Improving Disruption Management With Multimodal Collaborative Decision-Making: A Case Study of the Asiana Crash and Lessons Learned

Aude Marzuoli, Emmanuel Boidot, Pablo Colomar, Mathieu Guerpillon,
Eric Feron, Alexandre Bayen, and Mark Hansen

***Abstract*—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 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 U.S. and in Europe. This paper examines how it could be extended to the multimodal network level, discusses the supporting evidence, and provides recommendations for implementation. A case study on the disruption management following the Asiana Crash at San Francisco International Airport is presented. The crash led to a large number of flight diversions to many airports, such as Oakland, Los Angeles, but also Seattle for instance, disrupting the journeys of thousands of passengers. Passenger reaccommodation varied greatly from airline to airline and airport to airport. First, a passenger-centric reaccommodation scheme is developed to balance costs and delays, for each diversion airport. Second, assuming better information sharing and collaborative decision-making, we show 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. Based on this case study, recommendations for the adoption of multimodal CDM are elaborated. This paper paves the way for further data-driven research for increased resilience of passenger door-to-door journeys.**

***Index Terms*—Air traffic control, air transportation, rail transportation, road transportation, robustness.**

I. INTRODUCTION

IN 2012, 2.9 billion passengers boarded an airplane, whether for business or leisure, across the world [1]. 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. 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 [2]–[5]. 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 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 passenger keeps growing [1], congestion and snowball effects threaten the resilience of the whole multimodal transport infrastructure.

On the transportation side, there has been extensive research on disturbance propagation in the airspace [6]–[9], the impact on airline scheduling of aircraft and crew [10] and the best recovery optimization schemes [11], [12]. 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 recovery mechanisms are aircraft swaps, flight cancellations, crew swaps, reserve crews and passenger rebooking. Usually airlines react by solving the problem in a sequential manner. First, infeasibility of the aircraft schedule is examined, then crewing problems, then ground problems and the impact on passengers.

In the coming decades, air traffic demand is expected to increase significantly [13]. The present airspace capacity limits 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 [14]. In 2012, 18.22% of flights were delayed in the United States [6].

Most of the traffic demand growth is expected to take place 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 [15]. Atkins [16] examined the San Francisco Bay Area metroplex, providing a definition and an initial framework to measure metroplex performance.

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A. Marzuoli, E. Boidot, P. Colomar, M. Guerpillon, and E. Feron are with the Department of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: amarzuoli3@gatech.edu).

A. Bayen and M. Hansen are with the Department of Civil and Environmental Engineering, University of California at Berkeley, Berkeley, CA 94720 USA.

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Clarke *et al.* [17], [18] identified six types of interdependencies between traffic flows in a metroplex based on observations. Li *et al.* [19] studied the metroplex operational interdependencies, resulting from sharing limited common resources in airspace, such as common fixes, flight paths, airspace volumes and downstream restrictions. DeLaurentis [20] evaluated a concept of flexible operations at a metroplex to optimize the use of common resources.

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) [21]. The FADE (FAA Airlines Data Exchange) project aimed at the development of operational procedures and decision support tools for implementing and managing GDPs. However, the CDM philosophy and principles can and should be applied to a much broader class of problems in air traffic management. Prototype GDP operations started in 1998 at San Francisco and Newark airports [22]. The collaboration between government and industry was born out of the FAA's need for real-time operational information from the airlines and the airlines' desire to gain more control over their operations during a GDP [23]. Burgain *et al.* [24] developed a Collaborative Virtual Queue (CVQ), which uses virtual queuing to keep aircraft away from runway queues and enable last-minute flight swapping. Gupta [25] built an integrated system, SARDA-CDM, for improving surface operations by metering departing aircraft. 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.

Over the past few years, severe weather perturbations have paralyzed the transportation system. On the European side, the eruption of the islandic volcano in 2010 had the longest and biggest economic impact on aviation [26], with more than 100,000 flights canceled. Bolic *et al.* offer recommendations to better address such large disruptions, stressing the need for better information exchanges between all the stakeholders. Zhang [27] develops a framework to reduce passenger "disutility," to help airlines recover schedule more promptly, and to assist traffic flow managers to utilize 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. Such intermodalism triggered by disruptions was reported by Evans regarding Continental Airlines at Newark [28]. Real-time intermodalism includes the substitution of flights by ground transportation 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 airports, while limiting the impact on airlines.

Recently, a shift towards passenger-centric metrics in air transportation, as opposed to flight-centric, has been promoted, after the disproportionate impact of airside disruptions on passenger door-to-door journeys was highlighted [29]–[32]. Flight delays 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. [29] design propagation-centric and passenger-centric performance metrics, and compare them with existing flight-centric metrics. In [30], 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 the total passengers, but suffer 39% of the total passenger delay. Wang [31] showed that high passenger trip delays are disproportionately generated by canceled flights and missed connections. 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 airline cooperation policy are the most significant factors affecting total passenger trip delay.

The goal of this paper is to examine how Multimodal Collaborative Decision Making can support better crisis management at the network level, from passenger-centric and flight-centric perspectives. This paper tackles mitigation strategies following the Asiana Crash, both for passengers and for flights. Section II briefly describes the impact of the crash on operations and on passengers. In Section III, 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 example of massive flight diversions because of an unexpected airport closure. In Section IV, a passenger-centric optimization is proposed to analyze the reaccommodation, via bus or aircraft, of passengers diverted to airports within reasonable drive distance of San Francisco. In Section V, 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. Section VI provides recommendations for improved crisis management. Finally, Section VII draws the conclusions of the paper and suggests future research paths.

II. The Impact of the Asiana Crash

A. Impact on Operations

First let us briefly summarize the events leading to the Asiana crash at San Francisco International airport (SFO). SFO 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, 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 SFO. Of the 307 people aboard, 3 died, 181 others were injured. The accident investigation submission [33] 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."

The crash resulted in a five hour total closure of the runways at the 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. This crash is a powerful example of node failure leading to ripple effects on several networks. Indeed, an airport is a node for the air transportation network, for the road network because of easy highway access and for the transit network, with a BART (Bay Area Rapid Transit) station in the Bay Area.

The work presented is based upon publicly available data from the Bureau of Transportation Statistics (BTS) that are primarily used to evaluate airline on-time performance and ETMS data, that provides aircraft radar latitude and longitude every one minute.

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. Over four days, more than 660 flights to SFO and 580 flights from SFO airport had either been canceled or diverted. Diversions mostly occurred on Saturday as well as on Sunday. The proportion of domestic diversions is high: 74 arrival flights, that is 17% of arrival flights to SFO, were diverted on Saturday. There were also 180 cancellations of arrival flights, and 231 cancellations of departure flights from SFO on Saturday. On Sunday, the situation improved a little, with still 30 arrival flights to SFO and 30 departure flights from SFO diverted. According to the BTS, 0.2% of domestic flights were diverted in 2013, and it is a steady number since 2004. 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. Cancellations and delays due to the crash at SFO propagated through the airspace and the ripple effect lasted several days. 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. 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 entire US 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.

The major carrier flights were diverted to a number of airports. The other Bay Area airports, Oakland (OAK) and San Jose (SJC) accommodated most flights, from Saturday to Tuesday. Several other airports, as far as Denver (DEN), Los Angeles (LAX) and Las Vegas (LAS), received many diverted flights on the crash day. Fig. 1 displays the estimated number of diverted 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 SFO, their final destination, 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 on the spot. Twitter quickly started to be the most updated channel of information for passengers. In the ETMS data, we found 25 additional diversions, by analyzing the trajectories of international flights scheduled to arrive at SFO but landing elsewhere. These diverted flights landed in Vancouver (YVR), Calgary (YYC), SEA, LAX, SMF, LAS, OAK and SJC.

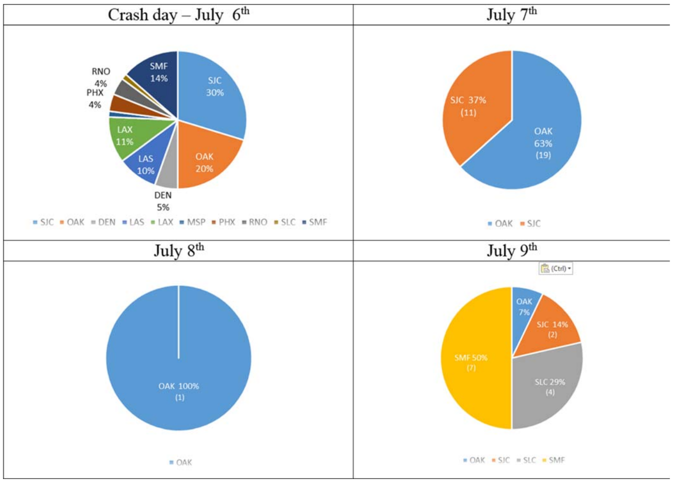


Fig. 1. Percentages of domestic flights diverted to different airports from July 6th to July 9th 2013.

