3.11 WEATHER SENSING AND DATA FUSION TO IMPROVE SAFETY AND REDUCE DELAYS AT MAJOR WEST COAST AIRPORTS *

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1. INTRODUCTION

In this paper we present results from a recently completed study of weather sensing and data fusion to improve safety and reduce delays at major west coast airports (Evans, et al., 1999; Crowe, et al., 2000). With the exception of a summer stratus burn-off prediction project at San Francisco (Clark and Wilson, 1996), these airports have received much less attention in terms of advanced FAA terminal weather decision support systems than major airports east of Los Angeles. This is because the principal concern for terminal weather decision support to date has been microburst-induced wind shear, which is very infrequent at the west coast airports.

However, three factors warrant a reexamination of weather decision support provided to these major west coast airports:

1. The increased emphasis on significantly improving aviation safety while reducing delays at major airports in the face of expected increases in operations rates within the National Airspace System (NAS),
2. New air traffic management technology such as terminal automation, collaborative decision making (CDM), and weather adaptive wake vortex spacing systems, and
3. Advances in terminal weather decision support technology represented by the Integrated Terminal Weather System (ITWS) [including various P^3I enhancements to ITWS (Evans and Wolfson, 2000)]

The airports considered in this study were the Los Angeles (LAX), San Francisco (SFO), Portland (PDX) and Seattle (SEA) International Airports. It should be noted that because these airports did not receive a Terminal Doppler Weather Radar, there currently is no plan to provide them with an ITWS. LAX, SFO and PDX are scheduled to receive an ASR-9 Weather System Processor (WSP).

The paper proceeds as follows. Section 2 discusses the study's methodology and provides background information on delays and weather phenomena for these airports in the context of other major US airports as well as applicable air traffic management (ATM) and terminal weather system technology. Section 3 summarizes the principal findings for the four airports. We conclude with a summary of the potential benefits of improved weather sensing and data fusion that might be provided at these west coast airports by an augmented ITWS as well as recommendations for further studies.

2. STUDY METHODOLOGY AND BACKGROUND INFORMATION

2.1 Methodology

The principal mechanism for obtaining information on delay causality, terminal-specific weather phenomena, capabilities of the current weather sensors, and terminal operational constraints was visits and phone calls to the various ATC facilities.A limited winter weather measurement program was conducted at Portland, OR (Crowe, et al., 2000) and a prototype terminal winds algorithm was developed for the LAX region that uses profiler data as well as the current ITWS terminal winds data sources.

The ATC and Center Weather Service Unit (CWSU) meteorologist data on weather characteristics were complemented with climatological data for the various airports. The calculations made for terminal winds and wake vortex benefits used the queueing model developed by Lincoln Laboratory for the IOC ITWS benefits studies and was the model subsequently used for Dallas and New York terminal winds studies (see Appendix D of Evans, et al., 1999).

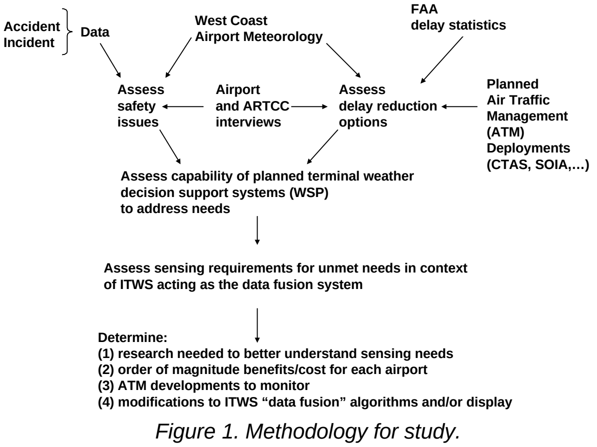

Figure 1. Methodology for study.

