though obvious, becomes clear when considering the role of the main stakeholders involved in the door-to-door travel experience in normal and disrupted conditions. Only passengers (or their luggage) interact with all stakeholders. Other stakeholders have one or a few connections up or down the line, but they do not have an immediate operational reason to be aware of the needs, priorities and issues facing the full run of stakeholders involved in the journey process. Passengers can differ significantly in their travel behavior, requirements and preferences.

Timing of passenger information The accuracy of exchanged data is critical to enable informed decisions for empowered travel. In the case of a long journey some uncertainties normally will cancel each other out which could be estimated with error propagation. However, some sources of delay may affect multiple stages, leading to greater-than-usual journey times throughout the journey. The timeliness of data exchange is very important for empowering the traveler, and also enables the travel service provider to make a good prognosis of the progress of the journey. The later information is exchanged, the more limited will be the availability of alternatives and/or countermeasures. For example, if the traveler received information on congestion on his or her way to the airport too late and is already within a traffic jam on the highway, either this delay can be absorbed through journey time buffers, or processes later in the journey could be shortened to allow the traveler to board their critical travel connection in time. If neither of these options are possible, the journey would have to be re-planned. For instance, when SFO closed after the Asiana crash, passengers with later flights were still trying to go to the airport.

In case of disruption, passengers could be asked to vote through airline mobile applications or social media channels such as twitter, and decide whether they are willing to take a bus or would rather wait a few days for a later flight, if their planned trip is not time-sensitive. This would offer a solution for passengers to weigh in on the rest of the journey.

A disruption corresponds to an episode of major disruption that results in many cancellations at one or more airports, for example, major snow events, volcanic ash, aircraft accidents, strikes, technical failures, fires or terrorism. Such situations differ from events which lead primarily to delays.

Performance Based Air Traffic Management has direct implications for Performance Based Travel Management, both under nominal conditions and during crisis events. A passenger-centric approach takes into account loyalty, lifetime value and passenger influence, in addition to direct costs. A passengers journey disruption may impact brand loyalty and future booking behaviour. For instance, passengers diverted to Sacramento were treated very differently depending on their airline. For passengers with no support, the comparison with passengers reaccommodated via shuttles must have been striking. Such disruptions may also influence other passengers opinions through social media channels. Thus performance-based travel management is essential for travelers and service providers / travel agents alike.

The European Norm EN 13816:2002-07 defines eight quality criteria connected to passenger satisfaction: availability, accessibility, information, time, customer support, comfort, safety and environmental impact. The overall price for travel is a further performance criterion because many customers are willing to sacrifice quality in return for cheaper travel. The areas include :

- *Availability* refers to the extent of the service offered in terms of geography, time, frequency and transport mode.

- *Accessibility* includes ticket accessibility, transport mode accessibility to passengers with reduced mobility, staff accessibility, connections within and between transport modes, and an accessible complaint handling mechanism. CDM at the multimodal network level aims at improving communication between passengers and transport providers and streamlining the rebooking process when flights are canceled or diverted. For instance, the rebooking of diverted passengers of international passengers who landed in Seattle was reported as very hectic, because the international airlines did not operate out of Seattle.

- *Information* : improving the provision of information to passengers implies that passengers are provided with earlier and more reliable information. Such information covers flight delays and cancellations, problems getting to/into the airport, available options if their flight is canceled and their rights in cases of disruption.

- *Time* : the objective of making the passenger journey more seamless includes reducing journey duration, both under non-disrupted conditions (via better information about journey and process times enroute) and in crisis situations (by offering the use of alternative modes).

- *Customer Support* : Travelers receive more and clearer information about their journey and can either make their own decisions about how to use that information or request extra support from a travel agent, for example with the selection and booking of alternative itineraries using ground transport.

- *Comfort under non-disrupted and/or delayed conditions* : more reliable estimates of journey and arrival times should lead to passengers being able to spend more time at their desired place (e.g. at home) and decrease uncertainty, which provides the potential to increase satisfaction on comfort-related criteria.

- *Safety, and passenger perception of safety*, should not change much under the concept proposed in non-disrupted or delayed conditions. Under crisis situations passengers may have the option (depending on their preferences) to trade off journey time for options that have reduced comfort or perceived safety, for example, taking an overnight bus or train journey, or ground travel through a country they do not speak the language of. In this situation the passenger would have reduced comfort/safety but an overall increased utility. Better information sharing and hence better decision making should also reduce passenger congestion and overnight passenger waits in airports, leading in turn to improvements in safety and comfort criteria.

The overall travel fare will act in many cases as a limitation for the types of connection that can be chosen.

The short term benefits of multimodal CDM are the improvement of passenger satisfaction by reducing door-to-door travel time, reducing uncertainty, and improving information provision.

5.1.2 Airlines

Airlines bear a high cost during disruptive events. Their objective is to recover from the disruption quickly and efficiently, while providing for the passengers' needs. If airlines were willing to share their connection matrices under disrupted conditions, the diversions might be able to land in airports more suited to facilitate the reaccommodation of diverted passengers. For instance, they could land closer to the final destination airport. A ranking process, similar to CTOP (Collaborative Trajectory Options Program) [60], could be envisioned. For flights still far away from the arrival airport that closes, but already airborne, the airline could be asked to provide a ranking of preferred diverted airports. Whether airlines can provide complete or partial preference information, the details of the expression of such preferences remain to be explored.

The short term benefits of multimodal CDM for airlines include reducing congestion in airport terminals, particularly at airline counters, both under normal conditions (as passengers spend less unnecessary time in the terminal) and in disruptive situations situations.

5.1.3 Airports, Ground Transportation, Infrastructures and Transportation Authorities

The short term benefits of multimodal CDM consist in:

- Helping airlines to better maintain schedules by reducing the uncertainty associated with late passenger arrival at the gate;

- Allowing stakeholders to optimize resource allocation (for example, improving prediction of how many immigration desks will need to be open at a given time in a given airport).