Most stakeholders only have access to a partial view of the crisis 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 more efficient. Our work therefore focuses on optimization of aircraft operations and diverted passenger reaccommodation. At the present stage, only hypotheses can be drawn when it comes to how diverted passengers who landed sometimes several hundred miles from their destination airport actually made it to their final destination. Social media, such as Twitter, provides pieces of information suggesting that the treatment of passengers and the crisis management varied greatly from airport to airport and from airline to airline.

B. *Impact on Passengers*

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 crisis, which is rarely taken into account while analyzing the air transportation performance under crises. When it comes to timing, tweets provide a means to access specific information about diverted passengers. 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.

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, [34] customer-service representatives collected travelers' names and phone numbers so the airline could rebook or cancel flights without the people standing in line. Passengers were advised 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 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 [35] how in Sacramento, located less than 100 miles from SFO, people waited for hours uninformed, queueing around help desks and 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. 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.

On July 6th, Salt Lake City International Airport (SLC) absorbed most of the international flights, instead of SJC or OAK. SLC was the closest airport with an international custom capable of processing international flights diverted, as OAK and SJC had no such facilities ready. However, some international flights could not be diverted to international hubs such as Seattle or Phoenix, due to low fuel reserves. Therefore, some of them were forced to land in Sacramento, which is not equipped in terms of customs, forcing the custom officers to enter the aircraft to proceed with the security checks in situ. Other customs issues were reported in Oakland.

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: rebooking 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. Tomorrow's (Sunday's) 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" [35]. "Transportation to San Francisco for passengers diverted to Sacramento (SMF) 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 SMF. 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" [36]. "Additional staff was brought in to help accommodate the more than 1,000 passengers that were diverted to SMF 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" [37]. 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 [38] 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." "Many passengers were diverted to airports where their airline operates at low frequency.

Regarding how airports handled flight diversions, San Jose airport stated [39]: "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 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."

The lack or the little amount of information delivered by airlines, added to the highly booked situation of the holiday week-end, created additional crisis situations in the diverted airports. At that point, a few airlines decided to implement inter-modal operational measures by 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.

III. FLIGHT DIVERSIONS

According to an FAA official [40], "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." Jenkins *et al.* [41] describe disruptions as follows: "Diversions are an expensive, chronic, and disruptive element of flight operations, costing at least $300 MM 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."

A. Airline Policy

Most airlines indicate on their websites how diversions are handled and what the consequences may be for passengers. Even for non-refundable tickets, 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 passenger's 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. (...) 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 (meaning it will not eventually reach its final destination), 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, the 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; ground transportation; passengers without baggage will be reimbursed upon presentation of receipts for reasonable incidentals such as toiletries needed until they are reunited with their baggage."

B. FAA Rules

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 have 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."

C. IATA Diversions Management

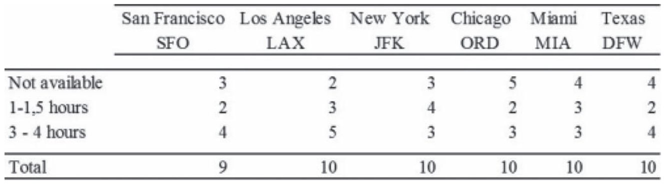
A representative of IATA summarized the criteria for selecting airports where diverted flights land as follows: Safety of Flight, Airspace or Airport Restrictions, Overflight authorization, Landing authorization, Immigration, Customs, Airport Services, Crew considerations, Service recovery options, Schedule 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.

IV. 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 [27] conducted a study on bus charter companies' response to service inter-modal service requests. To evaluate how promptly charter companies could respond to service requests, they conducted a telephone survey for ten randomly picked charter companies for six regions in the



	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

Fig. 2. Intermodal service times reported by Hansen and Zhang.

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, 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 Fig. 2 and show that buses can be made available at most airports in less than four hours.

After the Asiana crash, and considering the airports that welcomed most flight diversions, 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); Las Vegas 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 FAA, and are not to be updated for changes in price levels. The present analysis study only examines what could have been the best case scenario, in hindsight, based on the data recorded for this disruption.

A. Model Formulation

1) Nomenclature Used in the Model: Let us define the input sets as follows:

- $\mathcal{A} = a_1, a_2, \ldots, a_4$ be the set of diverted airports (RNO, SMF, LAS, LAX).
- $\mathcal{F} = f_1, f_2, \ldots, f_n$ be the set of departure flights from the diverted airports to the Bay Area (SFO, OAK, SJC).
- $\Gamma = t_1, t_2, \ldots, t_T$ the set of discrete time periods.
- $\mathcal{P} = p_1, p_2, \ldots, p_P$ the set of diverted passengers.
- $A = g_1, g_2, \ldots, g_{\text{MaxAircraft}}$ the set of aircraft available to charter in the diverted airport.
- $B = b_1, b_2, \ldots, b_{\text{MaxBuses}}$ 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.
- $\text{BDT}_{\text{OAK}}, \text{BDT}_{\text{SJC}}, \text{BDT}_a$: 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:

- β_{Wait}: Weight coefficient for passenger waiting time.
- β_{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: $\text{OAK}_f^a = 1$ if the destination of departure flight f from diverted airport a is OAK, $\text{OAK}_f^a = 0$ otherwise. $\text{SJC}_f^a = 1$ if the destination of departure flight f from diverted airport a is SJC, $\text{SJC}_f^a = 0$ otherwise.

Output binary variables:

The first type of output binary variables are $\text{Squeeze}_{p,f,a}^t$, $\text{Subst}_{p,b,a}^t$ and $\text{Charter}_{p,g,a}^t$. These three variables assign passengers to one of the three possible rerouting options: $\text{Squeeze}_{p,f,a}^t = 1$ if passenger p is squeezed into flight f departing from diverted airport a in time interval t; $\text{Subst}_{p,b,a}^t = 1$ if passenger p is rerouted with motor coach b from diverted airport a in time interval t; $\text{ACharter}_{p,g,a}^t = 1$ 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 $\text{DTBus}_{b,a}^t$ and $\text{DTCharter}_{g,a}^t$, indicating when a bus or an chartered aircraft leaves diverted airport a. $\text{DTBus}_{b,a}^t = 1$ if bus b departs in time period t; $\text{DTCharter}_{g,a}^t = 1$ if chartered aircraft g departs in time period t.

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.

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 arrival capacity for the chartered flights to land in the Bay Area.

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 a cost-effective way to bring passengers from the diversion airport to their final destination, 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:

$$\sum_t [\mathrm{CSqueeze}^t + \mathrm{CSubst}^t + \mathrm{CCharter}^t]. \tag{1}$$

Cost of squeezing passengers into departure flights

$$\begin{aligned}\mathrm{CSqueeze}^t = \sum_a \sum_p \sum_f \ & \mathrm{Squeeze}^t_{(p,f,a)} \\ & \times [\mathrm{FlightTime}_a \beta_{\mathrm{transp}}\ \mathrm{CostP} \\ & + \left(\mathrm{ADT}^a_f - \mathrm{ADivAT}^a_p\right)\ \mathrm{CostP}\ \beta_{\mathrm{wait}} \\ & + \mathrm{CostBV}\ \left(\mathrm{SJC}^a_f + \mathrm{OAK}^a_f\right) \\ & + \left(\mathrm{BDT}_{\mathrm{OAK}} \cdot \mathrm{OAK}^a_f + \mathrm{BDT}_{\mathrm{SJC}} \cdot \mathrm{SJC}^a_f\right) \\ & \times \beta_{\mathrm{transp}}\ \mathrm{CostP}] \,. \end{aligned} \tag{2}$$

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 β_{Wait}. 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 β_{Transp}.

Cost of reaccommodation via ground transportation substitution

$$\begin{aligned}\mathrm{CSubst}^t = \sum_a \sum_p \sum_b \mathrm{Subst}^t_{(p,b,a)} & \left[\mathrm{BDT}_a \beta_{\mathrm{wait}} \mathrm{CostP}\right. \\ & \left. + \left(t \cdot \mathrm{TimeFactor} - \mathrm{ADivAT}^a_p\right) \mathrm{CostP}\beta_{\mathrm{wait}} + \mathrm{CostBV}\right] . \end{aligned} \tag{3}$$

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 $\mathrm{BDT}_{\mathrm{Div}}$ by the passenger value of time CostP, weighted by β_{transp}. The third term computes the cost per passenger of contracting the motor coach service CostBV.

