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STRATEGY DEVELOPMENT FOR DUST CONTROL AND PREVENTION ON I-10

Final Report

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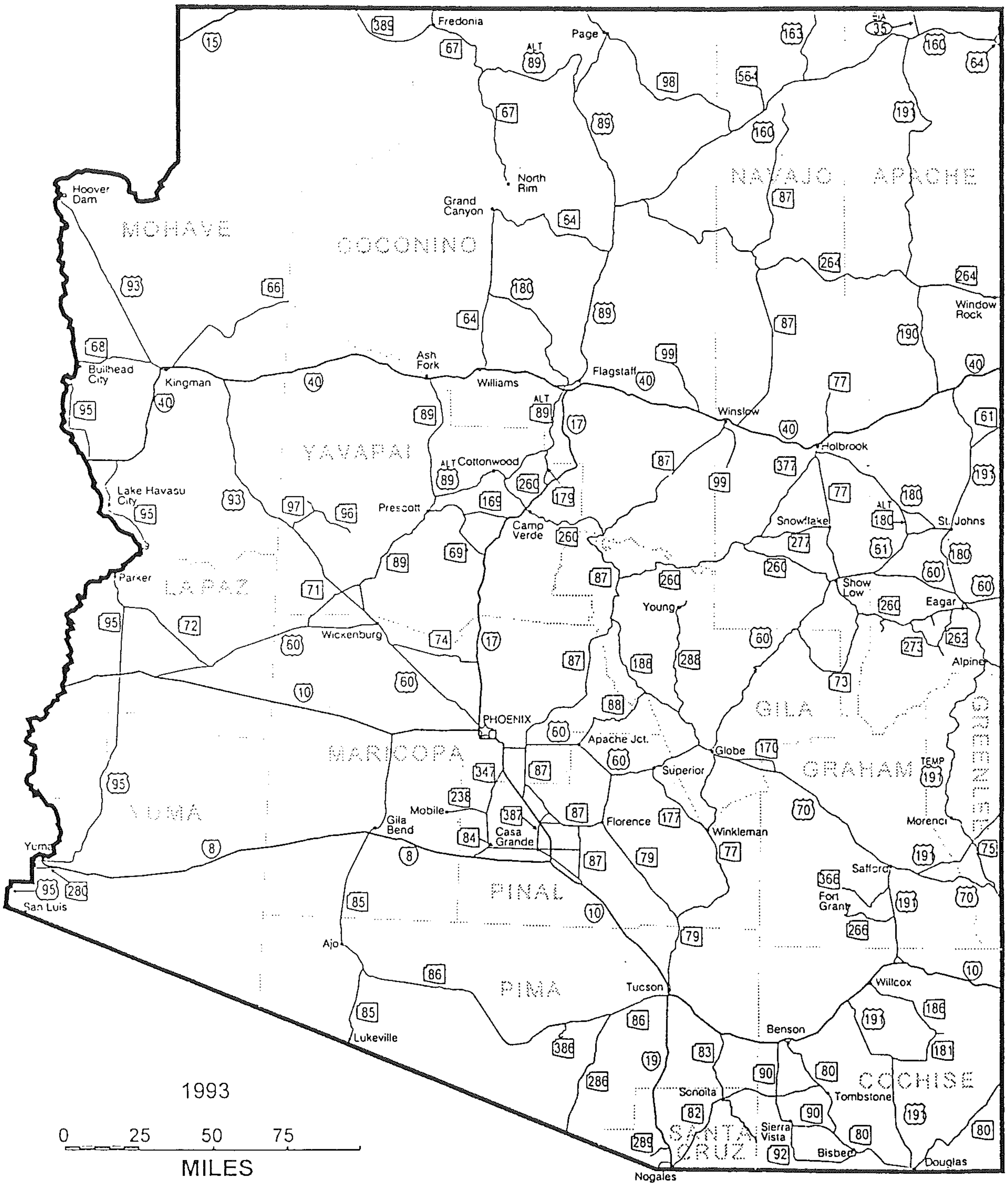

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16. Abstract

This study was directed to the development of dust control and mitigation strategies for improving visibility and preventing vehicle accidents during dust storms along Interstate I-10, in Arizona. During the period 1985 to 1996, 46 dust-related accidents occurred on I-10, mostly between Phoenix and the New Mexico border. Most of these accidents occurred in the summer monsoon months of July and August.

Based on wind direction analysis for each accident, fugitive dust originated from active and abandoned farmland, disturbed desert areas, an ostrich farm, unpaved parking lots and roads, and construction sites. Major accident sites were concentrated in the following areas: Vicksburg-Bouse Wash, Buckeye-Goodyear, Phoenix, Firebird Lake Complex, Gila River desert area, Casa Grande-Eloy, Marana, and Bowie-San Simon.

Recommended dust control measures include: conservation farming practices, e.g., reduced tillage and limiting livestock; revegetation with shrubs and plants (including orchards) that act as windbreaks; soil stabilization; and watering under limited circumstances. Rigorous dust control plans should be required of any new source areas such as construction sites. Many of these measures have already been implemented along I-10. This accounts for a significantly reduced accident frequency over the past several years.

This report also presents a historical overview of Arizona dust warning systems. In addition, state-of-the-art visibility sensors and sand movement sensors are discussed.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.452	centimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

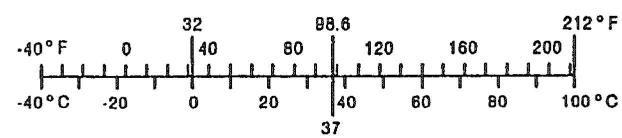
Note: Volumes greater than 1000 L shall be shown in m^3.

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
yd	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
yd^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	millimeters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

Midwest Research Institute (MRI) prepared this report for the Arizona Department of Transportation (ADOT) to identify strategies for mitigation of dust-related hazards on Interstate Highway 10 in Arizona. Midwest Research Institute (MRI) performed this work for the ADOT under Contract No. T9609A0014. Jiann-Jong (J.J.) Liu served as the project officer for ADOT.

MRI acknowledges contributions from the following individuals and agencies:

1. ADOT and Arizona Department of Public Service (ADPS) provided maps and traffic accident data for I-10.

2. The Arizona Department of Climatology provided detailed meteorological data for the times when dust-related traffic accidents occurred. We especially note the contributions of Dr. Tony Brazel, Arizona State Climatologist.

This report was prepared by Dr. Chatten Cowherd, Jr. (project leader for MRI), Mrs. Mary Ann Grelinger, Mr. Robert Blackburn (consultant), and Mr. Reza Karimvand (Arizona Department of Transportation). If you have any technical questions on the project report, please call Dr. Cowherd at (816) 753-7600, Ext. 1586.

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1. INTRODUCTION

Disturbed soils in Arizona are a significant wind erosion problem because precipitation is usually not adequate to create stable crusts or to provide a sufficiently high moisture content for stabilization of the erodible soil. If protective annual grasses, shrubs, and small trees are lost, land surfaces become exposed and will blow during periods of high winds. High wind events in Arizona are associated with thunderstorms, frontal passages, and other weather conditions producing strong pressure gradients (closely spaced isobars).

Dust entrained from open areas during high wind events is considered a major contributor to visibility problems and vehicle accidents on Arizona highways. Most notably, Interstate Highway 10 (I-10) in Arizona presents a difficult challenge regarding the prevention of dust-related vehicle accidents. While fewer visibility problems impact I-10 west of Phoenix, the portion of the interstate between Phoenix and the New Mexico border to the east is known to be the site of frequent dust-related accidents. These accidents have involved as many as 33 vehicles and multiple fatalities in a single event.

The primary sections on I-10 affected by serious dust storms and associated "gray- or black-outs" are located between Phoenix and Tucson. Dust-producing source areas include tilled and abandoned agricultural lands, livestock areas, and unpaved parking areas and roads. Blowing dust from these areas can reduce visibilities on I-10 to less than 1/16 mile.[a]

FOCUS OF STUDY

The purpose of this study was to develop dust control and mitigation strategies for improving visibility and preventing vehicle accidents during dust storms on I-10 in Arizona. In this study, MRI performed research to:

- Characterize vehicle accidents on I-10 in Arizona caused by dust storms that reduce driver vision;
- Identify and quantify dust sources contributing to the vehicle accidents; and
- Develop strategies to mitigate dust related hazards created by high wind events.

This project focused on the following items of critical information:

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[a] Other than zero visibility, 1/16 mile is the lowest visibility benchmark used by the National Weather Service.

1. **I-10 segments** where dust storms and related traffic accidents occur most frequently.

2. **Meteorology** (wind speeds and directions) associated with the dust storms that have caused multi-vehicle accidents.

3. Characteristics of **erodible soils** in the areas of the selected I-10 segments.

4. Appropriateness and effectiveness of **measures to control dust emissions** in desert areas.

5. **Alternative measures** to reduce dust related hazards on I-10.

The following critical questions were addressed:

- What are the area sources of visibility impairment on I-10?

- What are the relationships between the surface conditions of nearby lands, winds, and degradation of visibility on I-10?

- Can control measures be effectively applied to improve visibility and driver vision during high wind events?

- Are there other cost-effective ways to prevent vehicle accidents during poor visibility events?

STUDY METHODOLOGY

This study entailed the collection and analysis of data and other information on the focus items identified above. This information was obtained from technical publications, telephone contacts, and site surveys of dust source areas coupled with soil sampling and analysis. Each of these activities is described briefly below, and reference is given to the sections of this report that provide greater detail.

Literature and Internet Searches

MRI contacts in governmental agencies, including U.S. EPA and the USDA, provided the most recent wind erosion research information for this project. In addition, the substantial Internet resources on wind erosion, soils, meteorology, hydrology, and agriculture were reviewed. For example, the USDA Agricultural Research Service (ARS), Wind Erosion Research Unit (WERU), at Kansas State University at Manhattan, Kansas operates a World Wide Web page (http://www.weru.ksu.edu) that tracks new work in wind erosion quantification and control. WERU also publishes a bibliography of wind erosion on their Internet home page that includes over 1,000 reports, many of which were pertinent to this project. Section 2 describes the background information for this study.

Investigation of Related Data, Systems, Methods, and Partnerships

Related research programs were reviewed to determine if other agencies could provide information that would aid in the successful accomplishment of this project. Several Arizona agencies supplied data necessary for performance of this project. These included the Traffic Group at ADOT, officers of the Arizona Department of Public Safety (ADPS) and local Fire Stations, agricultural experts at the University of Arizona in Tucson, and the State Climatologist of Arizona. Section 8 identifies the organizations and individuals contacted for information during the progress of this project.

Analysis of ADPS Accident Records

The Arizona Department of Public Safety (ADPS) provided accident data for the period from 1985 through 1996 for this study. A majority of these data had already been collected and analyzed by Mr. Reza Karimvand of the Arizona Department of Transportation (ADOT). Locations where I-10 vehicle accidents were caused by dust storms are described in Section 3.

Analysis of Dust Transport

From the probable direction of the winds at the time of each accident, the upwind areas adjacent to I-10 were targeted for further examination to identify source areas. Dr. Anthony Brazel, State Climatologist of Arizona, provided meteorological data from multiple weather stations in Arizona for the times when accidents occurred. Meteorological data and the analysis to characterize specific dust sources along I-10 are discussed in Section 3.

Source Surveys/Soil Characterization

Two site surveys of dust source areas adjacent to I-10 were performed by MRI project staff during this study. The surveys were directed to (a) collection and analysis of surface soil samples for characterization of soil erodibility and (b) identification of specific erodible areas in the upwind locations for each accident. The survey results are discussed in Section 4.

Assessment of Dust Control Measures

Because several types of open area dust sources were identified along I-10 in Arizona from the California to the New Mexico border, numerous dust control measures were evaluated for suitability and effectiveness. Dust control strategies for open area sources along I-10 are discussed in Section 5.

Evaluation of Dust Warning Systems

Dust warning systems that have been implemented along I-10 have met with only limited success. Alternative traffic warning systems and related issues are examined in Appendix A.

2. DUST ENTRAINMENT PROCESSES

Wind-generated emissions from open dust sources, such as those present in areas adjacent to I-10, exhibit a high degree of variability from one site to another, and emissions at any one site tend to fluctuate widely. The site characteristics which cause these variations may be grouped into two categories: measures of energy expended by wind interacting with the erodible surface (e.g., wind speed) and properties of the exposed surface material (e.g., content of suspendable fines in the surface material and its moisture content or, for a crusted surface, the strength and integrity of the crust). These site characteristics are discussed further below.