Multimodal issues and bottlenecks resulting from operational processes, deficiencies in existing technology, and lack of information exchange have to be examined using the available data sources. Given the level of complexity encountered in the multimodal transportation system, advanced methods could be used to explore uncertainty issues and networked interdependencies in order to reveal both the current issues and bottlenecks which have not yet occurred, but may do in future due to currently-foreseen system changes (e.g. increases in demand). Public Transport authorities need to be involved to better manage the interconnections between transportation modes. Private transport companies (e.g. taxis) can be locally contracted to facilitate the reaccommodation process. For instance, the BART normally operates a reduced scheduled on Saturdays, thus it may be possible to have more trains operate a given origin-destination pair between airports in the metroplex to facilitate passenger movements on the ground. Regarding cooperation between airlines and ground transport, Anthony Evans [48] reported that Continental Airlines had an agreement at Newark to make buses available to air passengers in case of severe disruptions.

Understanding aviation disruption is also key in the context of wider societal risks. Disruption in the aviation system is inextricably linked to wider multi-system disruption, both as a cause (e.g. cancelled flights leading to problems with supply chains) and as a consequence (e.g. airport closures resulting from earthquakes, flooding or civil unrest). Similarly, aviation disruption may occur with no relation to ongoing wider disruptive events, but could require a response that is aware of them (e.g. making the decision to put passengers stranded by snow on ground transport during a flu pandemic). Understanding the links between aviation and other systems helps to devise ways of dealing with aviation disruption that are sensitive to what may be happening in a wider societal context and help rather than hinder responses to any wider disruptive events.

Overall, the long-term benefits for all stakeholders would be as follows:

- Airports increasingly compete with each other and also with alternative transport modes for passengers; a better passenger experience improves customer loyalty.

- A good passenger experience makes a good impression / enhances the reputation of the city/state/country, given that the airport is the first and last thing a visitor sees. Therefore from a tourism, business and economic point of view it can make sense to invest in the airport experience.

- A good passenger experience makes it very difficult for governments/regulators to argue that the airport is doing a bad job when the airport is clearly serving the community.

- Focusing on the customer binds an organization together. It gives all staff a clear goal and a clear understanding of the aims of the airport for example, what types of behavior are acceptable and should be encouraged.

- Staff who are committed to providing a great passenger experience tend to help their colleagues more making the airport more efficient and effective.

- Staff, passengers and the local community who are proud of their airport look after it better, want to be associated with it and are less likely to litter for instance.

- A good passenger experience keeps media onside and helps marketing/publicity for the airport. Passengers often prejudge an airport based on its media profile.

Given that media tend to publish negative issues more than positive ones, this can be a problem.

5.2 Support Tools for Multimodal Collaborative Decision Making

An analysis of how the conclusions of research in the previous areas may change under disruptive conditions, would help in setting recommendations for how data provision and exchanges would need to be modified when the aviation system is disrupted (e.g., if the passenger's flight is canceled).

A key research and development area identified is the need to further foster solutions that enable a seamless door-to-door journey for the passenger. However, due to significant barriers related to incompatibilities between systems and data, it is recommended to focus on the development of direct communications between the passengers (respectively their travel agents) and each transport provider (respectively alliances of transport providers). Technical and algorithmic aspects need to be addressed, they include computing abilities of decentralized solutions, fleet needs, communication channels, human decision-making support tools. Provision of door-to-door travel support, e.g. provision of alternatives in case of flight cancellation, could anyway be implemented as a de-centralized service, if supported by the required information sharing.

5.2.1 Information Sharing

According to SITA Air Transport IT review [87], "the air transport industry is shifting towards a new era of continuous engagement. It is increasingly empowering "digital travelers", (...) and it is creating rising demand for more relevant services and giving airlines and airports opportunities to offer passengers enhanced personalization".

This recent SITA survey indicates that " airlines' sights are set on providing a real-time service experience, targeted at their passengers' journeys, via smartphone apps: 65% of airlines plan to do this by the end of 2017, up from 13% today. High on the airport agenda, in the meantime, are updates on wait-times and local traffic issues: 18% offer them today, with another 55% making plans for this service". Moreover, it highlights that, in the recovery process, "[passengers] are expecting airlines and airports to provide a personal alert and response when flights are canceled or delayed. (..) Smartphones and other communication technologies open up a myriad of opportunities to provide disruption management services to passengers. The use of new technologies is becoming more and more commonplace in case of unexpected events: "A third of airports are able to provide real-time information to passenger mobiles in the event of disruption, with a further third doing so by 2017. Among the 50 top airports, where the consequences of disruption can have greater impact, the figures are higher." The continuous provision of information to the passenger is facilitated by the fact that "almost every passenger (97%) carries a smartphone, tablet or laptop when they fly, and that one in five travels with all three".

While information from all involved stakeholders is needed for consolidated decision-making the two main actors involved are the traveler (or their agent) and the service provider of the chosen mode of transportation (flight, train or bus) or combinations thereof. For the benefit of the travelers, service providers must be incentivized to share their information and make it publicly available. In the case of a disruptive event, the service provider should provide the traveler with intelligent re-accommodation to enable empowered traveling. A passenger-centric approach entails gathering information about each passengers preferences and trip purposes so they can choose an adequate alternative.