Cost of chartering an aircraft

$$\begin{aligned} & \mathrm{CCharter}^t \\ & = \sum_a \sum_p \sum_g \mathrm{Charter}^t_{(p,g,a)} \\ & \quad \times \left[\mathrm{CostCharter} + \left(t \cdot \mathrm{TimeFactor} - \mathrm{ADivAT}^a_p\right)\right. \\ & \qquad \left. \times \mathrm{CostP}\ \beta_{\mathrm{wait}} + (\mathrm{FlightTime}_a\ \beta_{\mathrm{transp}}\ \mathrm{CostP})\right] . \end{aligned} \tag{4}$$

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 $\mathrm{FlightTime}_{\mathrm{DivAirp}}$ by the passenger value of time CostP, weighted by β_{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) 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:

$$\sum_t \sum_p \mathrm{Squeeze}^t_{(p,f,a)} \leq \mathrm{Seats}^a_f \qquad \forall f, \forall a. \tag{5}$$

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

$$\begin{aligned} & \left(t \cdot \mathrm{TimeFactor} - \mathrm{ADT}^a_f\right) \times \mathrm{Squeeze}^t_{(p,f,a)} \\ & \qquad \leq 0 \quad \forall t, \forall f, \forall a, \forall p. \end{aligned} \tag{6}$$

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

$$\sum_p \mathrm{Subst}^t_{(p,b,a)} \leq \mathrm{CapBus} \quad \forall b, \forall a, \forall t. \tag{7}$$

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

$$\mathrm{DTBus}_{b,a}^{t} \geq \mathrm{Subst}_{(p,b,a)}^{t} \ \forall p,\ \forall b,\ \forall a,\ \forall t. \tag{8}$$

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

$$\text{If } \mathrm{DTBus}_{b,a}^{t} \geq 1, \text{ then } \sum_{p} \mathrm{Subst}_{(p,b,a)}^{t} \geq \mathrm{MinloadBus} \cdot \mathrm{CapBus} \quad \forall p,\ \forall b,\ \forall a,\ \forall t. \tag{9}$$

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

$$\sum_{t} \mathrm{DTBus}_{b,a}^{t} \ \leq\ 1 \qquad \forall b, \forall a,\ \forall t. \tag{10}$$

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:

$$\sum_{p} \mathrm{Charter}_{(p,g,a)}^{t} \leq \mathrm{CapAircraft}_{g} \qquad \forall g, \forall a,\ \forall t. \tag{11}$$

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

$$\mathrm{DTCharter}_{g,a}^{t} \geq \mathrm{Charter}_{(p,g,a)}^{t} \ \forall p,\ \forall g,\ \forall a,\ \forall t. \tag{12}$$

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

$$\text{If } \mathrm{DTCharter}_{g,a}^{t} \geq 1, \quad \text{then } \sum_{p} \mathrm{Charter}_{(p,g,a)}^{t} \geq \mathrm{MinloadAc} \cdot \mathrm{CapAc} \quad \forall p,\ \forall g,\ \forall a,\ \forall t. \tag{13}$$

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

An chartered aircraft g can only depart once:

$$\sum_{t} \mathrm{DTCharter}_{g,a}^{t} \ \leq\ 1 \qquad \forall g, \forall a. \tag{14}$$

Passenger conservation constraints

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

$$\sum_{t} \left[\sum_{f} \mathrm{Squeeze}_{(p,f,a)}^{t} + \sum_{b} \mathrm{Subst}_{(p,b,a)}^{t} + \sum_{g} \mathrm{Charter}_{(p,g,a)}^{t} \right] = 1 \qquad \forall p, \forall a. \tag{15}$$

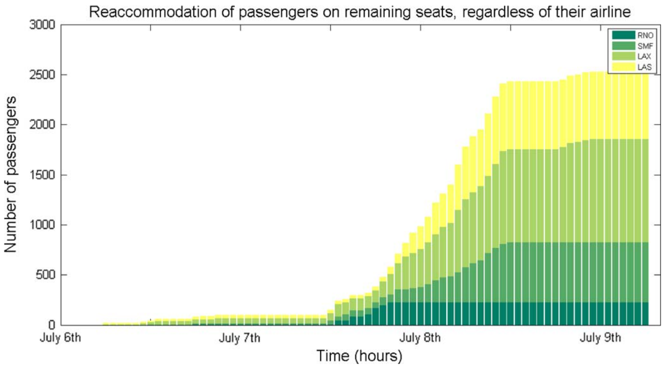


Fig. 3. Reaccommodation of diverted passengers on remaining seats in flights that reached the Bay Area, regardless of their original carrier.

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

$$\forall a, \forall p, \forall t, \forall f, \forall b, \forall g \quad [t \cdot \mathrm{TimeFactor} - (30 + \mathrm{ActualDivAT}_{p,a})] \times \left(\mathrm{Squeezed}_{(p,f,a)}^{t} + \mathrm{Subst}_{(p,b,a)}^{t} + \mathrm{Charter}_{(p,g,a)}^{t} \right) \ \geq 0. \tag{16}$$

B. Optimization Results

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. American Airlines policy indicates that, under special circumstances, passengers may be rebooked on another carrier. Fig. 3 shows how long it would have taken for all passengers to be rebooked depending on the airport they were diverted to: 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, fewer than 300 passengers would have reached the Bay Area before Monday, July 8th at noon, that is, less 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 described below.

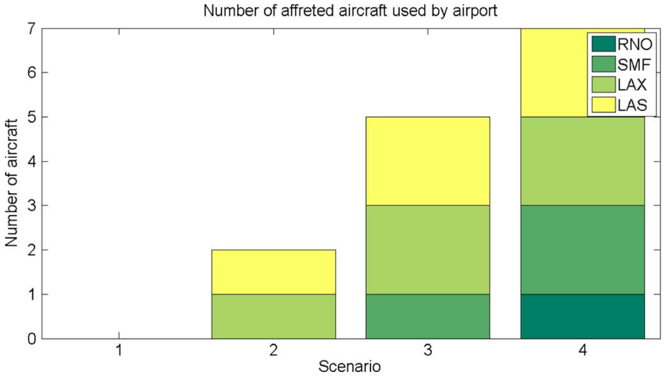


Fig. 4. Number of chartered aircraft available and used in each scenario.

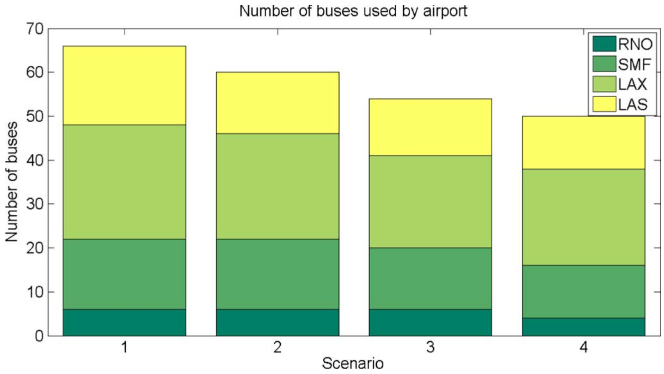


Fig. 5. Number of buses used in each scenario.

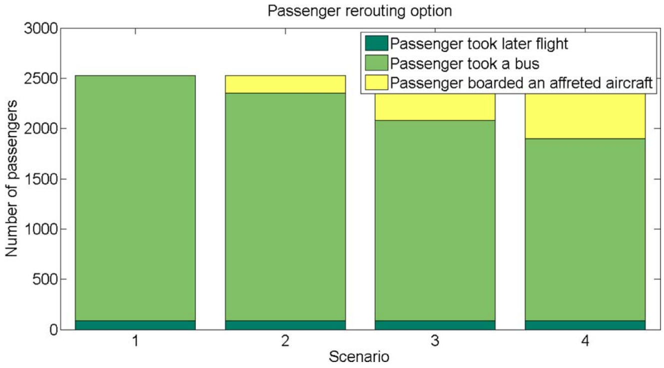


Fig. 6. Rerouting assignment of passengers in each scenario.

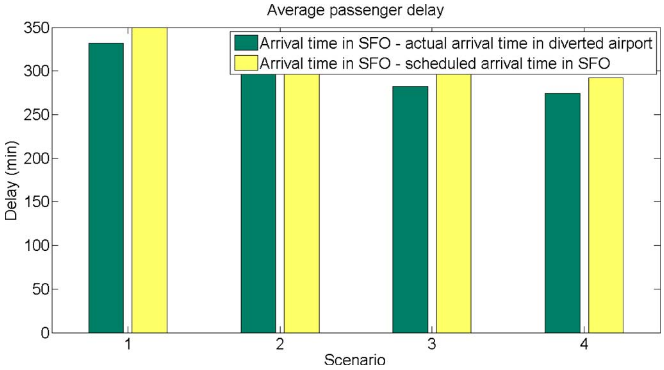


Fig. 7. Average passenger delay in each scenario.