SURFACE MATERIAL CHARACTERISTICS

Particle Size Distribution

The dry-particle size distribution of the exposed soil or surface material determines its susceptibility to wind erosion.[1] Wind forces move soil particles by three transport modes: saltation, surface creep, and suspension. Saltation describes the movement of particles that range in diameter from about 75 to 500 μm; these particles are readily lifted from the surface and jump or bounce within a layer close to the air-surface interface. Saltation provides energy for the release of particles in the PM-10[b] size range that typically are bound by surface forces to larger clusters. Particles transported by surface creep range in diameter from about 500 to 1000 μm. These large particles move very close to the ground, propelled by wind stress and by the impact of small particles that are transported by saltation.

Particles smaller than about 75 μm in diameter (referred to as "silt")[c] move by suspension and tend to follow air motions. The threshold wind speed for the onset of saltation, which drives the wind erosion process, is also dependent on soil texture, with 100-150 μm particles having the lowest threshold speed.

Nonerodible Elements

Nonerodible elements, such as clumps of grass or stones (larger than about 1 cm in diameter) on the surface, consume part of the shear stress of the wind which otherwise would be transferred to erodible soil.[1] Surfaces impregnated with a high density of

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[b] PM-10 denotes airborne particles no larger than 10 micrometers in aerodynamic diameter.

[c] The upper size limit of silt particles (75 μm in physical diameter) is roughly the smallest particle size for which size analysis by dry sieving is practical.

nonerodible elements behave as having a "limited reservoir" of erodible particles, even if the material protected by nonerodible elements is itself highly erodible. Wind-generated emissions from such surfaces decay sharply with time, as the particle reservoir is depleted. Surfaces covered by unbroken areas of grass, shrubs, or small trees are virtually nonerodible. Crop residues left by conservation farming practices are also highly effective in protecting the soil surface.

Moisture Content

Dust emissions from wind erosion are known to be strongly dependent on the moisture level of the erodible material.[2] Water acts as a dust suppressant by forming cohesive moisture films among the discrete grains of surface material. In turn, the moisture level depends on the water added by natural precipitation, and removed by evaporation, and moisture movement beneath the surface. The evaporation rate depends on the degree of air movement over the surface, material texture and mineralogy, and crust presence. The moisture-holding capacity of the air is also important, and it correlates strongly with the surface temperature.

Crust Formation

Following the wetting of a soil or other surface material, fine particles will consolidate to form a surface crust. The surface crust acts to preserve in soil moisture and resist erosion, but vehicle traffic or livestock movement will disturb protective crusts and create large reservoirs of dust particles that may become suspended during the next high wind event, depending on its intensity. Even if the surface is crusted, sand and dust deposited loosely on the surface from previous wind events are available for resuspension. A particular problem with crust integrity can occur on abandoned farmland and natural desert, where crusts fracture polygonally to expose some soil to the wind.

The degree of protection that is afforded by a soil crust to the underlying soil may be measured by the modulus of rupture and thickness of the crust.[3] This modulus of rupture is roughly a measure of the hardness of the crust. Exposed soil that lacks a surface crust (e.g., a disturbed soil or a very sandy soil) is much more susceptible to wind erosion.

Frequency of Mechanical Disturbance

Emissions generated by wind erosion are also dependent on the frequency of disturbance of the erodible surface. A disturbance is defined as an action which results in the exposure of fresh surface material. This would occur whenever a layer of aggregate material is either added to or removed from the surface, for example, in cut and fill operations at a construction site. The disturbance of an exposed area may also result from the turning of surface material to a depth exceeding the size of the largest aggregate material present, as for example will occur in an agricultural tilling operation. Each time that a surface is disturbed, its erosion potential is increased (a) by destroying the mitigative effects of crusts, vegetation, and friable nonerodible elements and (b) by exposing new surface fines.

WIND CHARACTERISTICS

Wind Speed

Under high wind conditions that trigger wind erosion by exceeding the threshold velocity, the wind speed profile near the erodible surface is found to follow a logarithmic distribution[4]:

$$u(z) = \frac{u^*}{0.4} \ln \frac{z}{z_o} \quad (z > z_o)$$

where:

u	=	wind speed, cm/s
u*	=	friction velocity, cm/s
z	=	height above test surface, cm
z_o	=	roughness height, cm
0.4	=	von Karman's constant, dimensionless

The friction (u*) is a measure of wind shear stress on the erodible surface, as determined from the slope of the logarithmic velocity profile. The roughness height (z_o) is a measure of the roughness of the exposed surface as determined from the y-intercept of the velocity profile (i.e., the height at which the wind speed is zero) on a logarithmic-linear graph. These parameters are illustrated in Figure 1.

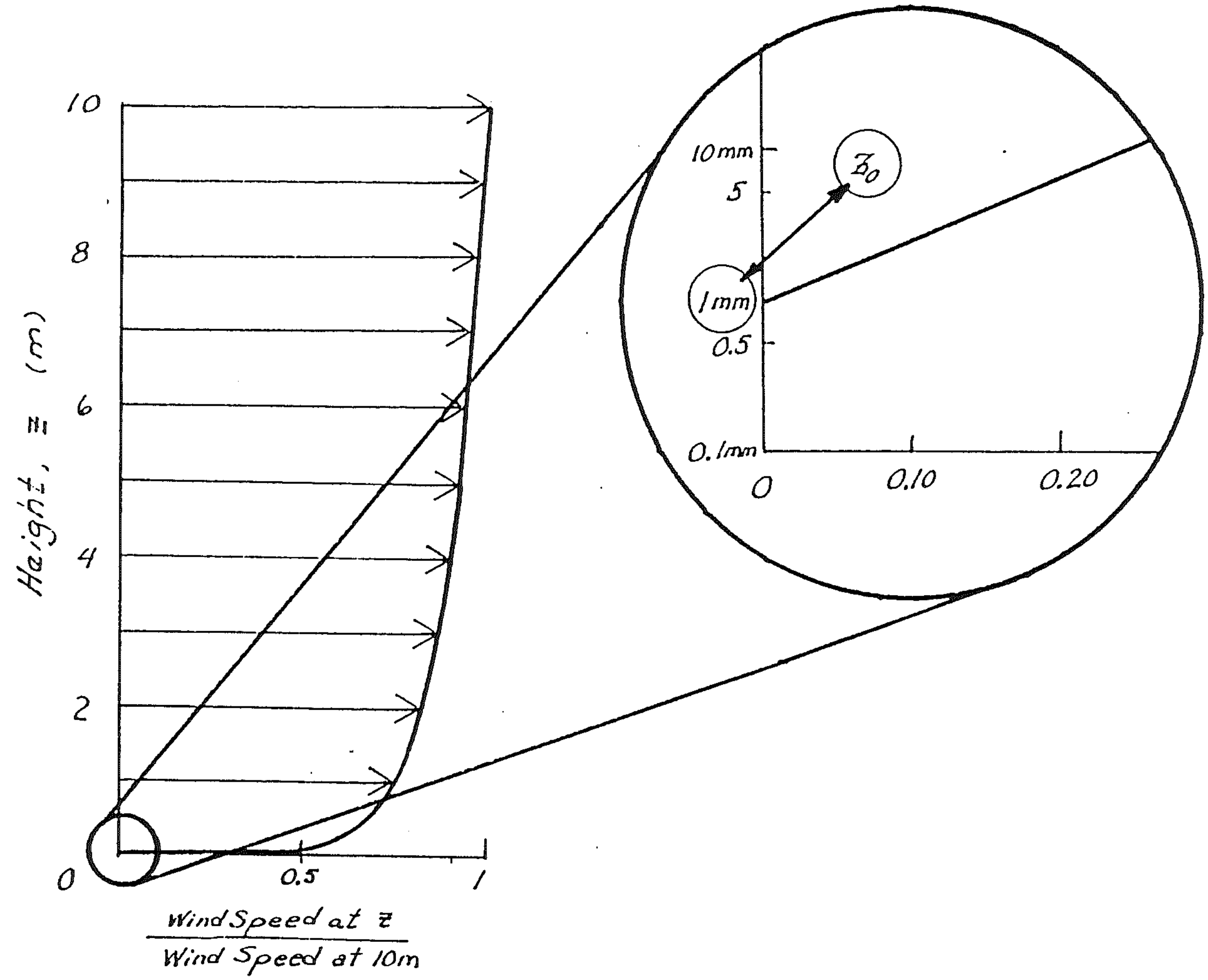

Figure 1. Logarithmic Wind Speed Profile

Agricultural scientists have established that total soil loss by continuous wind erosion of highly erodible fields is dependent roughly on the cube of wind speed above the threshold velocity.[2] More recent work has shown that the loss of particles in suspension mode follows a similar dependence. Soils protected by nonerodible elements or crusts exhibit a weaker dependence of suspended particulate emissions on wind speed.[5]

Wind Gusts

Although mean atmospheric wind speeds in many areas of the country are not sufficient to initiate wind erosion from "limited-reservoir" surfaces, wind gusts may quickly deplete a substantial portion of the erosion potential of surfaces having a "limited reservoir" of erodible surfaces. In addition, because the erosion potential (mass of particles constituting the "limited reservoir") increases with increasing wind speed, estimated emissions should be related to the gusts of highest magnitude.

The routinely measured meteorological variable which best reflects the magnitude of wind gusts is the "fastest mile of wind".[6] The quantity represents the wind speed corresponding to the whole mile of wind movement which has passed by the 1-mile contact anemometer in the least amount of time. Daily measurements of the fastest mile are presented in the monthly Local Climatological Data (LCD) summaries for weather stations throughout the United States.[7] The duration of the fastest mile, typically about 1-2 min (for fastest miles of 30-60 mph, respectively), matches well with the half-life of the erosion process, (i.e., the time required to remove one-half the erodible particles on the surface). It should be noted, however, that instantaneous peak wind speeds can significantly exceed the daily fastest mile.

The strong time decay of erosion rate is due not only to the limited availability of erodible particles but also to the efficiency of short-duration wind gusts in depleting the reservoir. Furthermore, because the threshold wind speed must be exceeded to trigger the possibility of substantial wind erosion, the dependence of erosion potential on wind speed cannot be represented by any simple linear function. For this reason, the use of an average wind speed to calculate an average emission rate is inappropriate.

Arizona Storms

Major dust events in Arizona result primarily from two types of storms: (1) summer thunderstorms; and (2) cold frontal systems.[8] The shear force of the wind acting on exposed particles lying on the surface creates rolling dust clouds that can lower visibility along I-10 to distances of less than 1/16 mi. Drivers entering into such clouds are unable to see either the highway boundary lines or motorists immediately in front of them.

During the summer monsoon season (July, August, and early September), the outflow of cool air from thunderstorms creates strong and gusty winds blowing directly from the storm (pseudo-cold fronts) to protrude into and displace warm air on the surface in the path of the storm. Most of the dust is produced on the forward side of a moving thunderstorm where the wind shear is greatest. Often these thunderstorms are "dry," with rain not reaching the ground. If sufficient precipitation reaches the surface, the soil becomes wet and dust production is mitigated or stopped, limiting visibility problems to less than 10 min at a particular location. Thunderstorms, which are most frequent during July and August afternoons, originate from three regions: (a) the Gulf of California; (b) the Sierra Madre (in north central Mexico); and (c) occasionally the Mogollon Rim.

Fall, Winter and Spring frontal systems (primarily from the north and west) produce consistent high winds that can last for several hours. These fronts can be identified by the sustained nature of winds, by the frequent absence of precipitation, and by the cooler seasons during which they occur. When frontal passage occurs, dust clouds may be enhanced because of resuspension of dust deposited previously on the downwind (now upwind) side of obstacles such as shrubs and rocks.

VISIBILITY OBSCURATION

Dust entrained from open areas during high wind events is considered a significant contributor to visibility problems on Arizona highways. Coarse particles directly block the line of sight, while fine particles scatter light to obscure visibility. Light scattering is especially severe for small particles, e.g., particles less than 2.5 μm in aerodynamic diameter (referred to as PM-2.5).

Visibility obscuration during Arizona dust storms is especially concentrated in a relatively thin layer (with thickness of the order of 1 to 2 meters) that hovers directly above the ground surface. This occurs because:

1. Saltating particles, which drive the erosion process, are restricted to this depth.

2. Suspended particle concentrations are reduced in the vertical direction because of turbulent mixing in the atmosphere above the saltation layer.

The saltation layer contains most of the particles that are coarse enough for sand blasting. Mr. Clif Taylor and others have noted the "sand-blasting" of their vehicles during dust storms in Arizona. These observations lend credibility to the conclusion that, in addition to the fine particles, the larger sand particles also contribute to significant reduction in visibility along I-10.

3. DUST STORM/ACCIDENT LOCATIONS

In this study, the computerized Arizona traffic accident reports from the Arizona Department of Public Safety (ADPS) were reviewed to identify specific accident locations and conditions on I-10 where dust storms contributed to vehicle accidents. Two recorded elements on the "Arizona Traffic Accident Report" helped to identify accidents where dust storms were a contributing factor:

1. "Weather Conditions" with a ***Dust*** option; and

2. "Vision Obscurement" with an option, ***Because of Bad Weather***.