Recent events such as the Asiana Crash and the ensuing transport ripple effects clearly illustrated the fragility of the system, the costs associated with not reacting effectively and therefore the importance of coordination. The FAA, the EC, Eurocontrol and others have responded positively to mitigate disruptive events and spread the CDM concept but more could be done, such as:

- Delivering protocols that enable levels of filtered alert information to be passed through the network;
- A web "dashboard" of status information to which stakeholders could contribute, which provides real-time information to all stakeholders requesting access. For instance, CDG website provides real-time on-time performance reports to anyone in the air transportation industry that previously requested an account. Airlines across the world use it to monitor their flights and evaluate if their passengers are likely to make their connections;
- The establishment of intelligence/alert units that can capture non-operational features such as meteorological or security data and make them available to the network.

Every passenger should expect to receive the following information in a timely manner:

1. Alerts of flight cancellation as soon as it happens with information on the fact that they will be informed soon (with a precise timeline) on the different options they will have. This alert may happen when the passenger is still at home, when they are traveling to the airport, or after they have arrived. Most passengers carry mobile devices and have provided an email address during their booking, so they can easily be reached at any stage. Online information can be more effective than having people stand in line waiting for personalized updates but only receiving the same information, as was observed for diverted passengers in Seattle after the Asiana crash.

2. Possible re-accommodation options:

   - Travel cancellation and reimbursement of the travel ticket
   - Transfer to another flight from the same airport platform with the corresponding schedules and application of passenger rights as required (meal, hotel). This happened for a lot of passengers rebooked on flights three days later from Atlanta to San Francisco after the Asiana Crash.
   - Transfer to another flight from another airport platform with the corresponding schedules, details of airport transfer and application of passenger rights as required (meal, hotel). After the Asiana Crash, some passengers departing from the Bay Area left from OAK instead of SFO.
   - Alternative transport mode solution to reach the destination without extra charge and with schedule details (departure and arrival times, successive transport modes, etc.). This is what was implemented by Delta airlines to reaccommodate diverted passengers in SMF.

3. Once the passenger has chosen a specific option, information should be communicated on the process to follow:

   - to get their ticket reimbursement and collect their luggage (if luggage has already been dropped off). In Seattle, diverted passengers complained that it was unclear which costs airlines would reimburse.
   - to find a meal and/or hotel booking and/or to go to the appropriate terminal area,
   - to obtain alternative transport mode tickets and/or be at least partly refunded from the original air ticket flight, to pick up luggage (if required) and to reach the ground transport area (train station, bus station, etc.). Maps and/or schedules regarding other modes should be provided

on screens or made available on mobile devices.

The identification of existing data availability, technology and data flows is necessary. This activity would identify available data, technologies and software that could be used to share data, and examine current data flows to passengers and between stakeholders. To accurately evaluate performance, the available data from many data sources and reporting methods used across the US and Europe needs to be understood as a whole. Unless given incentives or provided with potential benefits, stakeholders are concerned that by sharing their data they are submitting themselves to open comparison with competitors. Therefore, a cost/benefit analysis of action upon stakeholders and the overall system is necessary. One could imagine a trade between the data passengers are ready to provide and stakeholders data. Data provision and analysis could also be a way to enable multimodal ticketing, which could help significantly in streamlining multimodal journeys. Finally, identifying gaps in data provision could help to identify and address bottlenecks in the passenger journey, particularly where those bottlenecks arise from lack of information provision.

A real-world multimodal CDM implementation would involve (potentially substantial) data flows between many stakeholders. A data framework combining a Big Data process to collect the numerous data from the various stakeholders (including passengers, Airport or Surface CDM, landside transport operators and others) and data flow management should securely treat these data and distribute accurate and reliable information to each stakeholder. The technical issues surrounding such an implementation are another area where ongoing research would be useful.

The duality between competition and cooperation can be an obstacle to mutlimodal CDM. The proposed concept involves information exchange between various stakeholders who may be competing. The different data sources, their availability, and aspects of confidentiality have to be investigated. A trade-off between the performance of the solution of a multimodal network optimization and constraints in data provision should be established. Antitrust concerns should be adressed as well. Two systems can be envisioned. In the first one, airlines trade passengers for reaccommodation : they advertise that they have X passengers who were diverted to airport A and need to be rerouted to airport B. In exchange, they can reaccommodate passengers out of airport C, where they operate. In the second system, an auction mechanism can be envisioned, where one airline compensates another for reaccommodating some of its passengers.

In the area of service and products design, information needs to be delivered to passengers in a way that is user-friendly, simple and straightforward; passengers may need to access information at a variety of stages associated with their journey, ranging from months beforehand to whilst they are traveling. Similarly, the differing needs and preferences of passengers suggest that multiple approaches to data delivery are needed. Services should be useful, usable, desirable, efficient, and effective by drawing from the current customer experience and focusing on enhancing the quality of the journey as the key value for success. Inputs from the research activities described above would then help for the design of the required services. This could also lead to the development of the technological framework to deliver improved information via an integrated tool set. Once the tools and services have been designed and developed, the developed tools would have to be subject to modification based on the result of testing and experimentation in real-world situations.

5.2.2 Resource Allocation

Several limits to passenger reaccommodation need to be adressed. The capacity of other air services to provide spare seats for passengers from canceled flights is a key factor affecting recovery from crisis events. In normal operations, airlines try to maximize their load factors. In crisis events, however, faster recovery is aided by lower load factors on subsequent flights so that there is more space to reallocate passengers. However, putting passengers on ground transport is feasible only if there is sufficient capacity at suitable times for them. The ability of ground transportation providers to lay on extra services for stranded passengers varies greatly by location. Several limitations may arise from many sources, including lack of spare rolling stock, staff availability and training for the routes needed, and infrastructure limits. Even if these constraints can be overcome, a notice period is typically needed to assemble the necessary resources. Multimodal CDM could be decomposed into options, with several multimodal touch points, such as the BART station at OAK airport.