2) *Study of Different Scenarios Involving Various Numbers of Aircraft Available for Chartering:* The input coefficients are set to the following values:

- $\beta_{\text{Wait}} = 0.5$
- $\beta_{\text{Transp}} = 1 - \text{Beta}_{\text{Wait}}$
- $\text{MinloadBus} = 0.75$
- $\text{MinloadCharter} = 0.9$

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 Fig. 4. 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.

Solving the foregoing optimization problem for the four scenarios described, the results show different trends. First, Fig. 5 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 Fig. 6, showing that chartering a total of five aircraft in scenario 4 largely changes the proportion of passengers accommodated on new flights.

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. Fig. 7 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 further away from SFO. It also highlights that chartering aircraft reduces the average delay by about an hour. Figs. 8 and 9 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.

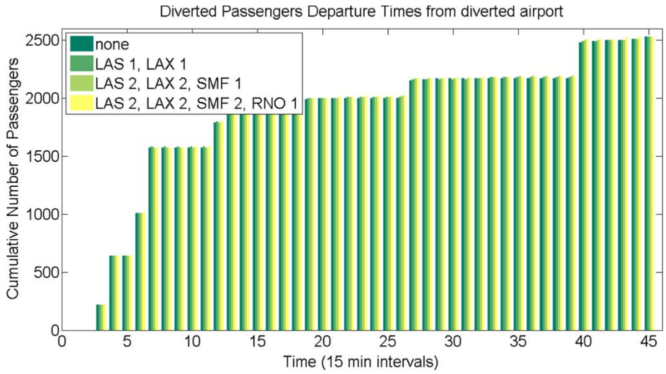


Fig. 8. Cumulative number of passengers by departure time from the diverted airport, for each scenario.

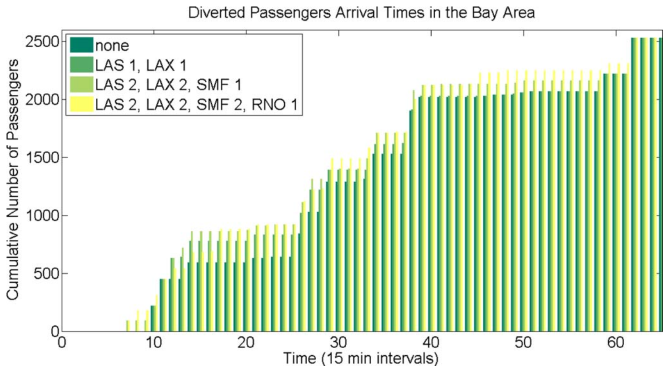


Fig. 9. Cumulative number of passengers by arrival time in the Bay Area, for each scenario.

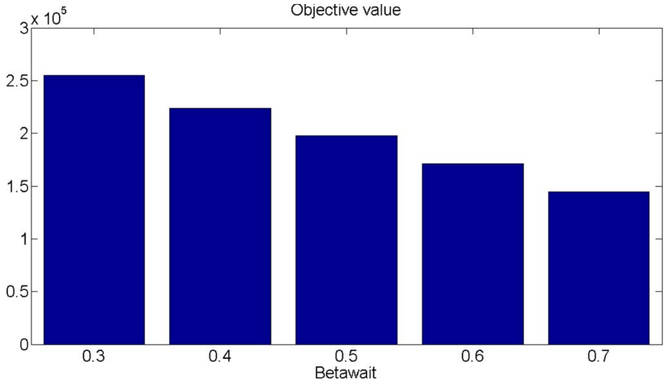


Fig. 10. Objective value for each value of β_{wait}.

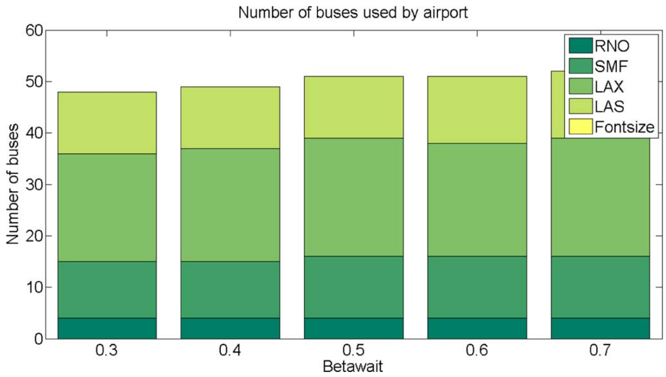


Fig. 11. Number of buses used for each value of β_{wait}.

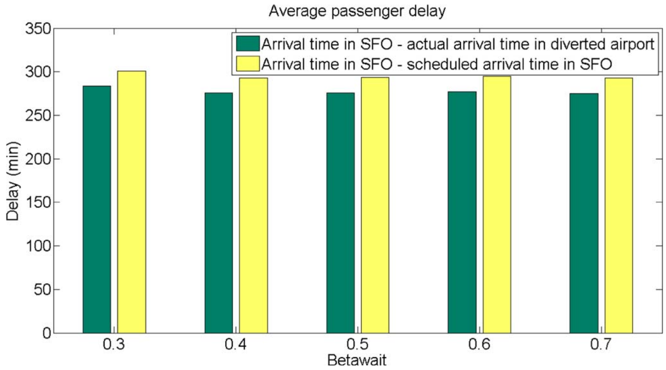


Fig. 12. Average passenger delay for each value of β_{wait}.

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 we consider 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 $\beta_{\text{wait}} = 0.3$, $\beta_{\text{wait}} = 0.4$, $\beta_{\text{wait}} = 0.5$, $\beta_{\text{wait}} = 0.6$, $\beta_{\text{wait}} = 0.7$.

Fig. 10 shows that the objective value decreases as β_{wait} increases. This is intuitive since the optimization model forces all passengers to be rerouted. Second, in Fig. 11, 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, Fig. 12 indicates that the influence of β_{wait} on passenger delay is limited.

V. METROPLEX GATE ASSIGNMENT

In the foregoing section, we studied how to better reaccommodate diverted passengers.[1] 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 Figs. 13 and 14, and show the unusual number of holding patterns and reroutings in the air, so that the flights can land at SJC or OAK.

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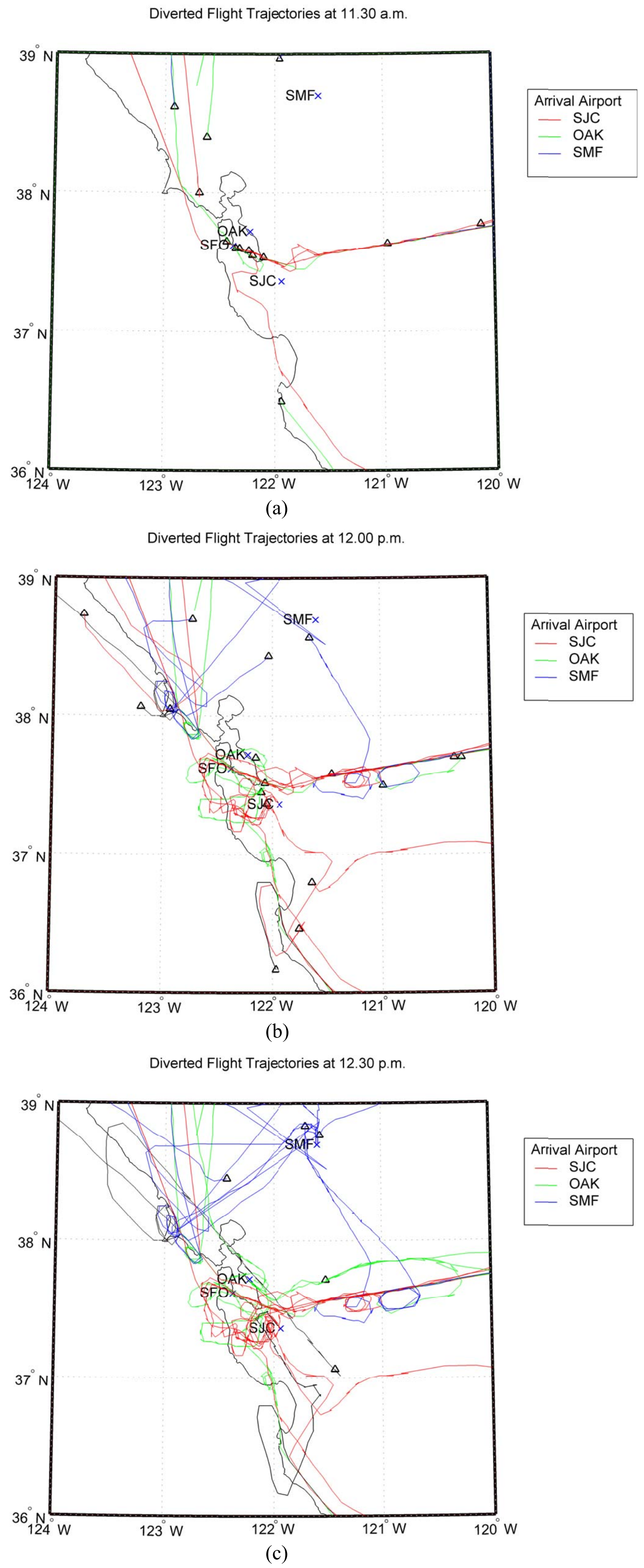
[1] Part of this research was previously published by the authors at the AIAA Infotech Conference [42].