The ADPS "Accident Supplement" forms were scanned for the "Dust" option under "Weather Conditions." I-10 mileposts, dates and times, and number of units involved in accidents were also obtained.

Table 1 presents the dates, times and locations of the 46 accidents that were identified to have occurred because of dust storms along I-10, during the period from 1985 to 1996. The accidents are listed in order of milepost, moving west to east from the California border to the New Mexico border.

The "direction of source" in Table 1 was obtained by identifying the likely wind direction for the date, time and location of each accident. A more comprehensive listing of meteorological data for the time period encompassing each accident can be found in Appendix B. A comprehensive review of the meteorology associated with Arizona dust storms is presented in Chapter 3 of a 1976 report on I-10 dust hazards.[8] which is reproduced as Appendix C.

As indicated in Table 1, 35 of the 46 dust-related traffic accidents on I-10 during the period 1985-1996 occurred in the summer monsoon months of July and August. The exception tended to be the accidents near Bowie-San Simon that occurred from February through April and were associated with strong westerly or southwesterly winds. If the accidents near Bowie-San Simon are excluded from the 1985-1996 data set, only 4 accidents out of a total of 38 accidents occurred during non-summer months, with 89 percent of the accidents occurring during the summer season. Almost all dust storms associated with vehicle accidents on I-10 took place during daylight periods of the afternoon and early evening.

An unusual situation occurred in the winter of 1995-1996; little rain fell in December and January when precipitation is normally expected, thus exacerbating dust problems on I-10. A 25-vehicle accident occurred on January 17, 1996, near the Firebird Sports Complex under frontal passage conditions and a gusty westerly wind.

Table 1. Dust-Related Traffic Accidents Along I-10

Accident		Time	Average MP	No. of Vehicles	Dir of Source	Probable Dust Sources
No.	Date					
1	7/29/91	19:00:00	43.6	1	E	Active farmland (approximately 0.3 mi N of I-10); also poorly vegetated desert immediately N of I-10
2	8/13/90	18:30:00	44.0	4	ENE	
3	7/20/86	17:40:00	48.5	16	—	
4	6/2/86	18:05:00	49.1	2	—	
5	8/5/90	18:30:00	49.3	4	ENE	
6	7/20/88	17:34:00	124.1	26	—	Active farmland, mostly cotton, to both N and S of I-10
7	8/27/88	13:55:00	125.8	8	—	
8	8/16/94	21:28:00	125.8	2	—	
9	7/29/91	15:25:00	132.4	7	—	
10	7/27/91	17:55:00	140.5	2	—	Construction sites; other bare areas
11	7/21/90	19:30:00	149.5	4	SE	
12	6/25/86	18:30:00	149.8	2	—	
13	6/13/91	18:00:00	153.0	2	SE	
14	8/29/90	21:00:00	153.6	2	SSE	
15	9//3/91	20:45:00	158.0	2	N	
16	6/20/88	18:45:00	162.0	2	SE	
17	7/21/89	18:15:00	163.2	6	W	Firebird Lake Complex W of I-10, including unpaved parking lots and roads
18	9/4/85	13:40:00	163.3	2	—	
19	3/11/94	17:58:00	163.5	7	W	
23	1/17/96	12:15:00	163.6	25	W	
20	7/28/91	16:25:00	164.4	2	NE	Poorly vegetated desert land
21	10/25/96	12:08:00	164.7	7	WSW	
22	8/5/90	18:05:00	165.0	6	NNE	
24	3/21/92	14:17:00	174.9	2	SSW	Abandoned farmland; poorly vegetated and bare areas
25	8/5/90	17:30:00	175.7	6	NNE	
26	8/27/88	15:12:00	176.1	18	N	

Table 1. (Concluded)

Accident		Time	Average MP	No. of Vehicles	Dir of Source	Probable Dust Source
No.	Date					
27	8/9/86	19:20:00	180.1	2	—	Active farmland to SW of I-10?
28	6/4/87	17:48:00	186.6	1	N	Dirt roads in land development area
29	7/4/91	17:50:00	199.9	6	NE	Bare and sparsely vegetated land to NE of I-8 and I-10 junction
30	5/29/89	13:55:00	205.4	3	—	
31	7/15/93	14:10:00	209.1	3	S	Active farmland SW of I-10 (just north of orchards)
32	7/7/90	11:44:00	222.7	3	S	Active farmland (MP 222) and grazed desert land (MP 223)
33	5/27/91	14:45:00	233.5	2	SW	Active farmland, mostly cotton; abandoned land of Producers' Gin at MP 236.6
34	7/10/87	12:30:00	234.7	2	—	
35	5/3/92	15:10:00	236.6	8	SSW	
35a	7/30/95	14:42:00	236.6	4	SW	
36	5/3/92	15:22:00	236.9	2	SSW	
37	9/13/86	13:00:00	250.0	3	—	Not observed
38	3/3/89	14:34:00	364.0	33	W	Unknown; now planted to orchards
39	6/3/85	16:35:00	366.8	1	—	Not observed
40	4/9/95	14:30:00	372.9	23	W	Active farmland to S of I-10
41	2/14/90	11:15:00	374.1	6	SW	Unknown, now grass and shrubs for cattle grazing
42	3/5/90	14:40:00	377.4	16	SW	
43	4/1/90	11:53:00	379.1	4	S	Former ostrich farm; now being revegetated with grasses
44	11/11/93	15:37:00	379.8	6	SW	
45	3/25/94	14:35:00	379.9	3	SW	

The locations of the dust-related traffic accidents occurring along I-10 during the period 1985-1996 are shown in Figure 2. Each accident is indicated by a tick mark. The accidents involving more than 10 vehicles are indicated by tick marks with knobs on each end.

In Chapter 3 (see Appendix C of this report) of the 1976 study by Marcus et al. identified 32 dust-related accidents between I-10 mileposts 170 and 240 are documented during the period from 1968-1975.[8] The accident frequency due to dust storms was approximately 4 accidents per year in this stretch of interstate highway. Twenty-seven of the 32 accidents (84 percent) occurred during the summer thunderstorm season of May through September.

In contrast, Table 1 indicates that 14 accidents occurred between mileposts 170 and 240 during the period 1985-1996, for an average of approximately 1 accident/year. This represents a clear reduction in frequency of accidents on this portion of I-10 between Riggs Road and Marana.

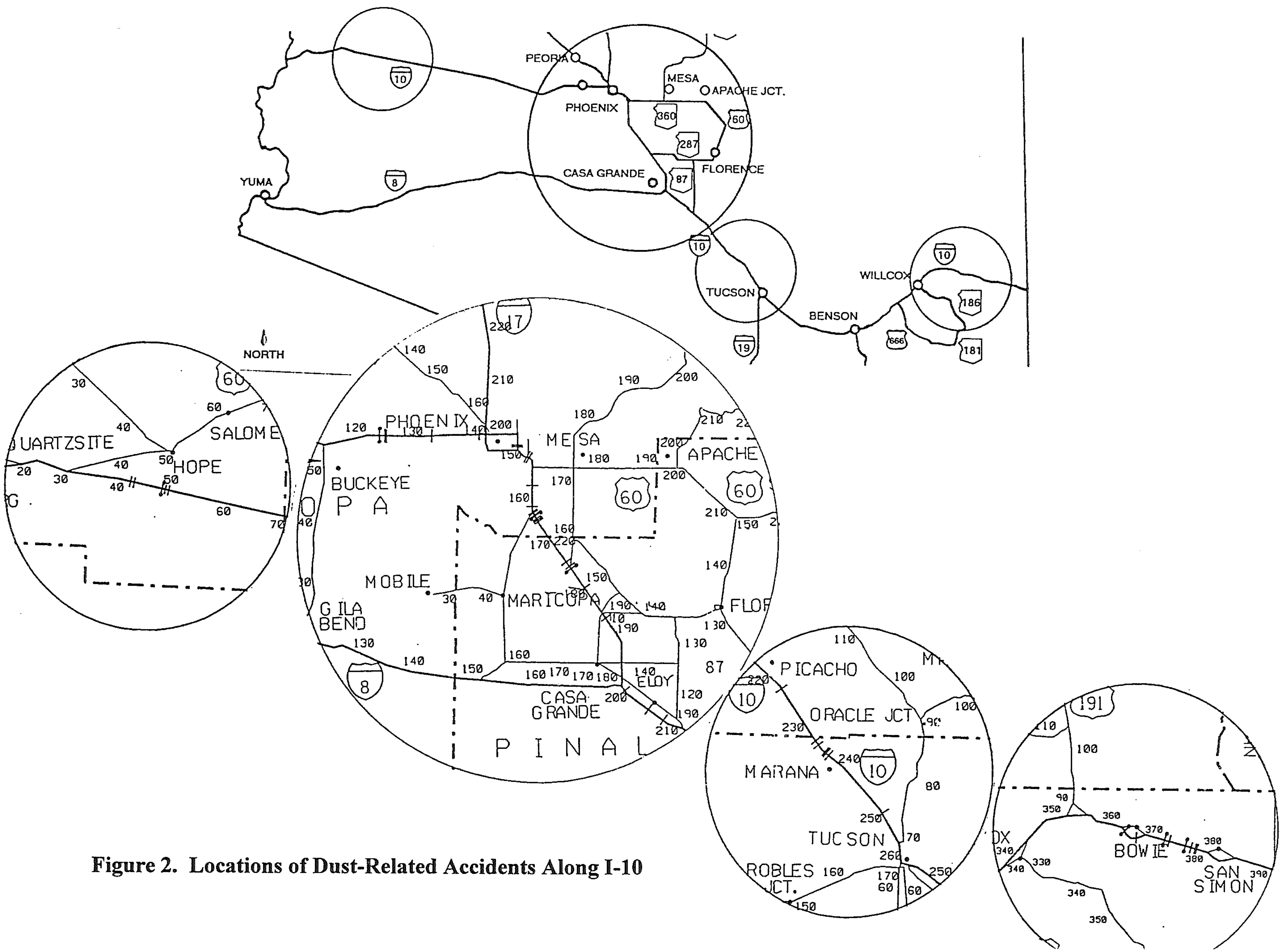

Figure 2. Locations of Dust-Related Accidents Along I-10

4. CHARACTERIZATION OF DUST SOURCES

Two site surveys were performed in this study to identify and characterize dust source areas that are likely contributors to reduced visibility during high wind events along I-10. As stated earlier, the wind direction for each event (see Table 1) was used to determine the locations (upwind) of the dust source(s) in relation to the affected highway segment.

Prior to the surveys, telephone interviews were conducted with persons who had witnessed or otherwise were familiar in the specific accidents. This information was used to target problem areas at an early stage of the survey process. Additional contacts were made during the surveys to clarify accident scenarios and wind storms.

For example, entrained surface soil and sand from the unpaved areas of the Firebird Sports Complex on Gila River Indian lands south of Chandler, Arizona, were verified to have caused dust-related accidents on I-10. Other accidents have been caused by agricultural soil blown from farms in the Hope, Goodyear-Buckeye, Casa Grande, Eloy, Bowie, and San Simon areas. The ostrich pens located below Picacho Peak [and formerly near San Simon] have a considerable amount of loose fine soil on the surface which erodes during wind events. Poorly vegetated abandoned farmland and natural desert along I-10 also contribute to high particulate concentrations and low visibilities.

SITE SURVEYS

During the surveys, the following conditions were used to identify sources of dust plumes that might seriously impact I-10 during high wind events:

- Large open unvegetated areas, especially when soil has recently been tilled or disturbed.
- Long fetch lengths for winds to blow across highly erodible lands without obstructions toward the roadway.
- Land gradient (slope) that increases winds through an upslope or channeling phenomenon.
- Dry soils with large erodible fractions (especially in the saltation size range) and little nonerodible material (rocks, crust, surface residue) to hold the soil and inhibit wind flow near the surface.

During the surveys a variety of disturbance processes that render the soil erodible were observed: agricultural activity, unpaved roads and parking lots, and road and building construction. Other examples observed during the site surveys were areas where mesquite had been cut for firewood, or small shrubs had been worn down by off-road vehicles.

The most widely observed erodible areas adjacent to I-10 were those resulting from agricultural activities. As shown in Table 2, agricultural lands in Pinal, Pima, and Cochise counties along I-10 are used to grow cotton, wheat, barley, and alfalfa. All crops are irrigated.

Table 2. Arizona Crop Production (1995)

County	Crop	Harvested area (acres)
Pinal	Cotton	120,000 to 160,000
	Wheat	38,000
	Barley	14,000
	Alfalfa	30,000
Pima	Cotton	12,000 to 13,000
	Wheat	44,000
Cochise	Cotton	15,000[a]
	Barley	16,000
	Alfalfa	6,000

[a] But most acreage away from I-10.