Michelle Karow [59] studied the impact of inclement weather on an airline hub airport and its repercussions on the airline network. She proposed to shift a small fraction of a connecting bank to strategically located, under-utilized airports during irregular operations. A virtual hub would host connecting traffic and reduce the demand on the hub. It would enable a significant decrease in passenger delay and flight cancellations.

Moreover, mathematical models, supported by the appropriate data sources and processes, and feeding into decision-support tools, need to be developed, for different time horizons, from strategic to tactical planning. Algorithms supporting distributed multimodal optimization with reasonable computational times and robust margins need to be studied and implemented.

For instance, Zhang et al. proposed a Regional Ground Delay Program [99]. Following previous research on real-time intermodalism, a Regional Ground Delay Program (Regional GDP) concept would be part of the CDM system when a hub airport located in a regional airport system encounters a severe airside capacity reduction. Zhang's idea is that air traffic flow managers evaluate not only the imbalance of traffic demand and terminal capacity at the hub airport but also excess capacity at other airports in the same region, assuming that airlines could incorporate ground modes into their disruption management and use ground vehicles to transport passengers and crew members between original scheduled and diverted airports. The case study of the Asiana Crash suggests that a regional GDP, including airports such as LAX, LAS, SMF and RNO might have helped mitigate the disruption following the crash. The feasibility of multimodal CDM could be facilitated through the existing and successful initiatives constituted by GDPs and CDM.

In the context of metroplex operations under disruptions, playbooks could be developed to provide structure and guidance. Cases such as a sudden airport closure for any of a number of reasons could be addressed.

5.2.3 Decision Making

Multimodal collaborative Decision Making necessarily involves multiple stakeholders. The systemic nature of aviation means that those stakeholders are international as well as national and local. In the case of the Asiana crash, not only was SFO airport involved and all entities dealing with airport closure and passenger evacuation, but also the California Highway Patrol, taxi companies operating out of SJC and OAK, custom and border representatives at any airport where flight diversions landed, to name a few. Hence, to effect meaningful CDM control and cooperation at the multimodal level, inputs from the higher level organizations are needed to help to prevent, forestall and contain any crises. Similarly, working together, these organizations can enhance the passenger experience in normal as well as disrupted conditions. The key to delivering effective multimodal CDM is communication. Communication is a means to an end: it will help improve decision making, and the data sharing will support the use of decentralized optimization models. Airport networks are generally thought to operate well but their scope can be limited to the first tier collaborators. It could be extended to second and third tier organizations, which requires introducing:

- Wider local to regional planning and resilience networks that deliver integrated service and share information;

- A national dialogue of interested parties under the auspices of the relevant government departments;

- National guidelines and protocols that make it easier for the sharing of knowledge and data and minimize the competitive sensitivities of business

- Simplified communication conduits for intelligence on transport disruption.

Efficiency, whether cost efficiency or time efficiency for instance, of the decision making aims at making the passenger journey seamless or recovering from a disruption as fast as possible. Multimodal CDM could also be tied to SWIM (System Wide Information Management), in the sense that it would provide a broad base information management system including passengers and local transportation networks.

The structure of the decision space for all stakeholders needs to be better understood. There could be a pre-established metroplex playbook indicating which stakeholder to involve at which stage of the decision process. Real-time, tactical and strategic decision-making may require the involvement of different stakeholders. Reaccommodation support tools are most needed in the tactical and strategic phases.

Regarding passenger reaccommodation in case of flight cancellation, solutions offered to the passengers can be grouped in four categories:

- Air ticket reimbursement without offering an alternative solution: this solution will be preferable in case of an outward flight for the passenger,

- Transfer to an alternative transport mode: this solution relating to ground transport modes (e.g rail or coach services) is more applicable to cancellations of short-haul flights (flight duration less than 3 hours),

- Transfer to another flight from the same airport platform: in this solution the transfer can be to the initial destination airport or to another airport in the same region.

- Transfer to another flight from another airport platform: in this solution a ground transport mode (often a bus transport mode) is necessary to reach the other platform. Moreover, the flight operated from the other airport can be to the initial destination airport (as booked by the passenger) or to another airport in the destination region.

In other words, the range of possible solutions strongly depends on two main criteria:

1. The characteristic of the canceled flight for the passenger: outward flight, inward flight or connecting flight.
2. The length of the canceled flight: short-haul flight (less than 3 hours) vs. medium or long-haul flight (more than 3 hours).

The timing of decisions on the Air Traffic Control side could be investigated. By comparing the initial flight plan and the trajectories followed by diverted aircraft, the timing of the diversions could be retrieved. More might be uncovered on the tactical traffic control aspects for the entire airspace, that have not been tackled in this thesis.

5.3 Conclusion

A more detailed network-wide benefit analysis of the concept would be necessary to support uptake and assess key economic and environmental aspects of the widespread uptake of a multimodal CDM concept (in particular the performance-based travel management) and the supporting tool set and services. This particular aspect can be tackled with the extension of case studies such as the Asiana crash, to support systemic management of substantial transportation infrastructure disruptions.

Achieving widespread adoption of the multimodal Collaborative Decision Making assumes a change in culture, attitudes and, to a certain extent, priorities. Many, if not most, of the delivery agents involved in providing an air transport service and its associated airside services have tended to be focused upon their own business imperatives and Key Performance Indicators. Whilst actors within the sector necessarily have to connect, the processes by which planning, communication and response actions are coordinated are still relatively limited. Often these are between a few key organizations that are one layer up or down in the hierarchy and mostly lack any system wide connectivity. Improving the systemic connection, communication, alerts and mitigation approaches requires recognition of current obstacles and implementing change.

CHAPTER 6

Conclusion

The present dissertation aimed at making the case for the extension of Collaborative Decision Making to the Multimodal Network level.

Chapter 2 presented the evidence for this need, as uncovered through the MetaCDM project in Europe and through the analysis of various disruptive events over the past decade.