2.2 Airport Delays and Weather Phenomena

Table 1 shows the weather phenomena that arise at the various airports along with operations rates and delays as summarized in the latest Aviation Capacity Enhancement Plan (FAA Office of System Capacity,

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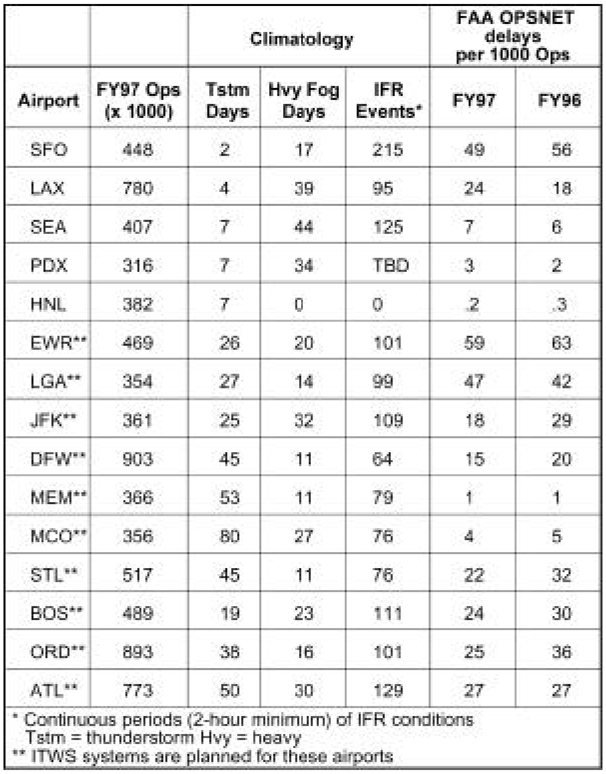
1999). We see that low ceiling/visibility conditions are key causes of delays for the west coast airports.

Table 1.
Operations, Climatology and Delays
for Major Airports



		Climatology			FAA OPSNET delays per 1000 Ops	
Airport	FY97 Ops (x 1000)	Tstm Days	Hvy Fog Days	IFR Events*	FY97	FY96
SFO	448	2	17	215	49	56
LAX	780	4	39	95	24	18
SEA	407	7	44	125	7	6
PDX	316	7	34	TBD	3	2
HNL	382	7	0	0	.2	.3
EWR**	469	26	20	101	59	63
LGA**	354	27	14	99	47	42
JFK**	361	25	32	109	18	29
DFW**	903	45	11	64	15	20
MEM**	366	53	11	79	1	1
MCO**	356	80	27	76	4	5
STL**	517	45	11	76	22	32
BOS**	489	19	23	111	24	30
ORD**	893	38	16	101	25	36
ATL**	773	50	30	129	27	27

* Continuous periods (2-hour minimum) of IFR conditions
Tstm = thunderstorm Hvy = heavy
** ITWS systems are planned for these airports

2.3 Air Traffic Management Technologies Applicable to Delay Reduction at the Major West Coast Airports

Low ceilings/visibility and unfavorable winds cause delays by making it impossible to use all of the available runways. In some cases, there is a difference in the number of aircraft landed on a runway per hour during instrument flight rules (IFR) conditions versus the rate during visual flight rules (VFR) conditions that further compounds the delay problems.

There are three basic approaches for reducing these delays:

1. Use a parallel runway monitoring (PRM) system with a wake vortex encounter avoidance system to permit the use of closely-spaced runways in IFR conditions;
2. Increase the number of aircraft landed per hour per runway; and
3. Match the traffic flow to the time-varying airport capacity (i.e., traffic flow management (TFM) optimization).

Approach (1) is under consideration for San Francisco and would also be appropriate for Seattle.

More aircraft can be landed per hour per runway by:

1. Reducing wake vortex separations on a weather conditional basis, and/or
2. Providing controllers with information that enables them to achieve the desired aircraft separations more precisely (e.g., no unnecessary “gaps” between planes), and/or
3. Optimum assignment of aircraft to runways.

A key element of a weather-adaptive wake vortex spacing system is very high-resolution vertical profiles of winds and temperature/humidity to determine whether wake vortices are not of concern due to advection (i.e., transport by the wind) and/or by dissipation (e.g., by turbulence) (Cole, et al., 1998; Dasey and Hinton, 1999).