Pre-irrigation for cotton near Casa Grande occurs in March, with planting from late March to early May. Cotton is harvested from October to December and leaves very little residue to protect the soil from wind erosion after harvesting. Many farmers were observed to work the cotton fields immediately after harvest in late November 1996, leaving relatively smooth and loose surface soil that would severely erode if winds were sufficiently high. A mandatory plowdown of cotton land occurs in January and February (dependent on the region), leaving fields bare and highly susceptible to erosion until pre-irrigation for the next crop.

Wheat and barley are planted in November and December and are harvested in May and June, with the land fallowed in the summer. If the land is ridge tilled, the surface clods and furrows will help to prevent erosion by summer thunderstorms. Milo and millet are also grown near I-10 in the Casa Grande-Marana agricultural region.

A significant number of acres of Arizona farmland along I-10 have been abandoned because of groundwater depletion, energy costs of pumping, and more recently because cities and other organizations have bought water rights and "retired" the farmland. A 1988 study identified over one-half million acres that could be "retired" because of transferred water rights.[9] Abandoned farmland constitutes a serious wind erosion problem because of the difficulty of revegetation under very dry conditions.

SOIL SAMPLING AND ANALYSIS

During the first site survey on September 19, 1996, field samples from representative dust source areas were collected and analyzed for dry soil texture, according to standard procedures published in EPA's emission factor handbook, AP-42 Appendix C.[10] The purpose of this work was to characterize the soils in terms of threshold velocity for wind erosion. The threshold velocity is the most suitable measure for soil erodibility.

The threshold velocity of loose surface material is related to the mode of the particle size distribution as determined by a gentle hand sieving operation. The procedure is presented in Figure 3.

The surface samples that were collected and analyzed during the survey are listed in Table 3. All of the samples were collected from areas immediately adjacent to I-10. Persons who had witnessed dust storms, most often stated that the dust that impacted visibility along I-10 came from localized sources adjacent to I-10, often no more than 100 acres in size.

The areas selected for sampling either were identified by local Arizona residents as primary dust sources or were otherwise observed during the survey to be representative of potential major dust source areas. Samples 1 and 2 were taken from crusted surfaces, both agricultural and desert; care was taken not to disturb the crusts when using a soft brush to collect the loose materials that lay on top of the crust. Sample 3 was obtained from an ostrich pen below Picacho Peak that was well disturbed by bird tracks. Samples 4 and 5 were duplicate samples obtained from a tilled, relatively flat area near Casa Grande. An adjacent agricultural field had been tilled to produce large clods and furrows that served as soil stabilizers against wind erosion, and consequently was not sampled. Sample 6 was taken from an unpaved overload parking lot at the Firebird Sports Complex; the surface was disturbed by driving over it prior to collection of the sample.

All of the surface soil samples were widely distributed in particle size, with significant sample mass present on all screens (and the catch pan) after sieving. However, in every case the mode of the size distribution was (as indicated by the sieve with the most sample mass) was found on sieve 3 or higher.

Table 3. Arizona Soil Samples from near I-10

Sample No.	Sample Description	Sample Location	Sieving Comments*
1	Wind deposited sand/dust on 30 cm x 60 cm surface area of crusted agricultural field	Tilled agricultural field located SE of 46th and Chandler Rd; approximately ½ mi west of I-10	Sieve 3 had most sample mass, but pan was also well loaded with soil
2	Wind deposited sand/dust on 30 cm x 30 cm surface area of crusted desert area	Desert area approximately ¼ mi south of Firebird Lake Sports Complex; in area with both shrubs and trails	Pan was most heavily loaded, but sieve 5 had considerable mass too
3	Very loose soil of approximate 1.5 cm depth and 20 cm x 20 cm area	Ostrich farm near Picacho Peak; within ostrich pen that was presently unused but which showed tracks of big birds	Sieve 3 had most sample mass
4	Sub-surface sample after removal of approximate ¼ inch crust	Agricultural field near Tanger Outlet Center at Casa Grande	Sieve 3 had the most sample mass
5	Sub-surface sample after removal of approximate ¼ inch crust	Agricultural field near Tanger Outlet Center at Casa Grande	Not sieved; collected for demonstration purposes
6	Before sample taken, parking lot traffic simulated by car tires on crusted surface; sample taken to approximate 1 cm depth and 30 cm x 30 cm surface area	Unpaved parking lot near main west entrance to Firebird Sports Complex	Sieve 4 had most sample mass, but sieve 5 and the pan were also well loaded with sample.

* Sieve characteristics are given in Figure 3.

1. Prepare a nest of sieves with the following openings: 4 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm. Place a collector pan below the bottom (0.25 mm) sieve.

2. Collect a sample representing the surface layer of loose particles (approximately 1 cm in depth, for an encrusted surface), removing any rocks larger than about 1 cm in average physical diameter. The area to be sampled should be not less than 30 cm by 30 cm.

3. Pour the sample into the top sieve (4 mm opening), and place a lid on the top.

4. Move the covered sieve/pan unit by hand, using a broad circular arm motion in the horizontal plane. Complete 20 circular movements at a speed just necessary to achieve some relative horizontal motion between the sieve and the particles.

5. Inspect the relative quantities of catch within each sieve, and determine where the mode in the aggregate size distribution lies, i.e., between the opening size of the sieve with the largest catch and the opening size of the next largest sieve.

6. Determine the threshold friction velocity from the following table.

Sieve Ref. No.	Tyler Sieve No.	Opening (mm)	Midpoint (mm)	Threshold Friction Velocity (cm/s)	Threshold Velocity @ 10 m	
					m/s	mph
1	5	4				
			3	100	18.9	42.3
2	9	2				
			1.5	76	14.3	32.0
3	16	1				
			0.75	58	10.9	24.4
4	32	0.5				
			0.375	43	8.1	18.1
5	60	0.25				

Figure 3. Field Procedure for Determination of Threshold Friction Velocity
(from a 1952 laboratory procedure published by W.S. Chepil[11])

The erodibility of each soil sample was characterized by threshold friction velocity, according to the table in Figure 3. Equivalent values of the threshold wind velocity at a reference height of 10 m are also given in the table; these values are based on a roughness height of 0.5 cm.[1] The calculated threshold velocities at 10 m range from 8 to 14 m/s (18 to 32 mph) for the six samples of Arizona soil.

As shown in Appendix B, the mean hourly wind speeds associated with dust-related traffic accidents during the period from 1985 to 1996 ranged from 7 to 18 m/s (16 mph to 41 mph). However, most of the dust storms were associated with wind speeds exceeding 30 mph. Moreover, peak wind gusts are typically 20 to 30 percent higher than the hourly mean values. Thus, it is concluded that all of the sampled soils would erode under wind speeds that were observed during the accident events.

The threshold friction velocities provide the basis for prediction of fine particulate emissions for each wind speed according to the predictive emission model published by EPA.[10] This model was developed by MRI based on field testing with a portable wind tunnel.[5]

SOURCE AREAS ALONG I-10

Prior to the second site survey, wind direction data for the dates, times and locations of most of the 46 dust-related traffic accidents listed in Table 1 were used to target the probable upwind areas that contained the sources of dust emissions. The purpose of the second survey was to identify likely dust sources along I-10 at the specific milepost locations of the accidents, especially within the areas of highest accident frequency (Figure 2). The candidate source areas were characterized with respect to the potential for dust generation, as related to areal extent and exposure cycles related to land use.

Dust sources along I-10 were comprehensively surveyed in a 3-day trip conducted during November 22-24, 1996. In the November period, the surveyor traveled east from Phoenix to San Simon, from San Simon west to the Vicksburg Exit south of Hope, and back to Phoenix. Area sources to each side of I-10 were observed, and local residents were queried for additional information. Photographic slides of likely dust sources were taken at most milepost locations where accidents were known to have occurred.

Prior to the November site visit, the State Climatologist of Arizona, Dr. Anthony Brazel, provided meteorological data for determination of likely wind direction at the time of each accident. These data are summarized in Appendix B.

The major locations of dust storm occurrence are evident from the accident clusters in Figure 2, which also shows I-10 mileposts. From east to west along I-10, the following major areas of wind erosion were identified:

- Vicksburg-Bouse Wash agricultural and desert areas (south of Hope)
- Buckeye-Goodyear (Roosevelt Canal west of Phoenix)
- Phoenix
- Firebird Lake Complex (between Maricopa Road and Queens Creek Road)
- Gila River desert area (south of Firebird Lake Complex)
- Casa Grande-Eloy
- Marana
- Bowie-San Simon

Table 1 identifies the probable dust sources along I-10 that have historically contributed to multi-vehicle accidents. These sources include: (a) active farmland; (b) sparsely vegetated desert, especially where disturbed by off-road traffic or livestock; (c) abandoned farmlands, cotton gin site, and campground; (d) confined ostrich area; (e) sports facility with large unpaved parking lots; (f) unpaved roads along agricultural fields, adjacent to irrigation channels, and in halted building development areas; (g) poorly vegetated areas near the on/off ramps at I-10 interchanges; and (h) construction sites and other soil surfaces near I-10 in the Phoenix and Tucson areas. Specific sources are commented on in the following paragraphs and are organized by I-10 milepost.

Vicksburg-Bouse Wash Area

From the Vicksburg Exit (near MP 45) to the Bouse Wash rest area, active farmland can be seen to the north, and begins approximately 1/3 mile north of I-10. Poorly vegetated desert land lies immediately north of I-10, to the south of the agricultural land; similar desert land lies to the south of I-10. A clerk at the Vicksburg Exit station said she believed dust blowing across I-10 originated from both the agricultural land and the desert area. A sample of surface soil that was obtained from the desert land, approximately 1.5 mi east of the Vicksburg Exit, appeared to be highly erodible with a large amount of fine dust available for resuspension. Accidents 1 through 5 listed on Table 1 were related to the dust sources associated with both agricultural land and poorly vegetated desert land.

Buckeye-Goodyear Area

West of Phoenix in the Roosevelt Canal district, large cotton fields were being harvested or tilled in late November, 1996. This agricultural land, which lies both to the north and south of I-10, is extensive in area, providing long fetch lengths for sustained wind erosion. Although no meteorological data were available to determine wind directions at the times of the accidents in this area, accidents 6 through 9 appeared to have been caused by active agricultural land, either to the north or south of I-10.

Phoenix

The Phoenix area contains a number of construction sites and other bare areas near I-10. These relatively small areas have been disturbed to produce a non-ridged bare surface, but with relatively small fetch lengths. Accidents 10 through 16 appeared to have been caused by these diverse sources.

South of Chandler Road and to the west of I-10, but before entering Indian lands, lie active agricultural fields. Two fields were observed to be both tilled and to have mature cotton. Only one accident (16) appears to be related to these fields located west of I-10 between the Chandler Road Exit to the Maricopa Road Exit.

Firebird Lake Complex

Four accidents (17-18 and 23) appear have been associated with westerly winds carrying dust from the unpaved and unvegetated areas of the Firebird Lake Sports Complex that lies immediately west of I-10 between Maricopa Road and Queens Creek Road. The Firebird Complex contains the Bob Bondurant race track, a drag strip, a concert area, and unpaved parking lots. Firemen and emergency medical staff stationed approximately 1 mi west of I-10 indicated that at the time of accident 23 while some suspended dust from a strong west wind was observed at the Fire Department building (located to the west of the Firebird Complex), it did not severely restrict visibility.

Additionally, an accident victim reported that while traveling south on I-10 immediately prior to accident 23, not much dust was observed north of Maricopa Road. The blowing dust that severely reduced visibility on I-10 to zero was observed to originate mostly from the Firebird Lake Complex. The victim, who formerly worked at the Complex, also noted that accident 23 was caused because the Firebird area had just been graded and that while water is usually applied afterwards to crust the surface, the ground had yet to be watered when high winds came from the west.

Gila River Area

Accidents 21-22 appear to have been associated with poorly vegetated desert land, some of which had been disturbed by off-road vehicle traffic. Accidents 24-26 occurred in areas where the probable dust source was abandoned farmland and poorly vegetated and bare areas.

Casa Grande-Eloy

From milepost 180 through 223, various areas of exposed soil were observed to have been the likely cause of accidents 27 through 32. These sources include active farmland to the southwest of the Casa Grande area, dirt roads in an incomplete housing development area to the east of I-10, bare and sparsely vegetated areas located immediately to the northeast of the junction of I-8 and I-10, and grazed desert land (especially a 100 m strip of unvegetated desert bordering on the southwest edge of I-10).

Tilled farmland immediately southwest of the Tanger Outlet Center at Casa Grande was observed in the September and November surveys to have a rough and cloddy surface. Lt. Mark Brown, Arizona Department of Public Safety (ADPS, Phoenix), reported that the ADPS has been able to persuade farmers in the Casa Grande area to use conservation measures that leave residue, ridges, or clods on the surface when not planted to crops. He believed that this new practice has almost entirely stopped dust storms in the area. Also, a rest stop attendant at milepost 182 noted that dust storms were considerably reduced by the nut orchards planted near mileposts 210-211.