In Chapter 3, a clinical study of the Asiana crash in San Francisco airport on July 6th, 2013 and the resulting propagation of disturbances on the multimodal transportation network was undertaken. The first analysis of a multimodal disturbance propagation was presented, examining three transportation infrastructure networks: air, rail and highway traffic, with additional insight obtained from Twitter data. The disturbance taook different forms and varies in scale and time : cancellations and delays snowball in the airspace; highway traffic near the airport is impacted by congestion in previously never congested locations, and public transit passenger demand exhibit unusual traffic peaks in between airports in the Bay area. Moreover, the analysis provided a passenger-centric point of view on disruptions in multimodal transportation systems, with the inclusion of passenger costs in a cost analysis, and passenger usage of social media to access information on the crash. Traffic data fusion helped quantify real-world examples of network inter dependencies.

Chapter 4 tackled, in hindsight, how the crisis management of the Asiana Crash could have been improved, at the system level. The consequences of the crash may have been better mitigated, both for the stakeholders and for the passengers, had Multimodal Network CDM been in place. Two optimization models were developed to improve the disruption management following the Asiana crash, when thousands of diverted passengers found themselves struggling to reach their original destination. The passenger-centric optimization aimed at balancing cost and delays with a multimodal reaccommodation scheme from each diversion airport. It showed that multimodal collaboration to reroute passengers could have helped passengers within an 8-hour bus drive radius reach the Bay Area on the crash day, instead of waiting up to several days for flight reaccommodation in diverted airports. The flight-centric optimization aimed at allocating flight diversions to SJC and OAK while balancing runway and gate capacity, and minimizing flight delays compared to their original schedule. It showed that there was potentially more capacity at SJC and OAK to accommodate more diverted flights on the crash day, which could have mitigated many of the ripple effects for both passengers, airlines and airports, for instance in Seattle, Salt Lake City and Denver. One of the main obstacles to optimal capacity utilization under disruptions is information sharing and collaborative decision making between all stakeholders. This would improve the performance of the air transportation system both from a flight-centric and from a passenger-centric perspective.

Chapter 5 provided recommendations to expand CDM to the multimodal network level and highlights the expected benefits for all stakeholders and passengers.

The higher-level goal of this dissertation is to foster a better understanding of multimodal transportation to increase its resilience and facilitate the passenger door-to-door journey. This research can provide the first experimental basis upon which several system engineering methods could be applied to improve the entire passenger journey.

Future work will aim at modeling the coupling between transportation networks, now that it has been shown for a specific examples. This coupling is due to passenger transit flows between modes, on which there is little data available. However, in a few airports, beacon and wifi data are now providing passenger flows inside the terminals, but flows of passengers in cars or in trains to and from the airport remains to be understood. Moreover, we can analyze a posteriori the impact of disturbances is possible, and elaborate mitigation strategies. Yet, predicting how the disturbance will propagate through the network and controlling this propagation will require more research. Finally, implementing the mitigation strategies has to be examined in more details, in terms of processes and information flows between stakeholders who are not necessarily in contact during routine operations.

REFERENCES

[1] "Aircraft Diversions at SJC due to Asiana Accident at SFO." http://www.piersystem.com/external/content/document/1914/1841923/1/07-09-13AIRPORT.PDF.

[2] "Airline on-time statistics and delay causes." http://www.transtats.bts.gov/ot_delay/ot_delaycause1.asp.

[3] "Domestic and International Flights diverted to Sacramento following San Francisco plane crash.." sacramento.cbslocal.com/2013/07/06/domestic-international-flights-diverted-to-sacramento-following-sf-plane-crash/.

[4] "Flights forced to land at Sacramento airport after SFO shuts down.." http://www.news10.net/story/local/2013/07/06/4755695/.

[5] "PeMS California Department of Transportation." http://pems.dot.ca.gov/.

[6] "San Francisco plane crash causes diverted flights to LAX.." http://abc7.com/archive/9164337/.

[7] "Some flights scheduled to land at SFO diverted to LAX." http://losangeles.cbslocal.com/2013/07/06/some-flights-scheduled-to-land-at-sfo-diverted-to-lax/.UdilzcAoKEM.twitter.

[8] "Unruly passengers can face hefty bills for flight diversions." http://www.cbc.ca/m/touch/news/story/1.1144398.

[9] "Development Office (JPDO)(2009). Concept of operations for the next generation air transportation system," Joint Planning and Development Office (Ed.), vol. 3, 2007.

[10] "Qantas gets rocked by Amadeus." http://www.theregister.co.uk/2012/07/02/qantas_network_down/, 2012.

[11] "Flights resume at BWI after lightning strike shuts down airport." http://articles.baltimoresun.com/2013-09-12/news/bs-md-bwi-lightning-20130912_1_lightning-strike-air-traffic-control-tower-bwi, 2013.

[12] "Sabre, airline reservation system, goes down causing major delays worldwide." http://www.huffingtonpost.com/2013/08/06/sabre-reservation-outage-airline-delays_n_3710964.html, 2013.

[13] Ageeva, Y. and Clarke, J.-P., "Approaches to incorporating robustness into airline scheduling," 2000.

[14] AhmadBeygi, S., Cohn, A., Guan, Y., and Belobaba, P., "Analysis of the potential for delay propagation in passenger airline networks," Journal of Air Transport Management, vol. 14, no. 5, pp. 221–236, 2008.

[15] Atkins, S., "Observation and measurement of metroplex phenomena," in Digital Avionics Systems Conference, 2008. DASC 2008. IEEE/AIAA 27th, pp. 3–E, IEEE, 2008.

[16] Aviation Brief, "FAA: Flights into Chicago area at reduced rate." `http://www.aviationbrief.com/?p=18438`, 2014.