Diverted Flight Trajectories at 11.30 a.m.

(a)

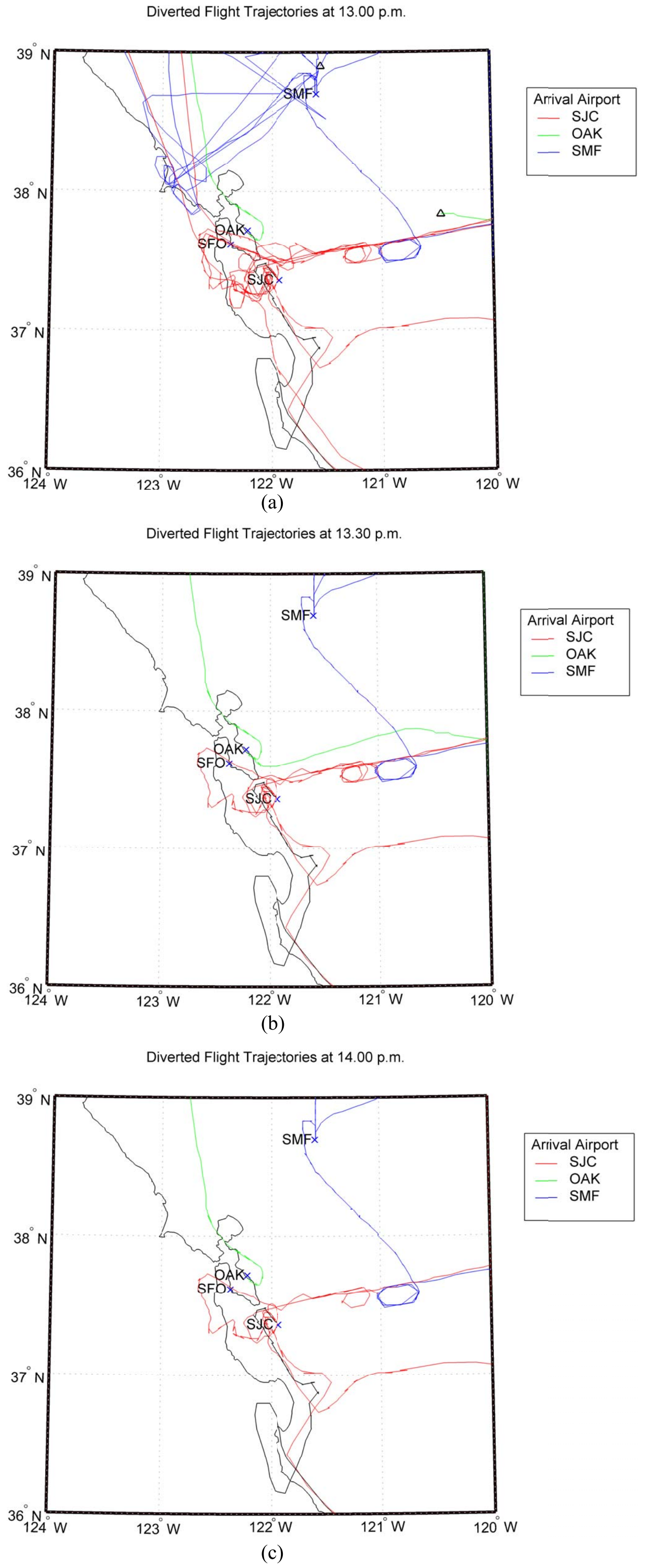
Diverted Flight Trajectories at 12.00 p.m.

(b)

Diverted Flight Trajectories at 12.30 p.m.

(c)

Fig. 13. Trajectories of diverted flights in the Bay Area following the Asiana crash at SFO from 11:30 to 12:30.


Diverted Flight Trajectories at 13.00 p.m.

(a)

Diverted Flight Trajectories at 13.30 p.m.

(b)

Diverted Flight Trajectories at 14.00 p.m.

(c)

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

A. Inputs

Consider the time period from 11:30 A.M. (local time at SFO) to 4:30 P.M.. The horizon is broken down into 15-minutes time intervals, 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 $\mathbf{A}$.

TABLE I
RESULTING DELAY PER FLIGHT FOR EACH OPTIMIZATION SCENARIO

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

For each flight $f \in \mathbf{F}$, its scheduled arrival time at SFO is denoted by arrSFO_f, where $\mathrm{arrSFO}_f = t$ corresponds to time bin t. The flight estimated arrival time (ETA) to the potential arrival airports at the time of the crash is denoted $\mathrm{timetoapt}_{f,a}$, corresponding to the arrival time bin. Assume that all flights stay gate_time time intervals 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 at 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 flights 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 at 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 $\mathrm{timetoapt}_{f,a}$ 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 a 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. 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 plus an additional 15 minutes if the flight is arriving from the North, or minus 15 minutes 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 $\mathrm{rwycapa}_{a,t}$. 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 $\mathrm{gatecapa}_{a,t}$. 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 (see Table I).

B. Problem Formulation

The objective is to minimize the arrival delay of the diverted flights in the Bay Area. In a disruptive situation, the goal is to land aircraft safely as close as possible to their original destination, i.e., 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 $\mathrm{arr}_{f,t,a}$, its gate occupancy time is indicated by $\mathrm{gateocc}_{f,t,a}$. The objective function can be formulated as follows:

$$\sum_{f\in\mathbf{F}}\sum_{t\in\mathbf{T}}\sum_{a\in\mathbf{A}} t\cdot\mathrm{arr}_{f,t,a} - \sum_{f\in\mathbf{F}}\mathrm{arrSFO}_f \tag{17}$$

The following constraints are defined:

Flight Duration 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. Aircraft are legally required to be dispatched with enough fuel to allow 45 minutes of airborne holding [43], therefore reserve time $=$ 2 time intervals, so it has to land before this time elapses

$$\forall f, \sum_{a\in\mathbf{A}} \sum_{t_e=\mathrm{timetoapt}_{f,a}}^{\mathrm{timetoapt}_{f,a}+\text{reserve time}} \mathrm{arr}_{f,t_e,a} = 1. \tag{18}$$

A flight can only land once and at one airport:

$$\forall f\in\mathbf{F}, \sum_{a\in\mathbf{A}}\sum_{t\in\mathbf{T}}\mathrm{arr}_{f,t,a} = 1. \tag{19}$$

A flight cannot arrive a gate earlier than 15 minutes after landing and not later then 45 min [44]

$$\begin{gathered}\forall f\in\mathbf{F},\ \forall a\in\mathbf{A},\ \forall t\in\mathbf{T},\ \text{if } \mathrm{arr}_{f,t,a}=1\\ \text{Then } \forall t_e\in[t+2, t+\text{gate\_time}],\ \mathrm{gateocc}_{f,t_e,a}=1\\ \text{and } \mathrm{gateocc}_{f,t+1,a}+\mathrm{gateocc}_{f,t+\text{gate\_time}+1,a}=1.\end{gathered} \tag{20}$$

An aircraft remains gate_time intervals time at one gate in one airport

$$\forall f\in\mathbf{F},\ \sum_{a\in\mathbf{A}}\sum_{t\in\mathbf{T}}\mathrm{gateocc}_{f,t,a} = \text{gate\_time}. \tag{21}$$

Airport Constraints

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

$$\forall t\in\mathbf{T}, \forall a\in\mathbf{A}, \sum_{f\in\mathbf{F}}\mathrm{arr}_{f,t,a} \le \mathrm{rwycapa}_{a,t}. \tag{22}$$

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

$$\forall t\in\mathbf{T}, \forall a\in\mathbf{A}, \sum_{f\in\mathbf{F}}\mathrm{gateocc}_{f,t,a} \le \mathrm{gatecapa}_{a,t}. \tag{23}$$

C. Results

Each one of the 90 diverted flights initially scheduled to land at SFO between 11:30 A.M. and 4:30 P.M. could theoretically have landed in the Bay area. The question remains whether good communication and information sharing regarding the remaining capacities at SJC and OAK could enable it. Even in the worse case scenario where each flight occupies its gate for two hours, OAK and SJC could accommodate the incoming