The Center-TRACON Advisory System (CTAS) (Ertzberger, et al., 1993) addresses (2) and (3) by balancing the traffic between the various runways, ordering the arrivals for a given runway, and delivering planes to the final approach fix with the desired inter-aircraft spacings while using descent trajectories that conserve fuel and comply with terminal procedures. To achieve these capabilites, the initial operational capability CTAS requires wind and temperature profiles for use in trajectory synthesis. It also requires information to permit the human user to identify terminal routes and runways which are usable for a prediction period of up to 40 minutes. The winds accuracy required is on the order of 10 knots (Evans, 1997; Cole, et al., 2000).

2.4 New Terminal Weather Decision Support Capabilities

The FAA has deployed the TDWR and LLWAS and is the process of deploying ASR-9 WSP systems. These systems will provide microburst and gust front wind shear products for nearly all major US airports.

However, the aviation community should be made aware that some of the newer products that have been developed through the FAA ITWS and Aviation Weather Research (AWR) programs and the NASA wake vortex program that are potentially applicable to improving safety and reducing delays at the major west coast airports. These include:

1. High-resolution (space and time), three-dimensional gridded winds estimates to support calculations of time-of-flight for controllers, terminal automation systems, and wake vortex advection calculations (Cole and Wilson, 1994).
2. Storm motion predictive products to facilitate traffic management when heavy precipitation is adversely impacting terminal operations (Chornoboy and Matlin, 1994; Wolfson, et al., 1999). It should be noted that the Terminal Convective Weather Forecast also appears to be skillful at predicting the ceiling and visibility changes associated with the lighter precipitation from winter coastal storms (Allan and Gaddy, 2000). A similar tracking algorithm has been used successfully to predict snowfall at east coast airports (Rasmussen, 1999).
3. Predictions of ceiling due to coastal stratus clouds for traffic flow management using a combination of special sensors and high-resolution numerical

weather prediction models (Clark and Wilson, 1997); and

4. Frequently updated temperature and humidity profiles at airports using aircraft reports and surface observations (Wolfson, et. al., 1994).

3. RESULTS FOR SPECIFIC AIRPORTS

3.1 San Francisco (SFO)

San Francisco has a very high rate of delays due to the impact of low ceilings and/or visibility at the airport. Under fair weather conditions, the airport operates at approximately 50-60 arrivals per hour and 50 departures per hour. When low ceiling/visibility prevent aircraft from approaching in pairs, arrival and departure rates can drop to as low as 25 per hour. Similarly, when strong winds force arrivals and departures to occur on the same pairs of runways, the arrival and departure rates are about 30-45 per hour (depending which runway pair is in use).

The demand at SFO is approximately 50-55 per hour from 10 am to 2 pm local time, with another peak in demand in the late afternoon and early evening. Two types of weather are the principal causes of delays: summer marine stratus clouds, which typically burn off between 9 am and 2 pm, and winter storms bringing wind and rain which may last all day. Since the delay depends on the weather duration during peak demand periods (Evans, 1997), the all-day weather events account for approximately as much delay as the more frequent summer stratus clouds that burn off by early afternoon. It should be noted that the SFO frequency of bad weather (both summer stratus and winter storms) and delays can vary significantly from year to year due to large-scale changes in the overall weather pattern (e.g., El Niño years are particularly bad.).

As noted earlier, there is an initiative already underway to better predict the summer marine stratus burn-off. This could provide significant delay reductions through the use of proactive traffic flow management programs to ensure that there is an adequate supply of planes when the stratus cloud dissipates. However, prior to this study there had been no consideration given to reducing the winter storm delays which account for a significant fraction of the current delay at SFO.

We have identified two options for improved winter storm operations at SFO:

1. Achieve a higher effective runway capacity during winter storms through improved aircraft merging and sequencing using an adapted ITWS terminal winds product. This is estimated to provide over 6,000 hours of delay reduction per year. Achieving this benefit may require installation of a profiler near the airport because the NEXRAD for San Francisco is sited in a location that makes it of very little utility for measuring the key terminal area winds.
2. Prediction of changes in ceiling and visibility during rain band passages using a modified version of the TCWF. The benefits of this option could not be quantified during this study.