[17] Babbitt, J. R., "Communicating in severe weather." `http://www.faa.gov/news/speeches/news_story.cfm?newsId=13252`, 2011.

[18] Ball, M., "Analysis of passenger delays: Developing a passenger delay metric," in NEXTOR NAS Performance Metrics Conference, ASilomar, CA, 2006.

[19] Ball, M. O., Chen, C.-Y., Hoffman, R., and Vossen, T., "Collaborative decision making in air traffic management: current and future research directions," in New Concepts and Methods in Air Traffic Management, pp. 17–30, Springer, 2001.

[20] BBC news, "Flights disrupted after computer failure at UK control centre." `http://www.bbc.com/news/uk-30454240`, 2014.

[21] Bertsimas, D. and Gupta, S., "Fairness in air traffic flow management," in INFORMS Meeting, San Diego, CA, Usa, vol. 32, p. 7, 2009.

[22] Bertsimas, D. and Gupta, S., "A proposal for network air traffic flow management incorporating fairness and airline collaboration," in Operations Research, 2011.

[23] Bolic, T. and Sivcev, Z., "Eruption of Eyjafjallajökull in Iceland: Experience of European Air Traffic Management," Transportation research record, no. 2214, pp. 136–143, 2011.

[24] Bratu, S. and Barnhart, C., "Flight operations recovery: New approaches considering passenger recovery," Journal of Scheduling, vol. 9, no. 3, pp. 279–298, 2006.

[25] Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., and Havlin, S., "Catastrophic cascade of failures in interdependent networks," Nature, vol. 464, no. 7291, pp. 1025–1028, 2010.

[26] Burgain, P., Feron, E., and Clarke, J.-P., "Collaborative virtual queue: Benefit analysis of a collaborative decision making concept applied to congested airport departure operations," Air Traffic Control Quarterly, vol. 17, no. 2, 2009.

[27] Carlson, J. M. and Doyle, J., "Complexity and robustness," Proceedings of the National Academy of Sciences, vol. 99, no. suppl 1, pp. 2538–2545, 2002.

[28] CDM-TF, EUROCONTROL, "Airport CDM Implementation–The Manual," EUROCONTROL, Brussels, 2005.

[29] Chan, S., "SFO Flights Suspended, Traffic Snarls on US 101." patch.com/california/millbrae/sfo-flights-suspended-traffic-snarls-on-us-101-after-deadly-plane-crash#.VDNKBvldWsg.

[30] Chang, K., Howard, K., Oiesen, R., Shisler, L., Tanino, M., and Wambsganss, M. C., "Enhancements to the FAA ground-delay program under collaborative decision making," Interfaces, vol. 31, no. 1, pp. 57–76, 2001.

[31] Chen, C., Jia, Z., and Varaiya, P., "Causes and cures of highway congestion," IEEE Control Systems Magazine, vol. 21, no. 6, pp. 26–32, 2001.

[32] Choe, T., Skabardonis, A., and Varaiya, P., "Freeway performance measurement system: operational analysis tool," Transportation Research Record: Journal of the Transportation Research Board, vol. 1811, no. 1, pp. 67–75, 2002.

[33] Civil Aviation Authority , "Aviation's response to major disruption ." http://www.caa.co.uk/docs/5/CAA%20review%20of%20snow%20disruption%20-%20Final%20Report%20-%20WEB%20VERSION%20_2_.pdf, 2011.

[34] Clarke, J.-P., Ren, L., McClain, E., Schleicher, D., Timar, S., Saraf, A., Crisp, D., Gutterud, R., Laroza, R., Thompson, T., and others, "Evaluating concepts for metroplex operations," in AIAA Aviation, Technology, Integration, and Operations Conference, 2010.

[35] CNN, "FBI: Suspect sent Facebook message: 'I am about to take out' FAA facility." http://www.cnn.com/2014/09/26/travel/chicago-ohare-midway-flights-stopped/index.html, 2014.

[36] Congress, Twenty-Fourth, "Transformations in air transportation systems for the 21st Century, General lecture by Bruce J. Holmes, DE Associate Director, Airspace Systems Programs Office," 2004.

[37] Conway, S., "Scale-free networks and commercial air carrier transportation in the united states," in 24th congress of the international council of the aeronautical sciences, vol. 29, 2004.

[38] Cook, A., Tanner, G., Cristóbal, S., and Zanin, M., "Passenger-oriented enhanced metrics,"

[39] Cook, A., Tanner, G., and Zanin, M., "Towards superior air transport performance metrics–imperatives and methods," Journal of Aerospace Operations, vol. 2, no. 1, pp. 3–19, 2013.

[40] Dan Nakaso, Bruce Newman, E. K., "Sfo crash causes chaos in california skies." http://www.willitsnews.com/ci_23610546/sfo-crash-causes-chaos-california-skies.

[41] DeLaurentis, D., Han, E.-P., and Kotegawa, T., "Network-theoretic approach for analyzing connectivity in air transportation networks," Journal of Aircraft, vol. 45, no. 5, pp. 1669–1679, 2008.

[42] DeLaurentis, D., Landry, S., Sun, D., Wieland, F., and Tyagi, A., "A concept for flexible operations and optimized traffic into metroplex regions," 2011.

[43] Dunn, T. P. and Sussman, J. M., "Multimodal infrastructure investment decision making: An institutional and funding perspective," in Journal of the Transportation Research Forum, vol. 50, 2012.

[44] Eurocontrol, "Network Operations Reports." https://www.eurocontrol.int/tags/network-operations-report.

[45] Eurocontrol, "CODA Digest: Delays to Air Transport in Europe." http://www.eurocontrol.int/sites/default/files/content/documents/official-documents/facts-and-figures/coda-reports/coda-digest-annual-2013.pdf, 2013.