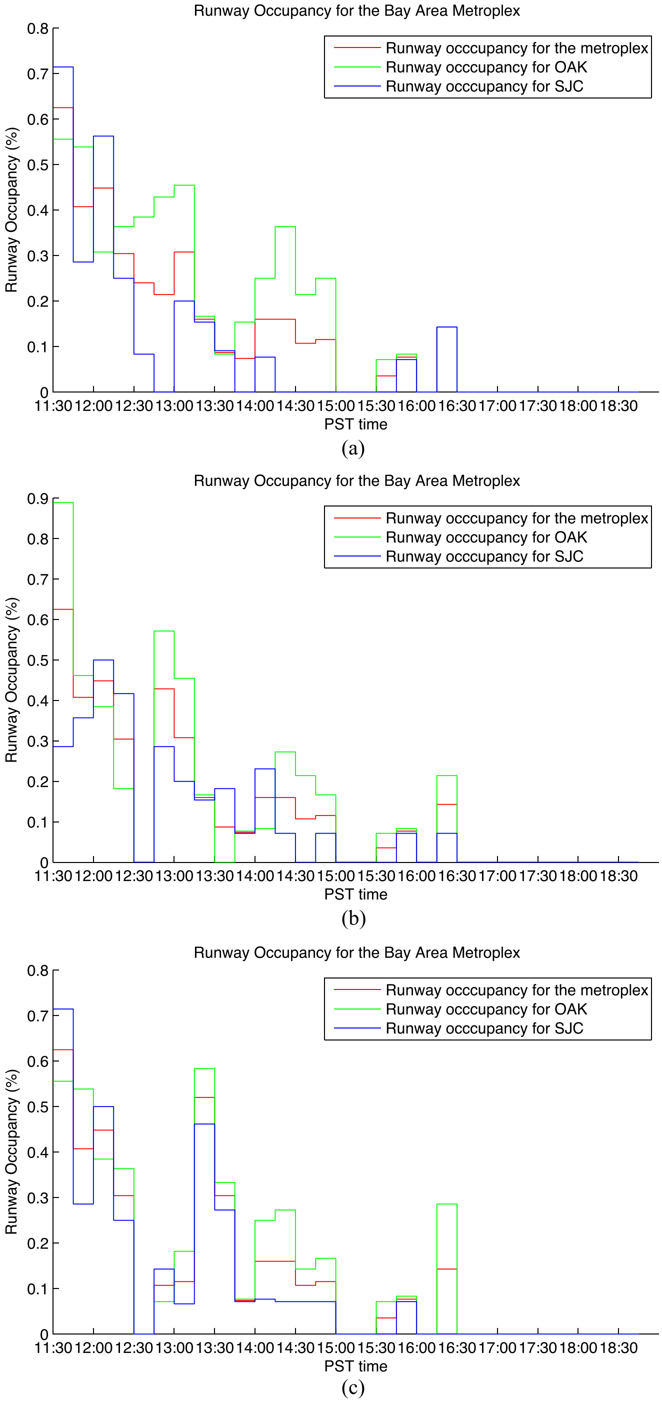


Fig. 15. Runway Occupancy at SJC and OAK for each scenario. (a) Runway occupancy for gate_time = 60 min. (b) Runway occupancy for gate_time = 90 min. (c) Runway occupancy for gate_time = 120 min.

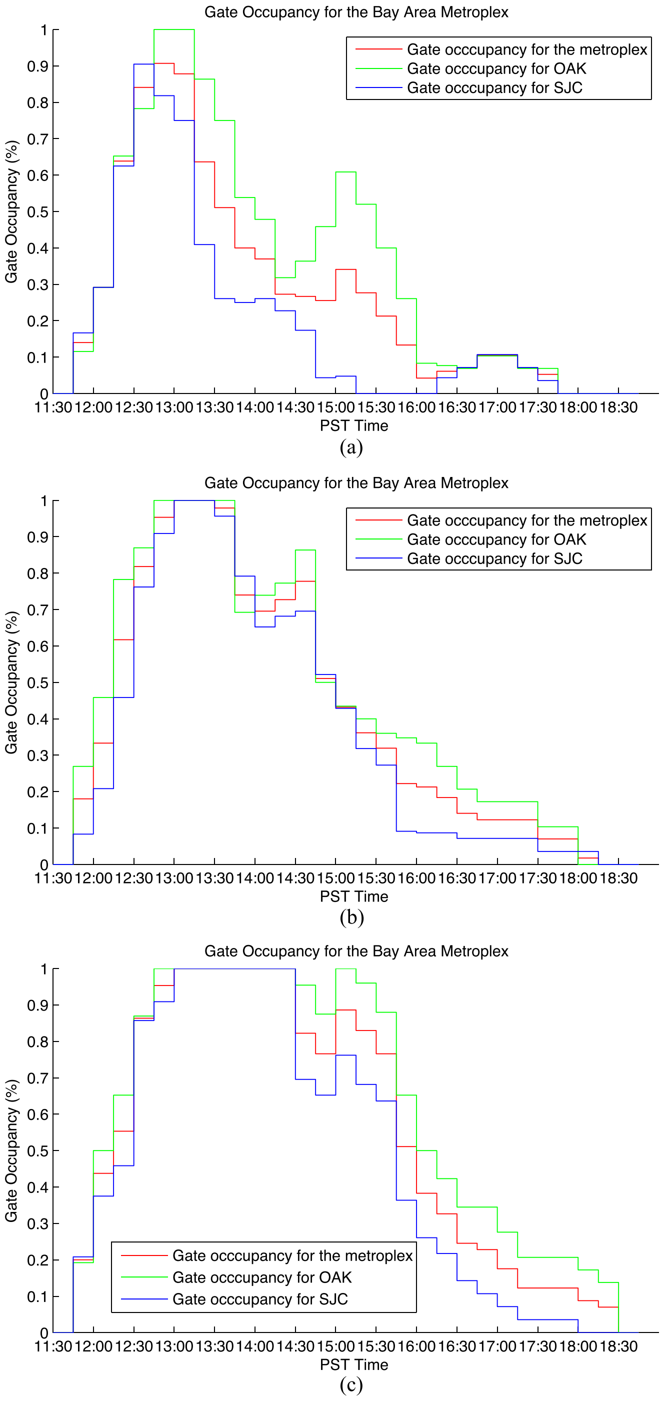


Fig. 16. Gate Occupancy at SJC and OAK for each scenario. (a) Gate Occupancy for gate_time = 60 min; (b) Gate Occupancy for gate_time = 90 min; (c) Gate Occupancy when gate_time = 120 min.

traffic, while keeping airborne flight delay relatively low and within safety limits.

Fig. 15 shows the runway capacity is stressed right after the crash, between 11:30 A.M. and 11:45 A.M.. 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% (see Fig. 16). Summarizing it all, 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 Figs. 17 and 18. The larger the gate time enforced, the more balanced the repartition is. A noticeable fact is that no flights lands between 12:30 P.M. and 12:45 P.M. 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

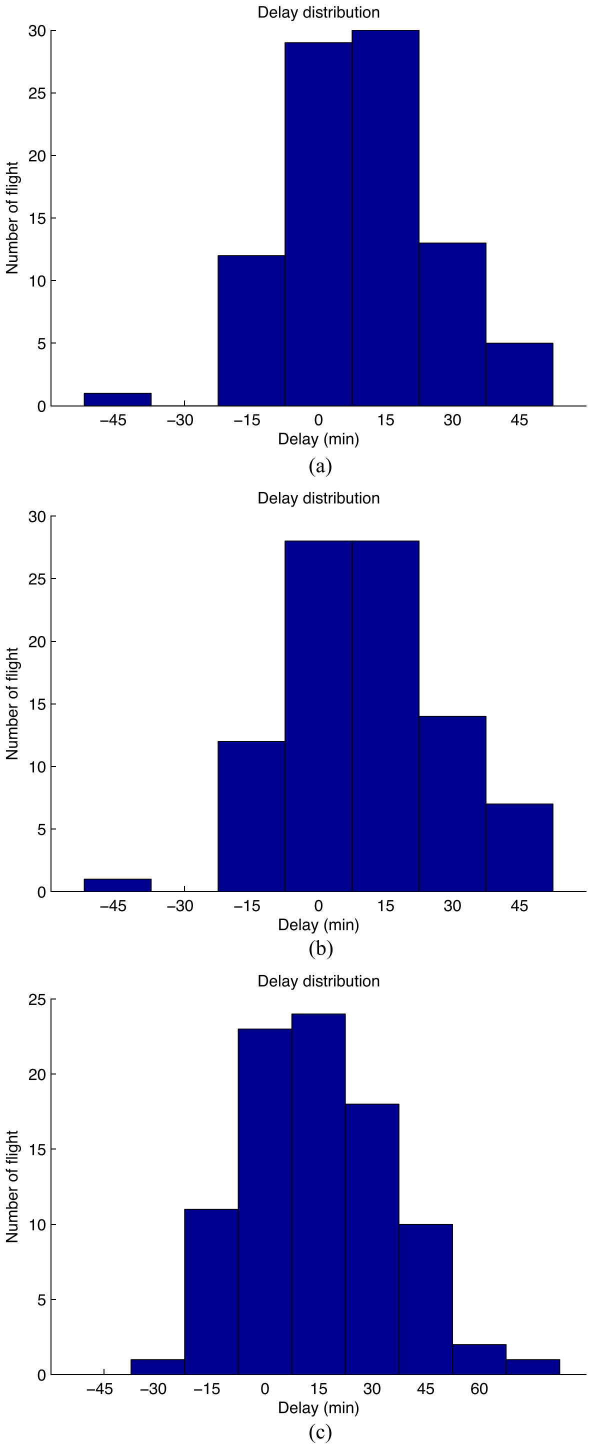


Fig. 17. Number of flights landing at SJC and OAK, and associated delays for each scenario. (a) Delays for gate_time = 60 min. (b) Delays for gate_time = 90 min. (c) Delays for gate_time = 120 min.