Although the active ostrich farm located on the southwest side of I-10 at milepost 221 was reported by several persons contacted in this investigation to be a major source of dust, only one accident was associated with this source, accident 32 at milepost 223 with a southerly wind. However, other potential dust sources were observed immediately to the south of the ostrich farm, including tilled agricultural land and cattle land which appeared to be heavily grazed in a relatively wide area near the fence line.

Marana

The Marana area is a heavy agricultural producer of cotton, milo, and millet. Farmlands extend to the southwest and west of Marana for some distance from I-10. Many of these agricultural lands are reported to use conservation tillage practices to control dust emissions. An abandoned cotton gin with surrounding plant property, which lies on the southwest side of I-10 at milepost 237 (just southwest of Exit 236 at Marana), appears to be both a primary source of dust emissions that affect driver visibility along I-10. Windblown dust is piled up along the chainlink fence surrounding the site, and footprints leave a deep impression in the loose soil outside the fence line. An attendant at a Marana gas station remembered several 1995 and 1996 dust storms that caused accidents within 1 to 2 miles of the Marana Exit. He stated the source was always the cotton fields that were tilled after the crop was harvested and winds blew from the southwest to the northeast. Both discing and land planing were observed on harvested cotton land in the Marana area during the November 1996 site visit.

Bowie-San Simon

Mr. Spencer of ADOT (stationed at San Simon; residence in Willcox) provided information on current and past dust sources in the Bowie and San Simon area. He observed that the Bowie area was a problem until they planted pistachio and pecan trees in the severely eroding areas. Both large and small orchards and one vineyard were observed to the north and south of I-10. He also noted that cattle were well managed and grasses were periodically replanted on abandoned farmland that had been converted to grazing land.

The site visit revealed active farmland south and southwest of the Olga road overpass at milepost 373. This is the most likely source of dust for Accident 40 which involved 23 vehicles and 63 people with 10 fatalities. Crosses have been placed as a memorial to the accident victims in the I-10 median immediately to the East of the Olga Road overpass. The San Simon ostrich farm on the south side of I-10 near milepost 380 has been abandoned, and the ground is now crusted and being revegetated with grasses.

Insignificant Sources

Some anticipated sources of dust were eliminated during the second site visit. Specifically, dust from the Willcox Playa does not appear to transport north and sufficiently reduce visibility along I-10 to cause vehicle accidents. Active cotton farmland is also not a major dust source during March (pre-irrigation) through October and November (harvest). Livestock grazing areas from Willcox to Bowie were well-grassed with interspersed shrubs, leading one to conclude that livestock densities were not excessive and that grazing land was well-maintained in this area. Dry river beds, such as the Bouse Wash, Centennial Wash, and the Gila River, also do not appear to be major sources of dust because of rocky bottoms and interspersed vegetation.

5. DUST CONTROL METHODS

It was evident from the site surveys performed during this study that most natural desert areas in Arizona are fairly well protected from severe wind erosion by grasses, shrubs, and small trees that hold the surface soil and trap moving sand particles. Figure 4 shows the distribution of natural vegetation and cropland across southern Arizona. Vegetation protects against wind erosion both by reducing the wind speed that reaches the surface and by trapping particles resuspended from other locations. However, if desert land has been disturbed by off-road traffic or livestock, the desert can be a major source of dust.

Information on preferred dust control measures was obtained from technical literature and from past MRI dust control programs, including controls designated by EPA as Best Available Control Measures.[13] Information gained in a 1996 MRI study for EPA[12] was utilized to determine appropriate agricultural and land management conservation measures to prevent soil from blowing. Many of the control measures that are recommended in this section have been approved for dust control projects in desert regions of Southern California.[14]

WIND EROSION CONTROLS

A variety of potential control measures for open area wind erosion are reported in the literature. These include:

- Wind barriers—natural
  - Annual or perennial buffer strips (grasses; sunflowers; etc.)
  - Woody or herbaceous plants (scrub vegetation)
  - Strip cropping (two or more crops planted together)
- Wind barriers—artificial (wood slats; plastic netting; rock or earthen walls, etc.)
- Crop rotations (crops planted 1 year only because of leaving soil in friable condition and not leaving sufficient residue)
- Soil cover—rubber "chips;" cotton gin trash
- Soil cover—temporary vegetative (live, or killed to save soil moisture)
- Emergency tillage (soil ridging and clod formation)
- Operational modifications to soil tillage and implements

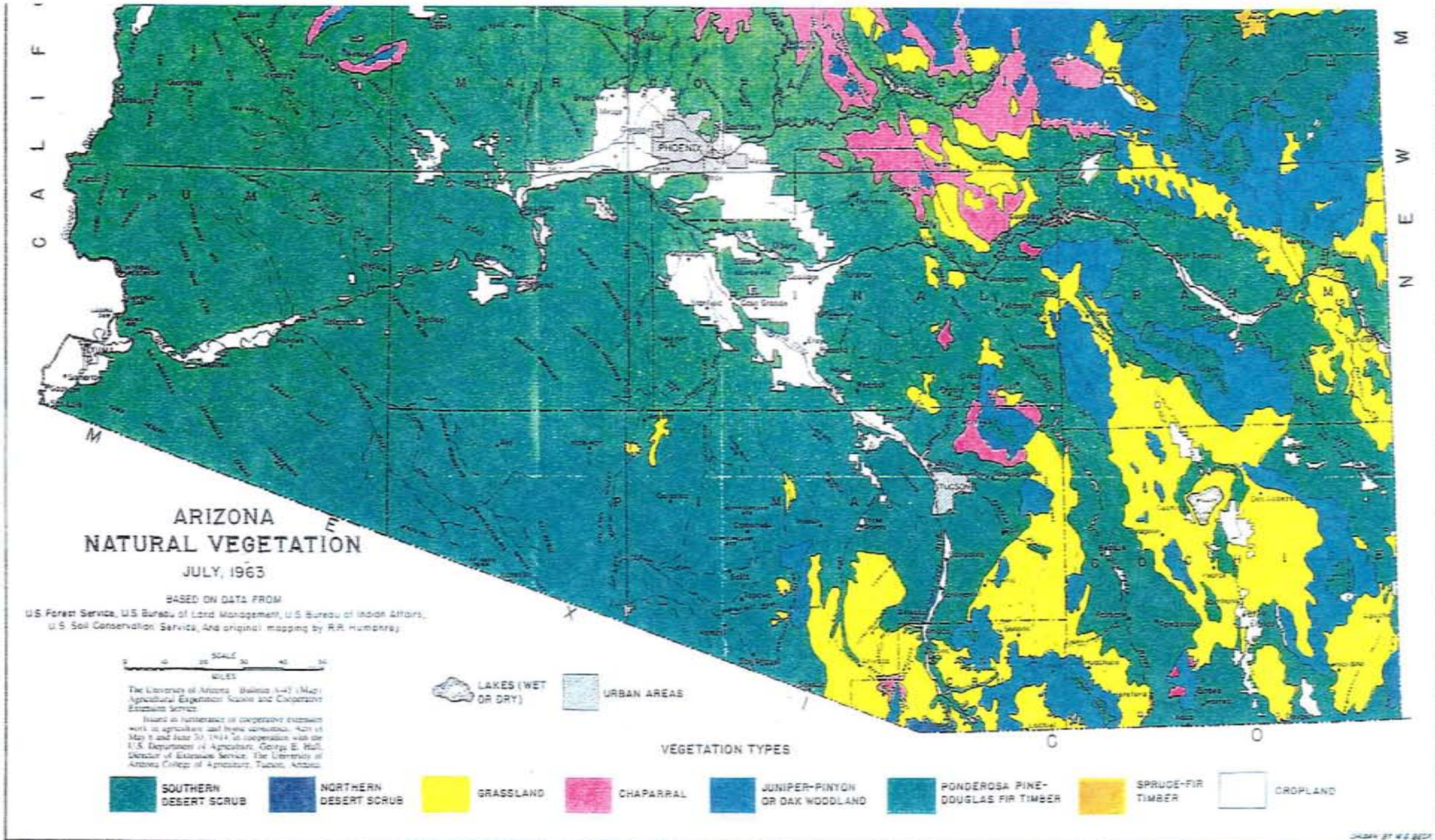

Figure 4. Arizona Natural Vegetation and Cropland

- Limitations on livestock grazing
- Watering (irrigation, cattle manure, or precipitation—snow/rain)
- Alternative crops
- Bans of off-road vehicles on highly erodible areas
- Chemical stabilization (asphalts, adhesives, etc.)

Some of these methods may not be appropriate for most desert areas, but may be suitable for special subareas that are very susceptible to wind erosion. Watering (other than irrigation) is not considered a reasonable control option in the Arizona desert, except in very limited circumstances.

AGRICULTURAL CONSERVATION PRACTICES

Crop residue management is an acknowledged conservation practice that usually reduces the number of agricultural field operations and eliminates plowing that inverts the surface layer of soil. The result is to keep sufficient vegetative residue on the soil surface and thereby to reduce wind and water erosion. For purposes of a Crop Residue Management (CRM) Survey conducted by the Conservation Technology Information Center, conventional and conservation tillage are defined, as follows:[15]

1. **Conventional tillage** leaves less than 30% surface residue after planting, either using a moldboard plow or other equipment. This class is divided into:

    a. **reduced till** (15%-29% residue), and
    b. **conventional till** (< 15% residue).

2. **Conservation tillage** is designed to maintain at least 30% surface residue after planting, or at least 1,000 lb/acre of flat, small grain surface residue equivalent during critical wind erosion periods. Conservation tillage is divided into:

    a. **mulch till**, which disturbs the soil prior to planting, but leaves at least 30% residue after planting.

    b. **ridge till**, which does not disturb the soil from the previous harvest until planting, except for nutrient injection. Seeds are planted on ridges with residue left on the surface between ridges.

c. **no-till**, which leaves the soil undisturbed except for soil fertilization, and utilizes planting or drilling equipment that creates a narrow seedbed or slot.

USDA staff at Big Springs, Texas, have characterized the effectiveness of crop residues to reduce wind erosion. Figure 5 shows the relationship of soil cover to soil loss ratio (SLR) as ascertained from wind tunnel studies by Bilbro and Fryrear.[16]

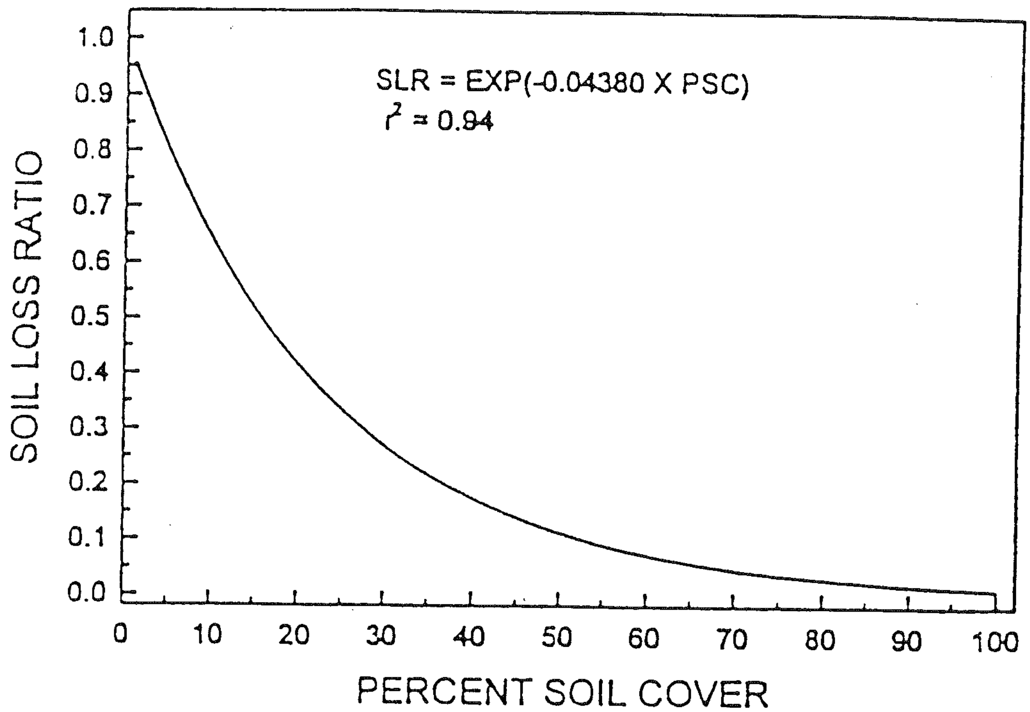

Figure 5. Soil Loss Ratio as a Function of Percent of Soil Covered by Nonerodible Materials

Conservation practices typically reduce emissions because:

1. Tilling activity levels (number of annual agricultural field operations) will be reduced;

2. Tilling emission factors for some conservation tillage implements such as no- till drills may be lower than the AP-42 emission factor because of less soil agitation, as estimated from remaining surface residue;

3. Wind erosion emissions will be reduced because of the minimum 30% surface residue required by conservation tillage; and

4. Land is taken out of production, e.g., long-term revegetation.

RECOMMENDED CONTROL MEASURES

Based on MRI[12] and University of Arizona[17] studies, conservation tillage of agricultural lands and other soil conservation measures will help to limit emissions. Other control measures focus on limiting off-road vehicle traffic and livestock grazing that remove surface vegetation and break surface crusts to increase the potential for wind erosion in areas that affect I-10. Wind fences and tree breaks may also be feasible in certain areas, and may be quite effective because of efficient capture of large particles that cross I-10 at heights below 2 m.