[46] European Commission, "Flightpath 2050 - Europe's Vision for Aviation (Report of the High Level Group on Aviation Research)." http://ec.europa.eu/transport/modes/air/doc/flightpath2050.pdf, 2011. [Online; accessed 18-July-2014].

[47] European Commission, "White paper: Roadmap to a single european transport area towards a competitive and resource efficient transport system." http://ec.europa.eu/transport/themes/strategies/2011_white_paper_en.htm, 2011.

[48] Evans, A. D., Responses to airport delays: a system study of Newark International Airport. PhD thesis, Massachusetts Institute of Technology, 2002.

[49] FAA, M., "Nextgen implementation plan," Washington, DC, Available: http://www. faa. gov/nextgen/media/ng2011_impleme ntation_plan. pdf (accessed March 18, 2011), 2011.

[50] Flight Aware, "Misery map." http://flightaware.com/miserymap/.

[51] GRA, Incorporated Economic Counsel to the Transportation Industry, "Economic values for faa investment and regulatory decisions, a guide." http://www.faa.gov/regulations_policies/policy_guidance/benefit_cost/media/ECONOMICVALUESFORFAAINVESTMENTANDREGULATORYDECISIONS10032007.pdf, 2007. [Online; accessed 18-July-2014].

[52] GUIMERA, R., MOSSA, S., TURTSCHI, A., and AMARAL, L., "The worldwide air transportation network: Anomalous centrality, community structure, and cities' global roles," Proceedings of the National Academy of Sciences, vol. 102, no. 22, pp. 7794–7799, 2005.

[53] GUPTA, G., MALIK, W., and JUNG, Y. C., "An integrated collaborative decision making and tactical advisory concept for airport surface operations management," in 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Indianapolis, IN, 2012.

[54] HILL, T., "FAA: Fire-damaged flight control center to reopen Sunday." `http://thehill.com/policy/transportation/220119-faa-fire-damaged-flight-control-center-to-reopen-sunday`, 2014.

[55] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO), "Annual passenger total approaches 3 billion." `http://www.icao.int/Newsroom/Pages/annual-passenger-total-approaches-3-billion-according-to-ICAO-2012-air-transport-results.aspx`, 2012.

[56] JAFARI, N. and HESSAMEDDIN ZEGORDI, S., "Simultaneous recovery model for aircraft and passengers," Journal of the Franklin Institute, vol. 348, no. 7, pp. 1638–1655, 2011.

[57] JENKINS and COTTON, "Improving Airline Profitability Through Better Estimated Times of Arrival and Terminal Area Flight Information: a Better Analysis of PASSUR." `http://www.passur.com`, 2002.

[58] JOHNSON, B., "Diversion management - airline cost conference." `http://www.iata.org/whatwedo/workgroups/Documents/ACC-2014-GVA/occ-5-diversion.pdf`, 2014.

[59] KAROW, M. J., Virtual hubs: An airline schedule recovery concept and model. PhD thesis, Massachusetts Institute of Technology, 2003.

[60] KIM, A. and HANSEN, M., "A framework for the assessment of collaborative en route resource allocation strategies," Transportation Research Part C: Emerging Technologies, vol. 33, pp. 324–339, 2013.

[61] KING 5 NEWS, "San Francisco crash sends ripple effect to Seattle." `http://www.king5.com/story/tech/science/aerospace/2014/08/04/13272742/`, 2013.

[62] LAPLACE, I., MARZUOLI, A., and FÉRON, É., "META-CDM: Multimodal, Efficient Transportation in Airports and Collaborative Decision Making," in AUN 2014, Airports in Urban Networks, 2014.

[63] Laplace, I., Marzuoli, A., Feron, E., Dray, L., Gardner, R., Gunther, T., and Spies, G., "Contributions of Information Sharing, Collaborative Decision Making and Multimodality in improving passenger experience during disruptive events." http://www.meta-cdm.org/Deliverables/META_CDM_D2.2_1.0.pdf, 2014.

[64] Larsen, T. D., A Behavioral Framework for Managing Massive Airline Flight Disruptions through Crisis Management, Organization Development, and Organization Learning. PhD thesis, University of Maryland, 2013.

[65] Li, L., Park, J. W., and Clarke, J.-P., "A simulation-based method for estimating metroplex efficiency," in Digital Avionics Systems Conference (DASC), 2011 IEEE/AIAA 30th, pp. 2E4–1, IEEE, 2011.

[66] Liu, Y.-Y., Slotine, J.-J., and Barabási, A.-L., "Controllability of complex networks," Nature, vol. 473, no. 7346, pp. 167–173, 2011.

[67] Mayer, C. and Sinai, T., "Network effects, congestion externalities, and air traffic delays: Or why all delays are not evil," tech. rep., National Bureau of Economic Research, 2002.

[68] McCoy, T., "Accident Investigation Party Submission by the City and County of San Francisco, NTSB Accident File: DCA13MA120 ." http://cbssanfran.files.wordpress.com/2014/01/sf-city-atty-asiana-crash.pdf, 2014.

[69] Mercier, A. and Soumis, F., "An integrated aircraft routing, crew scheduling and flight retiming model," Computers & Operations Research, vol. 34, no. 8, pp. 2251–2265, 2007.

[70] Modrego, E. G., Igaru, M., Dalichampt, M., and Lane, R., "Airport cdm network impact assessment," in Proceedings of the Eighth USA/Europe Air Traffic Management Research and Development Seminar, 2009.

[71] Monteiro, A. B. F. and Hansen, M., "Improvements to airport ground access and behavior of multiple airport system: Bart extension to san francisco international airport," Transportation Research Record: Journal of the Transportation Research Board, vol. 1562, no. 1, pp. 38–47, 1996.

[72] Mukherjee, A., Ball, M., and Subramanian, B., "Models for estimating monthly delays and cancellations in the nas," in NEXTOR NAS Performance Metrics Conference, Asilomar, Calif, 2006.