It should be noted that the adapted ITWS terminal winds product would also be useful in reducing summer stratus cloud delays if the Simultaneous Operation with Independent Approaches (SOIA) system under study for SFO were to be installed.

3.2 Los Angeles International Airport (LAX)

Los Angeles delays principally arise from two mechanisms:

1. Inability to land planes on closely spaced runways[1] when the visibility aloft is restricted by the Los Angeles smog layer, and
2. Problems with merging and sequencing when planes must land to the east during winter storms, or when there are unusual vertical wind shears in fair weather operations landing to the west.

It appears that an additional three to five aircraft per hour might be landed at LAX during the 15-20 days per year that east IFR operations occur. We project that in excess of 5000 hours of delay a year could be avoided at LAX with the terminal winds product. LAX is scheduled to be one of the first airports to receive a CTAS which would facilitate the effective operational use of the ITWS terminal winds.

Sensing of winds aloft at LAX to support aircraft merging and sequencing could be accomplished by using the Point Mugu NEXRAD, a combination of aircraft reports and data from the many air quality wind profilers in the LAX basin. An initial feasiblity study of this has been accomplished. NOAA’s Forecast Systems Laboratory (FSL) provided Internet access to data from the five wind profilers in the Los Angeles area. Software was developed to access the FSL data from Lincoln Laboratory, and the algorithms developed by Lincoln for the ITWS terminal winds algorithm were modified to utilize the profiler data.

Figure 2 shows the gridded winds estimates at 4500 ft. altitude, using only the profilers, MDCRS plane reports, and the NOAA rapid update cycle winds. These preliminary results seem quite promising, but an operational assessment during winter storms is clearly warranted.

Since increasing the departure rate per runway at LAX would permit a higher rate of arrivals, a departure wake vortex system at LAX could reduce delays by over 3000 hours per year. This would require high-resolution winds information and the ability to anticipate wind shifts of significance for wake vortex separations on departures. Achieving this level of winds information may require either a Doppler laser radar or a pencil-beam Doppler weather radar sited near LAX.