Several reduced tillage systems for cotton land in Arizona have been described by Coates and Thacker in a 1996 report produced by the University of Arizona.[17] Four alternative tillage systems were compared to a conventional system on research farms near Marana and Yuma. The conventional tillage system required 7 different operations, including 3 tillings with a tandem disk. Each of the alternative systems used only 3 to 4 operations on a field, thereby reducing dust emissions. The authors noted that reduced tillage systems also reduced field work time and offered energy savings. None of the reduced tillage systems were shown to reduce cotton yields.

When farmland is abandoned, short-lived species are the first to dominate in a process called secondary succession which finally results in longer-lived species populating the land. Tumbleweeds (Russian thistle) quickly take over in many areas to exclude virtually all over species. Because the landowner is legally liable when tumbleweeds blow onto adjacent properties, the tumbleweeds are mowed to keep them from blowing off the property. After a few years, London rocket and other mustards replace the tumbleweeds, and are then followed by Mediterranean grass and filaree. Burrowed and desert broom are the first native plants to become established, but it takes 20-40 years for saltbush and creosotebush to revegetate the land.

In certain very dry areas along I-10, the land may remain barren for over 30 years unless special steps are taken to promote revegetation. Thacker and Cox describe procedures to follow and species to plant in order to quickly and successfully revegetate abandoned farmland in Arizona.[18] No data are presented on costs of revegetation, but the effectiveness of good vegetative cover is noted as making "the difference between 30 tons of soil erosion per acre per year, and no soil erosion at all."

Recent and current studies in California's Antelope Valley[19] have investigated the effectiveness of furrowing and vegetative mitigation of abandoned agricultural fields, which are similar in wind erodibility characteristics to abandoned farmland in Arizona. The amount of PM-10 originating from controlled plots was measured as compared to emissions from untreated plots. Results show that a furrowed plot will reduced PM-10 emissions by about 50% compared to a barren plot. Future studies will evaluate the control effectiveness of mesquite shrubs planted in an array expected to mature in 1998.

CONTROL COST EFFECTIVENESS

Cost effectiveness is define as the ratio of the annualized cost of emission control to the amount of emission reduction achieved by the control measure. Control costs, which are normally annualized over the life of the control measure, are comprised of capital, operating, overhead, and enforcement/compliance costs.

Capital costs are incurred in purchase and installation of equipment, development of support facilities, and associated labor. Operating costs are associated with repeated applications or maintenance of control measures, including utilities, materials, labor, and fuel. Overhead represents the costs associated with worker compensation (such as fringe benefits), and worker support. Enforcement/compliance costs are a real expenditure associated with insuring that control measures are being implemented. These costs are likely to be incurred by any government agency responsible for permitting and monitoring programs. The annualized cost of an individual control measure is likely to vary because of geographic and environmental conditions.

Model control measure scenarios are presented by Dunkins and Cowherd[13] for fugitive dust sources, based on second quarter 1991 dollars. The calculations to prepare these model cost units are demonstrated in tables of component costs to control dust from unpaved roads, construction sites, and open areas. An example calculation for physical stabilization of a dirt parking lot is reproduced in Table 4.

One of the key findings of agricultural dust control cost analysis[12] is that cost savings rather than additional expenses usually accrue to the switching from conventional to conservation farming practices. The emission reductions and lower costs typically are associated with fewer tillage operations that requires less field labor and equipment. This was confirmed in a study of reduced tillage systems for Arizona cotton growers which concluded that reduced tillage systems offer savings in energy use, work time, and operating costs without reducing yield.[17]

The South Coast Air Quality Management District (SCAQMD) of California has recommended specific wind erosion controls for agricultural land, including:[14]

- etablishment of rows of vegetation across the prevailing wind
- cessation of tilling on high-wind days (wind speeds exceed 25 mph)
- establishment of snow (sand) fences
- establishment of end-of-row turn-around areas
- deep furrowing of fallow parcels
- prohibition of disking
- improved tillage practices

Table 4. Example Control Cost Calculation

Model unit	
Source:	Wind erosion
Source extent:	Wind erosion from an unpaved parking lot; dirt lot 100 m x 100 m; uniform daily disturbance; average particle size 0.56 mm
BACM:	Cover with a less erodable material (70% efficiency)

Cost categories	Annualized cost
Capital costs:	
Surface material and installation	$4,069
Operations and maintenance costs:	
Periodical grading	$5,750
Material replacement in erosion areas	$2,500
Overhead costs:	$4,125
Enforcement compliance costs:	
Permitting	$100
On-site inspection	$200
Recordkeeping	$50
Total	$16,794

Cost sources: MRI and *Means Building Construction Cost Data.*

SCAQMD has estimated the cost of requirements to implement the above soil conservation plans is approximately $150 per ton of PM-10 emissions reduced.

PROGRESS IN CONTROL APPLICATION

Based on conversations with residents along I-10, many of the worst wind erosion areas have already been mitigated by grasses and trees which serve to both hold the soil and provide windbreaks. Of particular note are mature nut orchards, reportedly pistachio and pecans, planted in the Picacho and Bowie areas. Highway edges and medians in many areas are also well vegetated with trees, shrubs, and grasses which receive additional moisture because of pavement runoff. However, I-10 right-of-way is poorly vegetated at Marana, apparently because of lack of right-of-way to the southwest (farmland comes very close to I-10). The ostrich farm on the south side of I-10 near San Simon has now been abandoned. The pens have been partially revegetated with grasses, and small remaining bare areas are crusted.

Additional dust control measures appear to be in place for agricultural fields in the Casa Grande and Eloy areas where conservation tillage practices are stated to be employed. These practices both reduce the number of tillage operations and also leave fields with furrows and clods that resist wind erosion.

Conservation tillage was not always observed in other areas during the November 1996 site visit. In two instances, pictures were taken that showed land planing and discing operations following the cotton harvest in the Marana and Goodyear areas to leave very loose and relatively smooth surfaces of bare soil. While the State of Arizona requires a mandatory plowdown of cotton land by February 15 (date varies by region), farmers till cotton land almost immediately after harvest to prevent weevil infestation of the next crop and to prevent volunteer cotton plants from growing.

The clear reduction in the frequency of accidents between mileposts 170 and 240, as discussed in Section 3, may be attributable to:

- revegetation of abandoned farmland
- improved soil management techniques, due to conservation farming practices

Accidents that occurred in 1994-1996 are of particular interest in this study because they indicate that current control measures were not adequately employed at selected locations along I-10. Only seven accidents were observed to have occurred in this recent time period, two of which occurred adjacent to the Firebird Lake Complex. This site was visually observed to be highly erodible, with little paving and no vegetation.

A list of 1994-1996 accidents and probable dust sources include:

#8—active farmland west of Phoenix (Buckeye-Goodyear area);

#19—disturbed bare areas of Firebird Lake Complex

#23—disturbed bare areas of Firebird Lake Complex

#21—poorly vegetated desert immediately south of the Firebird Lake Complex that appeared to have been disturbed by off-road traffic

#35a—active farmland and abandoned cotton gin site southwest of the Marana Exit

#40—active farmland south of I-10 Olga Overpass near Bowie

#45—a former ostrich farm near San Simon, now being revegetated

These seven most recent accidents indicate that only selected areas along I-10 are likely to continue to be affected by dust sources that can reduce visibility to a level that causes vehicle accidents.

6. DUST CONTROL STRATEGY

The recommended dust control strategies, developed as a result of this study, rely on vigilant field assessment to assure that (a) existing open dust sources are treated by effective dust control measures, and (b) land disturbance operations are controlled by preventive measures so that new open dust sources are not created.

This strategy should focus on the strips of land, 1 km in width, on either side of I-10. If these strips of land are controlled, they will act as buffers in mitigating the visibility obscuration impact of source areas located further upwind, by trapping most of the coarse and some of the fine particles transported from source areas beyond the buffer strips.

DUST HAZARD ASSESSMENT

The dust hazard assessment procedure begins with regular field surveys of the buffer strips along I-10 to monitor the condition of potential erodible dust source areas. Field surveys should be undertaken in the same manner as used in the MRI survey to identify source areas. Specifically, the following potentially erodible areas should be examined monthly, particularly during the period from March through September.

- Large open areas, unvegetated or poorly revegetated, especially when soil has recently been disturbed.
- Long fetch lengths for winds to blow across highly erodible lands without obstructions toward the roadway.
- Areas subject to "high winds" caused by topographical channeling.
- Dry soils with large erodible fractions (especially in the saltation size range) and little nonerodible material (rocks, crust, surface residue) to inhibit wind flow near the surface.

If a potentially erodible area adjacent to I-10 is identified, its surface should be examined to determine whether it contains a large proportion of erodible particles. If the surface is crusted, it is essentially nonerodible unless and until it is disturbed in such a manner that the crust is destroyed. Even a crusted surface, however, can act as a "secondary" source area, if loose fine particles lie on the surface of the crust. Such particles, which were probably deposited during a previous wind erosion event, originated from a nearby primary source area further upwind. If large areas of erodible particle deposits on crusted surfaces are observed, upwind source area should be identified. The hazard assessment survey should focus first on primary source areas adjacent to I-10 and then the primary source areas further upwind.

It is highly recommended that the hand sieving procedure used during the MRI site surveys, as described in Section 4 of this report, also be used to quantify more closely the erodibility of any observed dust source areas. This hand sieving procedure yields an estimate of the threshold wind velocity for the surface material in question. The threshold velocity is the lowest wind velocity for which the surface material begins to erode.

Of particular interest in the monthly surveys should be the areas along I-10 where dust-related traffic accidents occurred in the most recent 3-year period of accident statistics (1994-1996). These accidents are listed at the end of Section 5. The areas where recent accidents have occurred include:

- Active farmland west of Phoenix near Buckeye and Goodyear. In this area, large cotton farms lie to both north and south of I-10.
- Disturbed bare areas of the Firebird Lake Complex, including large unpaved parking lots.
- Poorly vegetated desert south of Firebird Lake Complex.
- Active farmland and an abandoned cotton gin site southwest of the Marana Exit on I-10.
- Active farmland south of I-10 at the Olga Overpass near Bowie.
- A former ostrich farm near San Simon, now being revegetated.

RECOMMENDED DUST CONTROLS

Based on evaluation of candidate control measures for the types of open dust sources implicated in the dust-related traffic accidents identified in Section 3 of this report, the following control measures are recommended:

- **Active agricultural land**:

  - encourage agricultural conservation measures, including reduced frequency of soil disturbance, and use of tillage implements designed to leave clods and furrows until soil preparation for the next crop;

  - plant wind breaks near fencelines (including orchards).

- **Poorly vegetated abandoned farmland and desert**:

  - replant native vegetation in selected border areas along I-10 using methodologies suggested by the College of Agriculture at the University of Arizona;

  - acquire wider right-of-way along selected sections of I-10 to plant vegetative windbreaks;

  - limit off-road vehicle traffic and livestock movement within 250 m of nearest I-10 traffic lane.

- **Unpaved roads, parking lots, and abandoned plant areas**:

  - pave or chemically stabilize surfaces;

  - in the interim, require wetting of soil immediately following a disturbance;

  - construct wind fences in selected areas.

- **Intensive livestock confinement areas**:

  - remove ostrich and similar high density confined livestock areas to at least 1 km from nearest I-10 traffic lane.

- **Construction areas**:

  - water areas during and after disturbance periods.

The recommended controls generally fall into the category of Best Available Control Technology measures recommended by the U.S. EPA. These measures represent the state-of-the-art in proven cost-effective control technologies. They are designed to bring into compliance with national ambient air quality standards areas that could not meet the standards without such measures, as required by the Clean Air Act Amendments of 1990. These areas are referred to as "nonattainment areas."