[73] Nash, J. M., Guidebook for Airport Irregular Operations (IROPS) Contingency Planning, vol. 65. Transportation Research Board, 2012.

[74] National Transportation Safety Board, "Public hearing final transcript, Investigation of the Asiana Airlines Flight 214 landing accident at San Francisco International Airport, California, July 6, 2013." http://dms.ntsb.gov/pubdms/search/document.cfm?docID=413233&docketID=55433&mkey=87395, 2014.

[75] Nayak, N., Estimation of the Impact of Single Airport and Multi-Airport System Delay on the National Airspace System using Multivariate Simultaneous Models. PhD thesis, University of South Florida, 2012.

[76] NBC news, "San Francisco fire department statement." http://www.nbcbayarea.com/news/local/AUDIO---215009141.html, 2013.

[77] Newman, M. E., "Analysis of weighted networks," Physical Review E, vol. 70, no. 5, p. 056131, 2004.

[78] Petersen, J. D., Sölveling, G., Clarke, J.-P., Johnson, E. L., and Shebalov, S., "An optimization approach to airline integrated recovery," Transportation Science, vol. 46, no. 4, pp. 482–500, 2012.

[79] Pyrgiotis, N., Malone, K., and Odoni, A., "Modelling delay propagation within an airport network," Transportation Research Part C: Emerging Technologies, 2011.

[80] Ren, L., Clarke, J.-P. B., Schleicher, D., Timar, S., Aditya, S., Crisp, D., Gutterud, R., Lewis, T., and Thompson, T., "Contrast and comparison of metroplex operations," 2009.

[81] Romero, D. M., Galuba, W., Asur, S., and Huberman, B. A., "Influence and passivity in social media," in Machine learning and knowledge discovery in databases, pp. 18–33, Springer, 2011.

[82] Schneider, C. M., Yazdani, N., Araújo, N. A., Havlin, S., and Herrmann, H. J., "Towards designing robust coupled networks," Scientific reports, vol. 3, 2013.

[83] Schumer, C. and Maloney, C., "Your flight has been delayed again: flight delays cost passengers, airlines, and the US economy billions," The US Senate Joint Economic Committee, 2008.

[84] Shao, J., Buldyrev, S. V., Havlin, S., and Stanley, H. E., "Cascade of failures in coupled network systems with multiple support-dependence relations," Physical Review E, vol. 83, no. 3, p. 036116, 2011.

[85] Sherry, L. and Donohue, G., "Us airline passenger trip delay report (2007)," Center for Air Transportation Systems Research. George Mason University. http://catsr. ite. gmu. edu/tHE HAMiLton ProJEct tHE BrookingS inStitUtion, 2008.

[86] SITA, "The passenger IT trends survey." www.sita.aero/system/files/Passenger-IT-Trends-Survey-2014.pdf, 2014.

[87] SITA, "Ready for the connected traveler." http://www.sita.aero/content/Air-Transport-IT-Review-Issue-1-2015, 2015.

[88] Slivka, D., Morris, K., Chancey, J., Ngu, A., Smith, B., Clarke, M., Lettovsky, L., Strothmann, R., Nagireddy, V., Abadzic-Ovcina, A., and others, "Methods, systems, and articles of manufacture for re-accommodating passengers following a travel disruption," Sept. 24 2002. US Patent App. 10/252,608.

[89] Spies, G., Piekert, F., Marsden, A., Suikat, R., Meier, C., and Eriksen, P., "Operational concept for an airport operations center to enable total airport management," in Proceedings of ICAS, 2008.

[90] Sridhar, B., "Relationship between weather, traffic and delay based on empirical method." NEXTOR Asilamor annual conference, 2007.

[91] Sridhar, B. and Sheth, K., "Network characteristics of air traffic in the continental united states," in Proceedings of the 17th International Federation of Automatic Control World Congress, Coex, South Korea, pp. 6–11, 2008.

[92] Wambsganss, M., "Collaborative decision making through dynamic information transfer," Air Traffic Control Quarterly, vol. 4, no. 2, p. 107, 1996.

[93] Wang, D., Methods for analysis of passenger trip performance in a complex networked transportation system. PhD thesis, George Mason University, 2007.

[94] World Economic Forum, "Connected World : Transforming Travel, Transportation and Supply Chains." http://www3.weforum.org/docs/WEF_MO_ConnectedWorld_Report_2013.pdf, 2013.

[95] World Economic Forum, "Smart travel: Unlocking economic growth and development through travel facilitation." http://www3.weforum.org/docs/GAC/2014/WEF_GAC_TravelTourism_SmartTravel_WhitePaper_2014.pdf, 2014.

[96] Xiong, J., "Revealed preference of airlines' behavior under air traffic management initiatives," 2010.

[97] Ye, S. and Wu, S. F., Measuring message propagation and social influence on Twitter. com. Springer, 2010.

[98] Zhang, Y. and Hansen, M., "Real-time intermodal substitution: Strategy for airline recovery from schedule perturbation and for mitigation of airport congestion," Transportation Research Record: Journal of the Transportation Research Board, vol. 2052, no. -1, pp. 90–99, 2008.

[99] Zhang, Y. and Hansen, M., "Regional gdpextending ground delay programs to regional airport systems," in Eighth USA/Europe Air Traffic Management Research and Development Seminar, Napa, CA, p. 6, 2009.

VITA

Aude C. Marzuoli attended the Classes Preparatoires at the Lycee Henri IV in Paris. She graduated with a Diplome d'Ingenieur from Supelec and a Master in Aerospace Engineering from the Georgia Institute of Technology in 2012. She has worked for ENAC (the French School for Civil Aviation), SESAR Joint Undertaking and NASA Ames.