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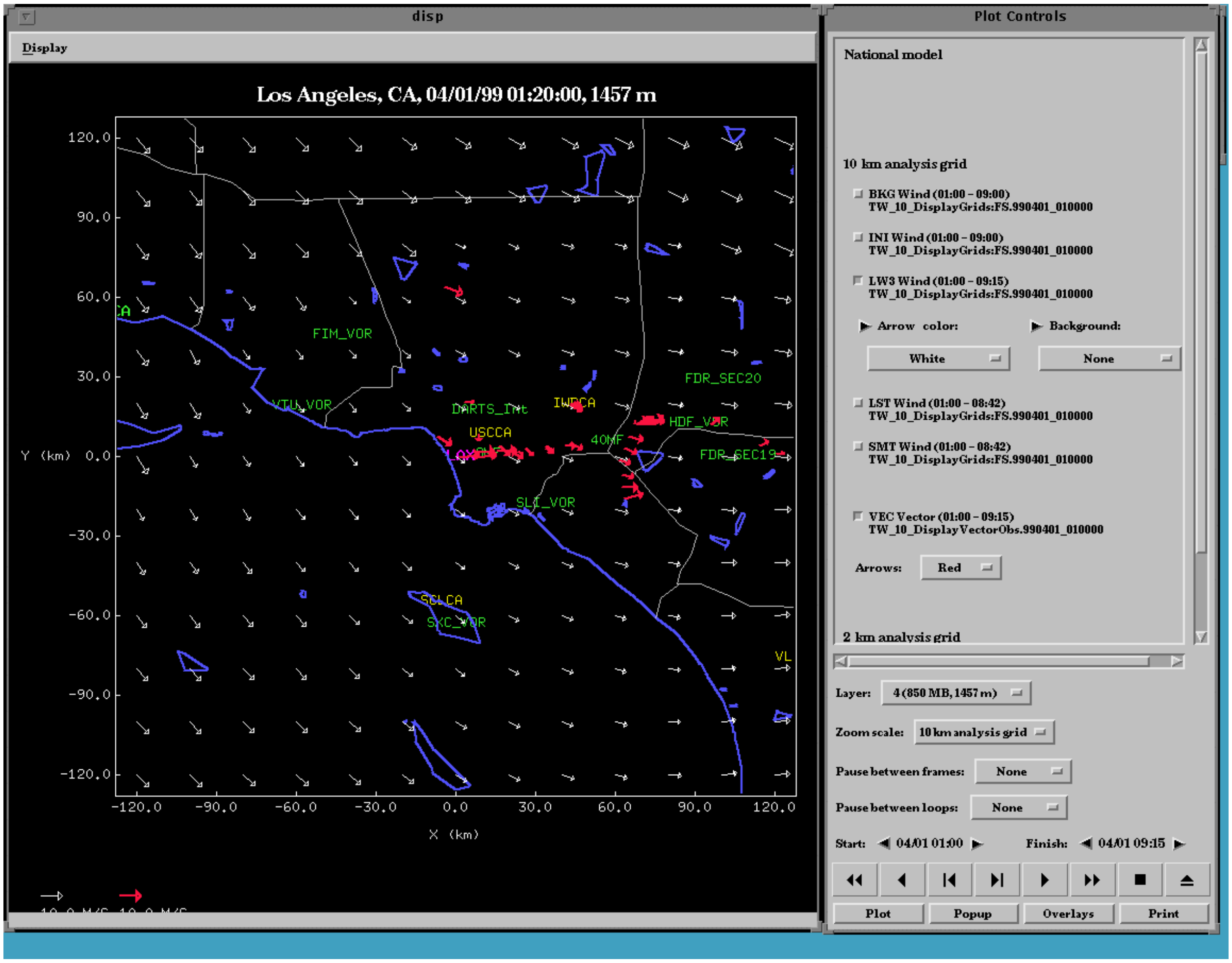
[1] LAX has two sets of closely spaced runways with over a mile separation between the runway pairs. Normally, planes arrive on the outer runways and depart from the inner runways. During peak inbound periods, one of the inner runways may be used for a mixture of arrivals and departures. This requires that there be visual separation between the planes simultaneously landing on a single runway pair.



National model

10 km analysis grid

☐ BKG Wind (01:00 – 09:00)
TW_10_DisplayGrids:FS.990401_010000

☐ INI Wind (01:00 – 09:00)
TW_10_DisplayGrids:FS.990401_010000

☑ LW3 Wind (01:00 – 09:15)
TW_10_DisplayGrids:FS.990401_010000

Arrow color: White
Background: None

☐ LST Wind (01:00 – 08:42)
TW_10_DisplayGrids:FS.990401_010000

☐ SMT Wind (01:00 – 08:42)
TW_10_DisplayGrids:FS.990401_010000

☑ VEC Vector (01:00 – 09:15)
TW_10_DisplayVectorObs.990401_010000

Arrows: Red

2 km analysis grid

Layer: 4 (850 MB, 1457 m)
Zoom scale: 10 km analysis grid
Pause between frames: None
Pause between loops: None
Start: 04/01 01:00
Finish: 04/01 09:15

Figure 2. LAX Terminal Winds at 4500 ft. The light arrows are the horizontal gridded wind estimates on a 10 km grid. The light text within the data field indicates the locations of wind profilers; the darker arrows indicate MDCRS reports from a 30-minute period. The length of arrows at the bottom left indicates a 10 m/s wind velocity. The darker text within the data field indicates ATC fixes for the TRACON.

The delay reductions due to improved traffic flow management—if there were better forecasts of the onset and cessation of low visibility aloft due to smog haze or winter storms at LAX—were not assessed but are believed to be substantial.

3.3 Seattle International Airport (SEA)

SEA was found to have delays due to both low ceilings and visibility during winter storms (analogous to those at SFO) and safety concerns due to triggered lightning.