As shown in Figure 6, the Phoenix Metropolitan area has been designated as a "serious" nonattainment area for PM-10. There are also numerous other areas in southern Arizona that are currently designated as "moderate" nonattainment areas for PM-10. Thus, the State of Arizona must develop a PM-10 control strategy that utilizes Best Available Control Measures for fugitive dust sources. The Arizona State Implementation plan, which must demonstrate compliance with National Ambient Air Quality Standards for PM-10, outlines a regulatory strategy for implementing the necessary controls on

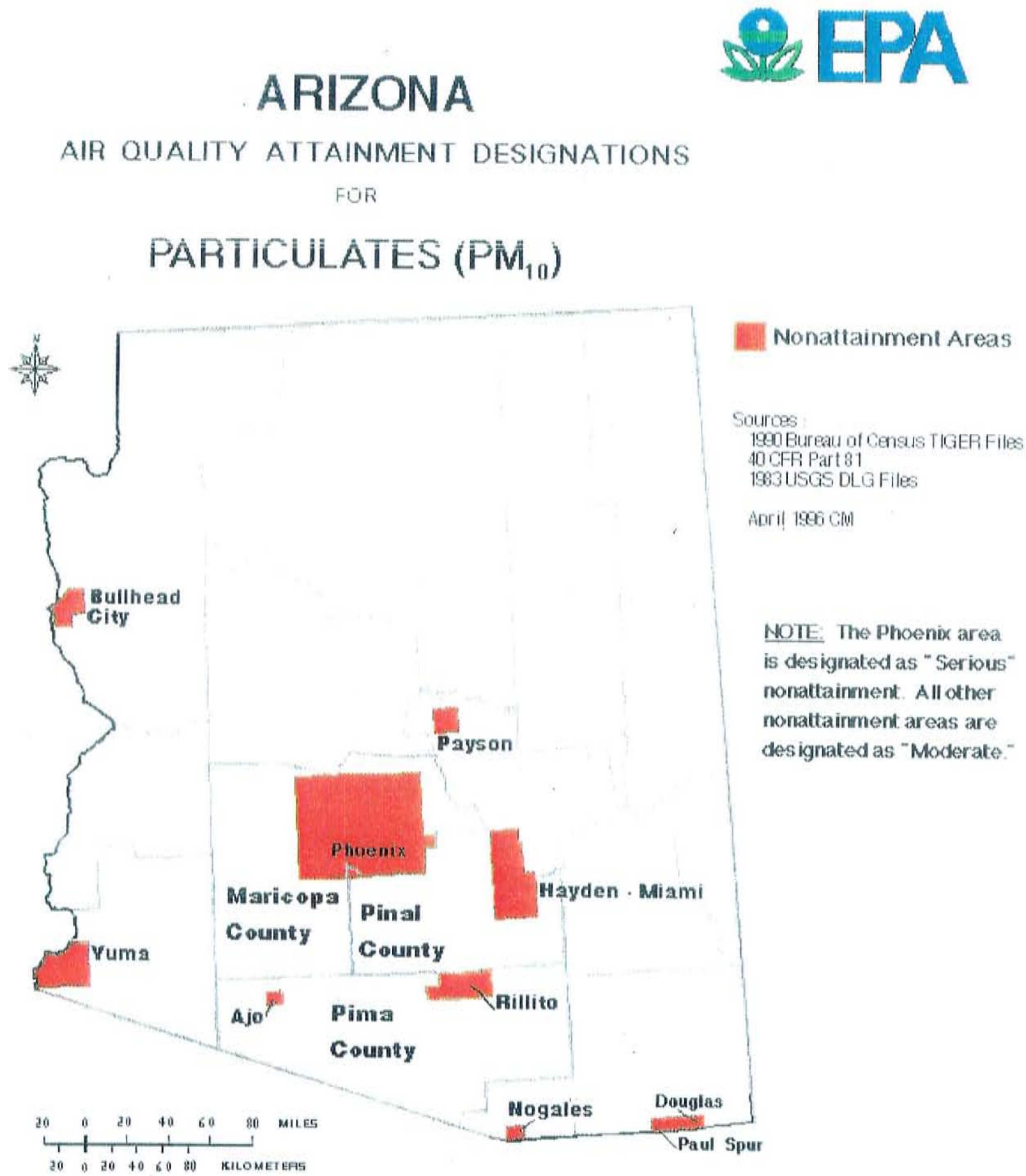

Figure 6. PM-10 Nonattainment Areas in Arizona

PM-10 sources in the state. In particular, more stringent controls are required for sources that lie within the following "non-attainment areas" for PM-10. The dust controls specified in the Arizona State Implementation Plan, especially those applicable to the Phoenix area, should be consulted as representative of those that could be applied to erodible areas along I-10.

IMPLEMENTATION PARTNERSHIPS

Dust sources near I-10 will need to be controlled using land management techniques that require the cooperation of individuals and agencies in the specific areas where accidents have occurred or are likely to occur in the future. MRI contacted many individuals in the private and public sector to develop the mitigation strategies recommended in this report. For example, visits and calls were made to the University of Arizona, College of Agriculture, and county agricultural agents to obtain relevant reports and advice on controlling dust from specific agricultural practices in Arizona, especially cotton production. Tilled cotton land is acknowledged as a potential dust source that can be controlled through conservation tillage.

Partnerships in implementing pollution control strategies are usually dependent on formal relationships and legal requirements. The control of dust from agricultural operations is primarily associated with the Farm Bill of 1996, which mandates farmer participation in land conservation programs in order to qualify for federal subsidies. Consequently, the county agricultural agent is often the best person with which to discuss and devise programs to control dust from tilled or livestock areas near I-10. The county agent can help arrange meetings with farmers that own lands suspected of eroding easily in high wind events. For example, a farmer will be more receptive to discussing tilling or crop alternatives, or livestock density issues in the presence of an informed county agricultural agent who may be able to identify financial incentives or agricultural subsidies for the farmer, including revegetation of abandoned farmland. County agricultural agents also may be able to facilitate additional water rights for new orchards to serve as windbreaks along I-10.

Local permitting authorities in Arizona are the best organizations to deal with privately owned sources in municipal areas. These construction and operating permit agencies have the power to deny a source to build or operate, and are mandated to control dust in the Arizona PM-10 nonattainment areas shown in Figure 6. Their duties require them to inspect sites for proper implementation of dust control measures specified in construction or operating plans.

Native American tribal authorities are recognized by the U.S. EPA as has having the same responsibility as individual states for controlling pollution on their lands. Environmental staff are employed by almost all tribes to control pollution and maintain a pristine environment. The U.S. EPA deals directly with the environmental staff of an Indian nation, and this organization is best able to serve as an intermediary in controlling fugitive dust from Indian lands.

Public sources of dust can be controlled by local, state, or federal entities. If a public unpaved road should require paving or a highway construction site require periodic watering to prevent accidents on I-10, the necessary relationships that need to be established will involve municipal, county, state and federal authorities who are responsible for land use planning.

When the responsible parties are shown clear evidence that wind erosion of their land leads to accidents, injuries, and deaths on I-10, they are usually cooperative. For example, the ostrich farmer near San Simon was persuaded to shut down his livestock operation that was located adjacent to I-10 at milepost 373, because of a 23-car accident that killed 10 people in April 1995. Similarly, farmers near milepost 211 have planted orchards in former high dust storm areas to replace cotton.

7. CONCLUSIONS

The following conclusions were derived from the findings of this study:

1. The dust that causes reduced visibility and related traffic accidents on I-10 originates mostly from erodible land immediately adjacent to the highway.

2. The particle size analyses of soils collected from potential source areas along I-10 indicate substantial wind erodibility for typical wind speeds recorded at nearby weather stations during the accident events.

3. Source areas that were upwind of I-10 during the most recent accident events should be monitored most closely in the dust hazard assessment survey process. They include:

    - Active farmland west of Phoenix (Buckeye-Goodyear area);
    - Disturbed bare areas of Firebird Lake Complex
    - Poorly vegetated desert immediately south of the Firebird Lake Complex that appeared to have been disturbed by off-road traffic
    - Active farmland and abandoned cotton gin site southwest of the Marana Exit
    - Active farmland south of I-10 Olga Overpass near Bowie
    - A former ostrich farm near San Simon, now being revegetated

4. A range of Best Available Control Measures are applicable to these dust sources, but the costs and efficiencies of these controls depend on the specific conditions of the treated source areas.

5. Many of these Best Available Control Measures have already been applied along I-10, thereby reducing the number and size of the source areas and the frequency of dust-related vehicle accidents in recent years.

6. New source areas, such as construction sites, that involve frequent land surface disturbance, should be subject to rigorous dust control plans as conditions of their permits to construct and operate.

7. Although improved sensing technology is available for dust warning systems, such systems are recommended only if preventive source controls prove infeasible.

8. PROJECT CONTACT LIST

A comprehensive list of persons and organizations contacted on this project appears in Table 5.

Table 5. Project Contacts

Name/Title/Phone	Agency/Address
Jiann-Jong (J.J.) Liu (602) 407-3134	Intermodal Transportation Division, Arizona Transportation Research Center 1130 N. 22nd Ave. 075R Phoenix, AZ 85007-3716
Reza Karimvand (602)255-7219	ADOT Traffic Group 206 S. 17th Avenue Phoenix, AZ 85007
Dr. Tony Brazel Arizona State Climatologist (602) 965-7533	Office of Climatology Arizona State University Tempe, AZ 85287-1506
Clifton Taylor (602) 255-7398	ADOT Natural Resource Management
Lt. Mark Brown (602) 223-2000	ADPS University Station 2102 West Encanto Blvd. Phoenix, AZ
Dennis Alvarez (520) 620-5412	ADOT Tucson Assistant District Engineer
George Chin (602) 255-7193	ADOT Phoenix Regional Traffic Engineer
Bob LaJeunesse (520) 445-5391	ADOT Prescott Regional Traffic Engineer
Steve Husman Maricopa Agricultural Agent (602) 470-8086	USDA
Jim Williams (602) 255-7132	ADOT Traffic Group
Mike Manthey (602) 255-8880	ADOT State Traffic Engineer

Table 5. Project Contacts

Name/Title/Phone	Agency/Address
Richard Moeur (602) 255-6661	ADOT Traffic Design
Mark Schalliol (602) 255-6552	ADOT, Phoenix Maintenance District
George Wendt (602) 255-7327	ADOT
Gary Zimmerman (602) 223-2504	ADPS Central District
Lt. Roephle (602) 223-2372	ADPS
Mr. Spencer	ADOT
Personnel in Arizona Geologic Survey and Natural Resources (520) 621-5694	University of Arizona Arizona State University
Personnel from Chandler and Gila River Fire Departments and Emergency Medical Services	Chandler Fire Department Gila River Fire Department
Alphonse Voza Project Engineer (908) 247-0900 Ext. 5866	New Jersey Turnpike Authority
Various clerks in stations along I-10	

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APPENDIX A

DUST WARNING SYSTEMS

DUST WARNING SYSTEMS

This project also evaluated alternative traffic warning systems that may perform well to reduce accidents in dust storms. Appendix D contains an assessment of satellite imaging to identify dust storms and sources along I-10.

DRIVER REACTIONS

A review of early studies analyzing driver reactions to adverse visibility conditions due to dust, fog, smoke, and snow shows that most motorists slow down very little on the open highway. [20] Moreover, drivers do not know how to react under limited visibility conditions. Most motorists overrun their sight distance and are unable to stop their vehicles when stationary hazards are identified. The most difficult problem is that drivers do not drive at predictable speeds. In particular, trucks often have better visibility than cars because of being at a greater height above the road, and consequently may travel at faster speeds.

While there is no national agreement among experts as to specific steps to be taken when drivers enter and operate under limited visibility, several studies [16] recommended several preferred driving tactics while traveling on limited access highways:

- Do not enter a dust cloud, but pull off to the right side of the highway and wait until the storm passes, or exit to a slow-speed alternate road
- Slow down to about 55 km/h (34 mph) or lower, and tap brake slightly so that brake lights will warn cars immediately following
- Do not overestimate your visual range and the stopping capability of your vehicle
- If caught in zero-visibility dust cloud, turn off lights and pull off highway to the right as far as possible. Do NOT apply brakes because the following vehicle may follow your brake lights thinking you are still on the highway!)
- Use low headlight beams or low-placed fog lights if visibility is not reduced to zero; watch for approaching faster vehicles in rear, and slower drivers in front.
- Watch constantly for escape routes, and use evasive action if necessary.

While these actions may help to prevent serious accidents, many highway authorities believe that closing a highway to vehicle traffic is the only realistic way to prevent accidents.