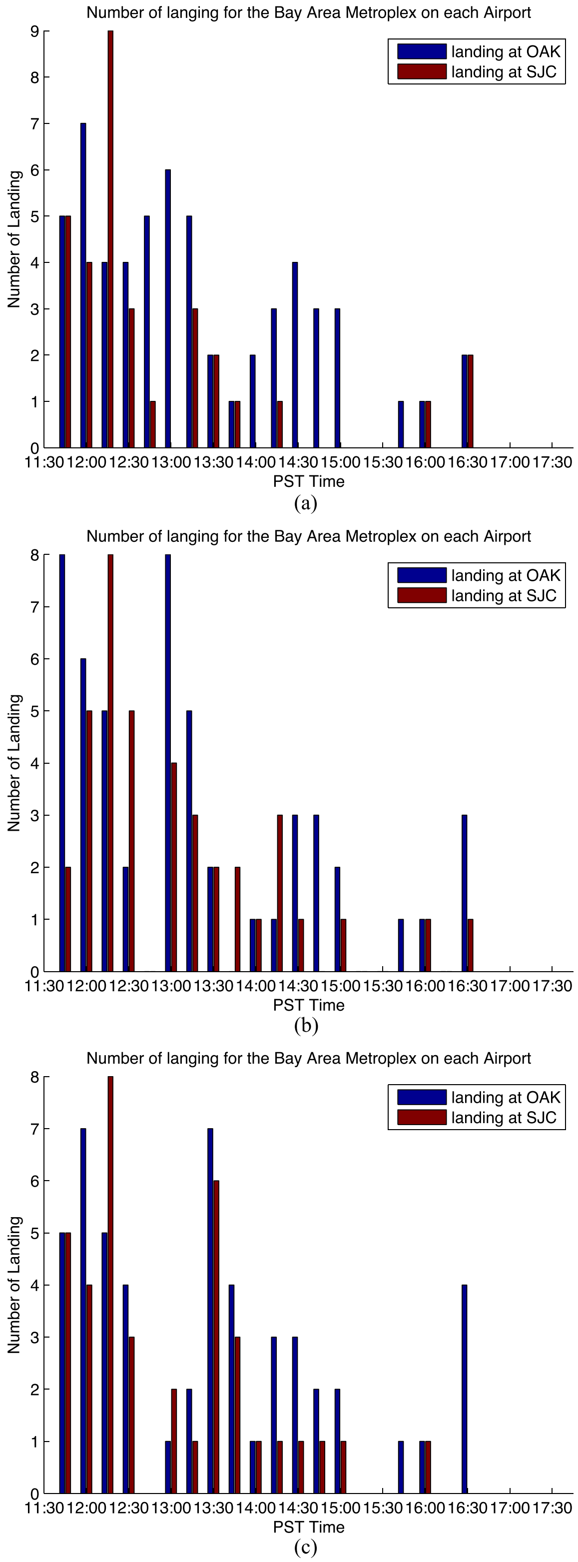


Fig. 18. Number of flights landing at SJC and OAK, and associated delays for each scenario. (a) Number of flights landing for gate_time = 60 min. (b) number of flights landing for gate_time = 90 min. (c) number of flights landing for gate_time = 120 min.

margins are not enough to mitigate the peak, and therefore airborne holding time is used to delay aircraft. However, as shown in Fig. 19, 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. Fig. 20 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.

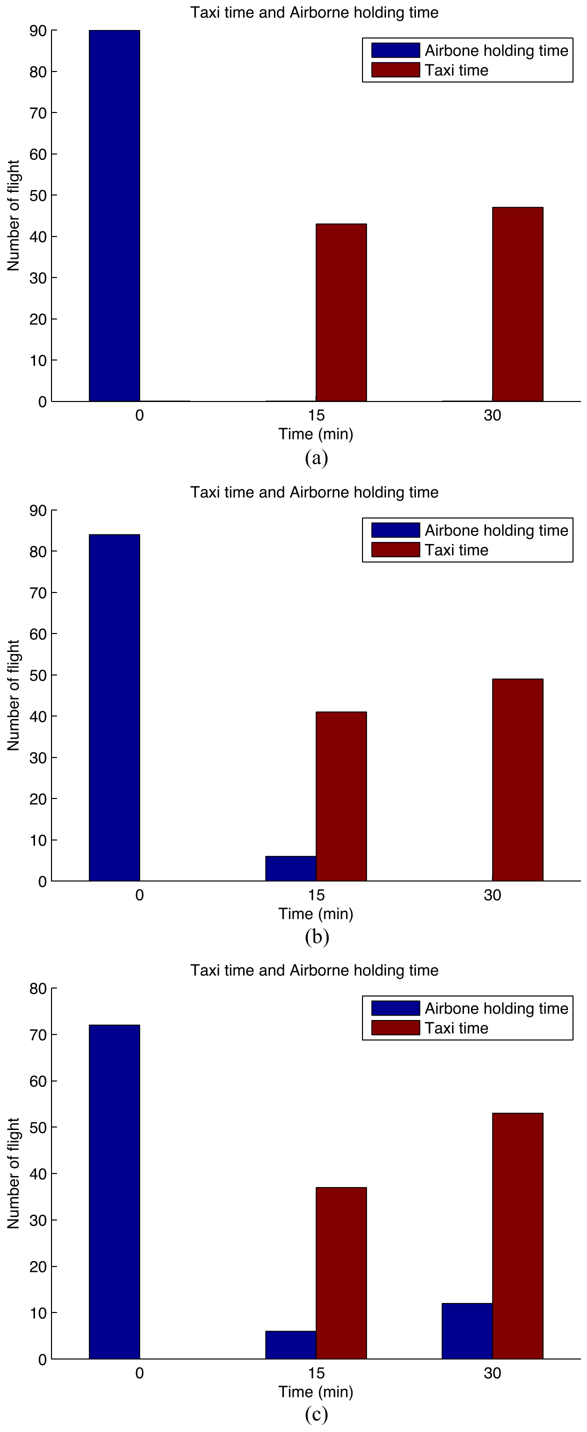


Fig. 19. Trade-offs between Airborne holding at SJC and OAK for each scenario. (a) Average Taxi vs airborne holding time for gate_time = 60 min; (b) Average Taxi vs airborne holding time for gate_time = 90 min; (c) Average Taxi vs airborne holding time for gate_time = 120 min.