The SEA winter storm capacity constraints should be alleviated in the relatively near future when an additional runway is constructed that will permit simultaneous parallel approaches during adverse weather. Should this runway be delayed, the ITWS terminal winds product could assist in achieving higher landing rates much the same as discussed previously for SFO and LAX. In the case of SEA, there is a vertical wind profiler relatively near SEA which would be of assistance in providing better winds estimates.

While our study of the west coast airports was going on, two commercial aircraft were hit by lightning near the Seattle-Tacoma International Airport (SEA) on February 28, 1999. The first, NWA946, was a DC10 bound for Seattle from Honolulu. The aircraft was struck by lightning at about 1147 UT while on final approach for SEA. The lightning strike reportedly "took out" one of the DC-10's engines and the pilots asked for emergency vehicles to stand-by on the ground when it landed. As far as we know, the plane landed without incident and there were no injuries.

The second aircraft, ASA110, (unknown type and origin) was the first plane in line behind NWA946. ASA110 broke off its approach to SEA (possibly as a result of the emergency on NWA946) and turned left—apparently into a storm. The aircraft completed a single loop and landed at SEA. ASA110 was reportedly struck by lightning at 1257 UT. According to informal communication with Alaska Airlines, the lightning strike did not result in any significant damage.

A detailed analysis [see (Evans, et al., 1999)] of these incidents using NEXRAD and national lightning network data together with flight track data suggests that the aircraft were hit by aircraft-triggered lightning strikes in marginally electrified storms. Previous studies (Mazur, 1984; 1993) indicate that more than 90 percent of lightning strikes to aircraft are initiated by the aircraft itself.

It is interesting to note that in a recent study of thunderstorm penetrations and deviations by commercial aircraft in the Dallas-Fort Worth area that hundreds of aircraft were observed penetrating late spring and summer thunderstorms, and to the best of the authors' knowledge, none of the aircraft experienced significant lightning strikes (Rhoda and Pawlak, 1999).

Research needs to be carried out on the feasibility of generating warnings for triggered lightning strikes in the terminal area from storms such as occurred at SEA on 28 February. Thermodynamic soundings should be used to identify the freezing level heights. Given these heights, three-dimensional reflectivity data could be used to produce two-dimensional maps of the integrated condensate above the freezing level (a quantity known as VIF, a derivative of the better known VIL, vertically integrated liquid water, and a well recognized signature for electrification). Threshold values for VIF could be selected to cordon off hazardous regions.

3.4 Portland International Airport (PDX)

Portland has significant weather-related safety and delay concerns in the winter due to adverse winds and icing (especially freezing rain). The local topography around the airport (near the Columbia River Gorge) causes wind shear and icing during winter storms. Cold air to the east of Portland pours out of the Gorge at low altitudes, causing decoupling of the winds aloft from the surface winds, with the result being very sharp vertical wind shears and a potential for freezing rain (Crowe, et al, 2000). In a winter storm, surface winds may be from the south, with the winds aloft strong from the east.

The cold air at the surface can create freezing rain when the relatively warm rain from coastal storms falls into the cold air. Due to the topography, the region of freezing rain can be very localized (e.g., it is not uncommon for there to be freezing rain at the airport but not in the city, which is approximately 30 miles away).

Since the winter storms in Portland are similar aloft to those in Seattle, it is not surprising that lightning strikes to aircraft in the terminal area are a safety concern. The PDX TRACON has indicated that a number of lightning strikes to aircraft occurred in the terminal area between October 1998 and June 1999:

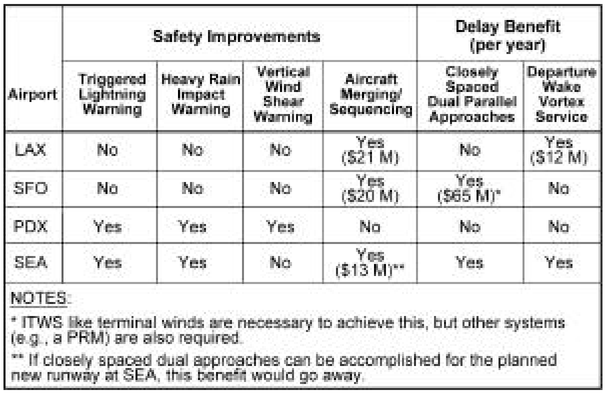
- Arriving aircraft on 10/4/98, 4/8/99 (two aircraft on this date), 4/26/99 and 5/8/99
- Departing aircraft on 2/7/99

The flight track data for these PDX events has been erased, so it could not be determined whether these were triggered lightning strikes similar to those at SEA. The approach to predicting triggered lightning for SEA should be applicable to PDX.

4. SUMMARY

All four of the airports studied (SFO, LAX, SEA and PDX) have aspects of their operations which would benefit significantly from weather products which could be produced by an ITWS, augmented with additional sensors. Table 2 summarizes these benefits. The projected delay reduction per year at LAX, SFO, and SEA is many times greater than the marginal cost of an additional ITWS (approximately $500K with hardware costs of about $150K, and $350K for site-specific engineering and installation).[2]

Table 2.
Projected Benefits of an Augmented ITWS for Major West Coast Airports



Airport	Safety Improvements				Delay Benefit (per year)	
	Triggered Lightning Warning	Heavy Rain Impact Warning	Vertical Wind Shear Warning	Aircraft Merging/ Sequencing	Closely Spaced Dual Parallel Approaches	Departure Wake Vortex Service
LAX	No	No	No	Yes ($21 M)	No	Yes ($12 M)
SFO	No	No	No	Yes ($20 M)	Yes ($65 M)*	No
PDX	Yes	Yes	Yes	No	No	No
SEA	Yes	Yes	No	Yes ($13 M)**	Yes	Yes

NOTES:

* ITWS like terminal winds are necessary to achieve this, but other systems (e.g., a PRM) are also required.

** If closely spaced dual approaches can be accomplished for the planned new runway at SEA, this benefit would go away.

We recommend a reexamination of the terminal weather system deployments planned for the west coast that considers the safety and delay reduction issues identified in this study. The wind shear system deployment study (Rovinsky, et al., 1996) did not consider the delay reduction options discussed in this paper nor were the safety issues noted above for SEA and PDX considered. The ITWS deployment was a priori restricted to TDWR airports even though ITWS can provide a number of useful products without a TDWR.

The winter weather phenomena at PDX warrant experimental measurements to better understand the phenomenology and to provide a database for assessing sensing/data fusion options for addressing the winter phenomena. The measurements reported in (Crowe, et al., 2000) represent a first step at this.

An operational evaluation of the LAX terminal winds product using aircraft reports, the Point Mugu NEXRAD VAD product, and the air quality vertical profilers near LAX as the principal local sensors should be carried out

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[2] These cost estimates were derived from the current prices (with university discounts) of the likely ITWS hardware and our estimates of the level of effort for site-specific installation based on experience with the Lincoln ITWS prototypes. In addition to these costs, one must also consider the non-recurring costs to modify the ITWS to access and utilize additional data sources (especially the vertical profilers) as well as the cost for the additional sensors. The augmented terminal winds software treats profiler data as point measurements (similar to aircraft reports) at a number of altitudes above the profiler. Hence, the only additional software required is profiler data ingest software which was 200 lines of C code in the implementation developed as a part of this study. We estimate the implementation cost for this software to be less than $40K.

to determine if an operationally useful capability is available with these sources alone.

Progress in the development of a departure wake vortex monitor and the closely staggered approaches at San Francisco should be monitored closely to determine whether either or both of these approaches will create a near-term need for high-resolution vertical wind data to predict wake vortex behavior.

Research needs to be carried out on the feasibility of generating warnings for triggered lightning strikes in the terminal area from Pacific Northwest storms.

The potential benefits from forecasting of haze aloft at LAX in the summer and rain-band-induced ceiling/visibility in winter storms at LAX, SFO, and SEA should be determined.

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