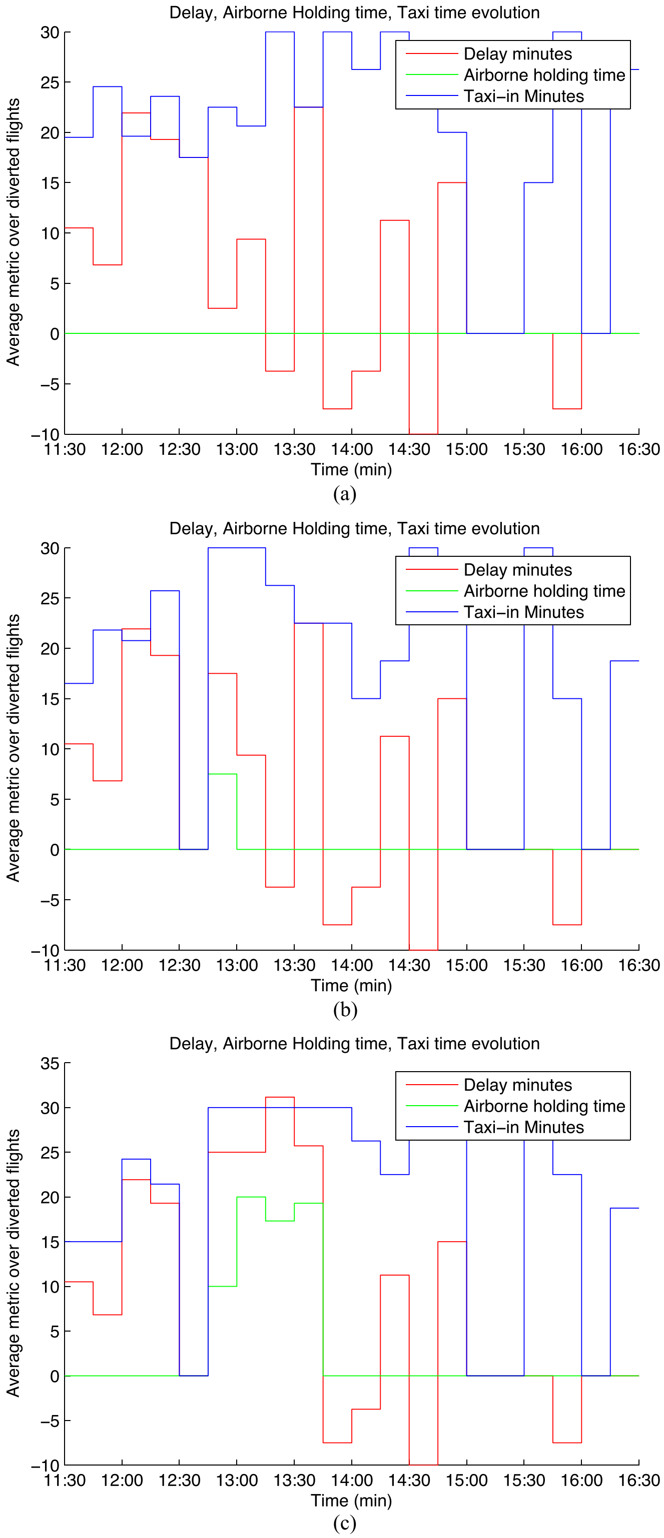


Fig. 20. Average Flight Delay, Airborne Holding and Taxi-in Times at SJC and OAK for each scenario. (a) Delay, taxi and airborne holding time evolution for gate_time = 60 min. (b) Delay, taxi and airborne holding time evolution for gate_time = 90 min. (c) Delay, taxi and airborne holding time evolution for gate_time = 120 min.

Overall, the optimization performed demonstrates that 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, including better information sharing throughout the system between airports, carriers, regarding estimated arrival times and remaining capacities, it is expected that crisis management will be handled better and avoid the diversions of thousands of passengers to far-away airports, causing many issues related to reaccommodation, customs, and carrier support to name a few.

VI. RECOMMENDATIONS FOR THE ADOPTION OF MULTIMODAL COLLABORATIVE DECISION MAKING

The Asiana crash constitutes one of many adversarial events that significantly disrupt the passengers and airlines alike. In this context, it contributes factual information supporting how operations could be improved under what we call a "multimodal CDM" concept of operations.

A. Stakeholders and Action Plans

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.

a) Timing of passenger information: The accuracy of exchanged data is critical to enable informed decisions for improved 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 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 were 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.

A disruption corresponds to an episode 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 that lead primarily to delays.

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.

2) Airlines: Airlines bear a high cost during disruptive events. Their objective is to recover from the disruption quickly and efficiently, while supporting 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) [45], 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.

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 (taxi for instance) can be locally contracted. For instance, the BART operates a reduced scheduled on Saturdays. 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, Evans [28] reported that Continental Airlines had an agreement at Newark to make buses available to air passengers in case of severe disruptions.

B. 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. 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. 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 and each transport provider. 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, such as alternatives in case of flight cancellation, could be implemented as a de-centralized service.

1) Information Sharing: According to SITA Air Transport IT review [46], “the air transport industry is shifting towards a new era of continuous engagement. (...) it is creating rising demand for more relevant services and giving airlines and airports opportunities to offer passengers enhanced personalization.” This 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 are updates on wait-times and local traffic issues: 18% offer them today, with another 55% making plans for this service.” Moreover, 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.” The continuous provision of information to the passenger is facilitated by the fact that “almost every passenger (97%) carries a smartphone, tablet or laptop.”

Recent events such as the Asiana Crash and the ensuing multimodal ripple effects clearly illustrated the fragility of the system, the costs associated with not reacting effectively and hence the need 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: delivery 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.

The identification of existing data availability, technology and data flows is necessary. To accurately evaluate performance, the available data from many data sources and reporting methods 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. Data provision and analysis could also be a way to enable multimodal ticketing, which could help significantly streamline multimodal journeys.

The duality between competition and cooperation can be an obstacle to multimodal 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 tradeoff between the performance of the solution of a multimodal network optimization and constraints in data provision should be established. Antitrust concerns should be addressed as well.

2) Resource Allocation: Several limits to passenger reaccommodation need to be addressed. 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. Putting passengers on ground transport is feasible only if there are enough seats at suitable times. The ability of ground transportation providers to support stranded passengers varies greatly by location. Several limitations may arise, including lack of spare rolling stock, staff availability and training for the routes needed, and infrastructure limits. Multimodal CDM could be decomposed into options, with several multimodal touch points, such as the BART station at OAK airport. In the context of metroplex operations under disruptions, playbooks could be developed, to provide structure and guidance. Cases such as a sudden and unforeseeable airport closure could be addressed.

Zhang *et al.* proposed a Regional Ground Delay Program (Regional GDP) [47]. When a hub airport located in a regional airport system encounters a severe airside capacity reduction, air traffic flow managers could not only evaluate 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 LAX, LAS, SMF and RNO airports, may have helped mitigate the disruption. The feasibility of multimodal CDM could be facilitated through the existing and successful initiatives constituted by GDPs and CDM.

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.

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. 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. 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. 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 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.

VII. CONCLUSION

The present paper aimed at making the case for the extension of Collaborative Decision Making to the Multimodal Network level. It tackled, in hindsight, how the disruption caused by the Asiana Crash could have been better managed, at the system level. The consequences of the crash may have been better mitigated, for both the stakeholders and passengers, had Multimodal Network CDM been in place. Two optimization models were developed to improve the crisis management following the crash. 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 flights 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. 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. One of the main obstacles to optimal capacity utilization in crises 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 a passenger-centric perspective. Then recommendations were elaborated to expand CDM to the multimodal network level and highlighted the expected benefits for all stakeholders and passengers.

The higher-level goal of this paper 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.

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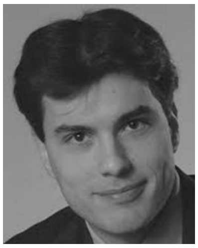
Aude Marzuoli received French Engineering Diploma from Supelec in 2012 and the Master’s and Ph.D. degrees in aerospace engineering from Georgia Institute of Technology, Atlanta, GA, USA, in 2012 and 2015, respectively. She previously worked with NASA Ames, SESAR Joint Undertaking, and the French National School of Aviation.

Emmanuel Boidot received the Master’s degrees in computer science and in aerospace engineering from Georgia Institute of Technology, and the Master’s degree in electrical engineering and computer science from Supelec in 2011. He is currently working toward the Ph.D. degree in aerospace engineering with Georgia Institute of Technology. His research interests include robotics, game theory, networks, and air transportation.

Pablo Colomar received the Master’s degree in industrial engineering from Polytechnic University of Catalonia in 2014 and the Master’s degree in mechanical engineering and management from Technische Universitat Munchen in 2015.

Mathieu Guerpillon received the Master’s degree in aerospace engineering from Georgia Institute of Technology and the French Engineering Diploma from Supelec in 2014.

Eric Feron received the B.S., M.S. and Ph.D. degrees from Ecole Polytechnique, France, Ecole Normale Superieure, France and Stanford University, U.S. Since 2005, he has been the Dutton-Ducoffe Professor of Aerospace Software Engineering, Georgia Institute of Technology. From 1993 to 2005, he was with the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology. His interests include the fundamental concepts of control systems, optimization and computer science to address important problems in aerospace engineering, such as aerobatic control of unmanned aerial vehicles, multi-agent operations, air traffic control systems, and aerospace software system certification.



Alexandre Bayen received the Engineering degree in applied mathematics from Ecole Polytechnique, France, in 1998; the M.S. degree in aeronautics and astronautics from Stanford University in 1999; and the Ph.D. degree in aeronautics and astronautics from Stanford University in 2003. He was a Visiting Researcher with NASA Ames Research Center from 2000 to 2003. In 2004, he worked as a Research Director of the Autonomous Navigation Laboratory at Laboratoire de Recherches Balistiques et Aerodynamiques, (Ministere de la Defense, Vernon, France), where he holds the rank of Major. He is currently an Associate Chancellor Professor, and has been the Director of the Institute for Transportation Studies (ITS) since 2014.

Mark Hansen received the Bachelor of Arts degree in physics and philosophy from Yale University in 1980 and the Master’s degree in city planning and the Ph.D. degree in transportation engineering from UC Berkeley in 1984 and 1988, respectively. He is the codirector of National Center for Excellence in Aviation Operations Research (NEXTOR). His research interests include transportation economics, policy and planning, air transportation, and public transportation.