ARIZONA EXPERIENCE

In the 1960s and early 1970s, Arizona dust-related accident studies culminated in recommendations for, and installation of, static warning signs. These signs contained fixed messages warning motorists of blowing dust areas where reduced visibility was a possibility. Some of the signs were of the fold-down type that could be unfolded by the Highway Patrol when they felt the blowing dust problem was severe enough to warrant alerting motorists. Static warnings were not as effective as desired because the signs did not define when the danger was present, the extent of the danger, or what to do when the danger was present. Some of the dust-related accident studies that involved signage showed a reduction in accidents. However, it was difficult to prove the reduction in accidents was attributed to the signage because of the confounding influence of the drivers' behavior and the severity of the blowing-dust event.

In the early 1970s, a number of governmental and civic agencies cooperated in a joint venture directed at averting dust-related accidents in Arizona. The agencies involved were the Arizona Department of Transportation (ADOT), the Department of Public Safety (Highway Patrol), the National Weather Service, and the Arizona Broadcaster's Association. The objective of this venture was to determine if detection and early warning could be implemented in an area of impending dust storms and how this information could best be transmitted to the public via traffic control devices, and news media—newspaper, radio and television.

A dust warning system was installed on Interstate 8 and 10 between Phoenix and Tucson. The system consisted of 40 changeable message signs approximately five miles apart in both directions. The purpose of the signs was to provide motorists with dust storm warnings. Each sign was capable of displaying one of three message. The actual dust warning message had the legend "BLOWING DUST—REDUCE SPEED." This warning was further emphasized by two high-intensity amber strobe lights.

The system became operational in July 1973. The operational strategy used until early 1976 was directed at providing spot warnings of specific wind and dust conditions in the immediate vicinity of each sign. The operation of the 40 warning signs during the three dust seasons was under the control of the Highway Patrol. Radio requests for appropriate sign messages were made to the Phoenix Control Console by highway patrolmen. The signs were changed remotely to the appropriate message by the Phoenix dispatcher. Field personnel could also make radio requests to the dispatcher during the storm to remotely change the sign messages to match the current weather conditions.

The study was temporarily suspended in early 1976 when it became evident that the timeliness of the message (match between the sign messages and the prevailing weather condition) had to be increased from the 65 percent level. Also, there was a need to more specifically inform motorists on "what to do in a dust storm."

Modifications to the dust warning system went into effect on June 1, 1976. These modifications changed the strategy from a spot warning to an area-wide alert and provided more guidance to the drivers through "audio signing." The audio signing changed the previous blowing dust message to "DUST STORM ALERT—RADIO 550/620/910. Three commercial radio stations in Phoenix would voluntarily broadcast a 60-second dust alert message at 10-minute intervals, once the dust storm alert system was activated. The news media was requested to disseminate information at the earliest possible time when there was a probability of visibility-reducing dust storms. This information not only included the general location where a storm could be expected, but also gave advice as to what a motorist should do upon encountering a dust storm; namely, pull completely off the road, to the right-of-way boundary or fence if possible, and turn off all lights and wait. They were advised that the dust storms normally pass in a matter of 15 to 20 minutes.

The modification in the operation of the system increased the timeliness of the warning from 65 percent to 98 percent. Also, the percentage of drivers who took evasive action because of the system rose from 21 percent to 37 percent. Of those taking evasive action, 12 percent pulled off the road compared to only 8 percent under the previous message warning. The accident reduction recorded during the multi-year study was not statistically significant. The study was discontinued later in 1976.

The dust warning systems used in the 1970s were manually activated. Automatic activation technology was not fully developed at that time. Now, visible dust plumes that transport across roads can be automatically monitored using visibility sensing equipment mounted near the roadway. Warning systems that include visibility sensors to detect when dust storms obscure drivers' vision are alternative measures to reduce the hazards associated with windblown dust on I-10.

CURRENT TECHNOLOGY

Current visibility sensors operate on one of three main principles. These principles are atmospheric transparency, light scattering by airborne particles, and luminance contrast. The transmissometer requires a laser source carefully aimed at a receiver some distance away. The light-scattering sensor uses a light transmitter with the receiver placed from 33 to 70° off the light-source axis, or a backscatter system which has the transmitter and receiver aligned on the same axis. Video cameras may also be used to measure visibility from the video images captured on a frame grabber.

There are at least five manufacturers of visibility equipment that are being investigated or used by State DOTs as part of their Road Weather Information Systems (RWIS), which are part of the Rural Intelligent Transportation Systems (ITS). The five manufacturers are Scientific Technology Incorporated (Weather Identifier and Visibility Sensor (WIVIS)), HHS Incorporated (VR-3-18 Digital Visibility Sensor), Belfort Instrument (Models 6000 and 6210 Visibility Sensors), Vaisala (Vaisala Visibility Meter FD-12), and Sten Löfving (Sten Löfving Visibility Sensor). The WIVIS system is most commonly used in connection with fog and blowing snow.

The HSS system was developed for the military for use in desert warfare. These and other visibility sensors are described in an October 1995 FHWA report "Environmental Sensor Systems for Safe Traffic Operations," Publication No. FHWA-RD-073.

The use of current visibility sensors in connection with a dust warning system needs further evaluation before it can be totally implemented. There are a number of questions that need answering relative to blowing dust events. For instance: What is the appropriate height above the ground for the sensor? What is the appropriate alignment of the sensor relative to the roadway? What are the appropriate calibration procedures for dust? What are the problems associated with intermittent day-time lighting conditions? Finally, what are the siting requirements for the sensors relative to the potential dust plume locations? These, plus other questions, need to be resolved because a majority of the visibility sensors were developed for fog and snowfall conditions.

A sand flux sensor has been used in the Owens Dry Lake and Mono Lake areas to quantify dust emissions and estimate control efficiencies.[21] Sensit™ readings are proportional to sand flux if calibrated against a sand transport sampler at the site where it is operated. The Sensit™ consists of a piezoelectric sensor ring around a one-inch diameter rod. When particles hit the sensor, electrical signals are sent to a data logger that records particle counts and kinetic energy. Sensits cost about approximately $2,000 each (not counting a data logger).

A similar device was used in an experimental study by the Oregon Department of Transportation to warn motorists of visibility hazards from blowing dust storms.[22] The alarm sensed electrification of a metal antenna by blowing dust particles and transmitted measures by telemetry to a microcomputer. The author reported that the "sensor responded favorably under conditions of half mile visibility and 20 mph winds." The study also discussed an experimental acoustic sensor for blowing sand.

APPENDIX B

SUPPLEMENTARY METEOROLOGICAL DATA FOR ACCIDENT PERIODS

Acc. No.	Date	Time	Average MP	No of Vehicles	Met station	Wind speed		Wind direction	Dir of source
						m/s	(mph)		
1	7/29/91	19:00:00	43.6	1	Parker	2.8	6.3	177	
					Parker	18.4	41.2	95	E
					Parker	14.7	32.9	100	
2	8/13/90	18:30:00	44.0	4	Parker	2.6	5.8	161	
					Parker	7.0	15.7	58	ENE
					Parker	6.5	14.5	113	
3	7/20/86	17:40:00	48.5	16	-				
4	6/2/86	18:05:00	49.1	2	-				
5	8/5/90	18:30:00	49.3	4	Parker	3.0	6.7	339	
					Parker	11.5	25.7	9	
					Parker	14.6	32.7	61	ENE
6	7/20/88	17:34:00	124.1	26	-				
7	8/27/88	13:55:00	125.8	8	-				
8	8/16/94	21:28:00	125.8	2	-				
9	7/29/91	15:25:00	132.4	7	-				
10	7/27/91	17:55:00	140.5	2	-				
11	7/21/90	19:30:00	149.5	4	Maricopa	13.4	30.0	149	
					Maricopa	14.2	31.8	141	SE
					Maricopa	5.7	12.8	140	
12	6/25/86	18:30:00	149.8	2	-				
13	6/13/91	18:00:00	153.0	2	Maricopa	10.0	22.4	133	
					Maricopa	13.4	30.0	149	
					Maricopa	14.2	31.8	141	SE
14	8/29/90	21:00:00	153.6		Maricopa	2.8	6.3	232	
					Maricopa	13.0	29.1	167	SSE
					Maricopa	7.5	16.8	193	
15	9/3/91	20:45:00	158.0	2	Maricopa	1.6	3.6	91	
					Maricopa	2.9	6.5	44	
					Maricopa	17.0	38.0	5	N
16	6/20/88	18:45:00	162.0	2	Maricopa	3.5	7.8	162	
					Maricopa	14.8	33.1	142	SE
					Maricopa	12.2	27.3	149	
17	7/21/89	18:15:00	163.2	6	Maricopa	7.0	15.7	233	
					Maricopa	15.8	35.3	265	W
					Maricopa	8.0	17.9	347	
18	9/4/85	13:40:00	163.3	2	-				
19	3/11/94	17:58:00	163.5	7	Maricopa	9.4	21.0	270	
					Maricopa	14.4	32.2	277	W
					Maricopa	12.1	27.1	303	
20	7/28/91	16:25:00	164.4	2	Maricopa	2.7	6.0	220	

Acc. No.	Date	Time	Average MP	No. of vehicles	Met station	Wind speed		Wind direction	Direction of source
						m/s	(mph)		
					Maricopa	14.7	32.9	41	NE
					Maricopa	15.2	34.0	54	
21	10/25/96	12:08:00	164.7	7	Maricopa	11.2	25.1	251	
					Maricopa	14.0	31.3	255	WSW
					Maricopa	13.6	30.4	253	
22	8/5/90	18:05:00	165.0	6	Maricopa	4.7	10.5	113	
					Maricopa	5.1	11.4	147	
					Maricopa	7.2	16.1	29	NNE
23	1/17/96	12:15:00	163.6	25	Maricopa	11.1	24.8	256	
					Maricopa	11.6	25.9	259	
					Maricopa	14.2	31.8	276	W
24	3/21/92	14:17:00	174.9	2	Maricopa	9.5	21.3	203	
					Maricopa	11.4	25.5	212	SSW
					Maricopa	9.1	20.4	180	
25	8/5/90	17:30:00	175.7	6	Maricopa	4.7	10.5	113	
					Maricopa	5.1	11.4	147	
					Maricopa	7.2	16.1	29	NNE
26	8/27/88	15:12:00	176.1	18	Maricopa	6.1	13.6	251	
					Maricopa	11.3	25.3	305	
					Maricopa	11.9	26.6	359	N
27	8/9/86	19:20:00	180.1	2	-				
28	6/4/87	17:48:00	186.6	1	Maricopa	9.0	20.1	2	
					Maricopa	10.0	22.4	358	N
					Maricopa	8.5	19.0	11	
29	7/4/91	17:50:00	199.9	6	Eloy	4.6	10.3	345	
					Eloy	16.7	37.4	40	NE
					Eloy	12.9	28.9	112	
30	5/29/89	13:55:00	205.4	3	-				
31	7/15/93	14:10:00	209.1	3	Eloy	5.8	13.0	348	
					Eloy	12.9	28.9	178	S
					Eloy	10.1	22.6	182	
32	7/7/90	11:44:00	222.7	3	Eloy	2.8	6.3	170	
					Eloy	4.9	11.0	178	
					Eloy	13.0	29.1	160	SSE
					Marana	4.3	9.6	244	
					Marana	16.3	36.5	192	SSW
					Marana	9.7	21.7	141	
33	5/27/91	14:45:00	233.5	2	Eloy	9.0	20.1	222	
					Eloy	9.7	21.7	220	SW
					Eloy	9.6	21.5	227	

Acc. No.	Date	Time	Average MP	No. of vehicles	Met station	Wind speed m/s	Wind speed (mph)	Wind direction	Direction of source
					Marana	9.4	21.0	183	
					Marana	9.3	20.8	213	SW
					Marana	10.8	24.2	245	
34	7/10/87	12:30:00	234.7	2	-				
35	5/3/92	15:10:00	236.6	8	Marana	5.5	12.3	167	
					Marana	4.0	8.9	132	
					Marana	14.7	32.9	201	SSW
35a	7/30/95	14:42:00	236.6	4	Marana	7.2	16.1	291	
					Marana	14.4	32.2	233	SW
					Marana	13.7	30.6	185	
36	5/3/92	15:22:00	236.9	2	Marana	5.5	12.3	167	
					Marana	4.0	8.9	132	
					Marana	14.7	32.9	201	SSW
37	9/13/86	13:00:00	250.0	3	-				
38	3/3/89	14:34:00	364.0	33	Bonita	10.8	24.2	251	
					Bonita	12.7	28.4	256	
					Bonita	11.4	25.5	259	
					Bonita	15.7	35.1	253	WSW
					Guthrie*		45.0	246	
					Guthrie*		51.0	269	
					Guthrie*		54.0	266	W
					Guthrie*		53.0	291	
39	6/3/85	16:35:00	366.8	1	-				
40	4/9/95	14:30:00	372.9	23	Bonita	15.6	34.9	264	
					Bonita	17.2	38.5	258	W
					Bonita	16.1	36.0	260	
					Bonita	16.7	37.4	263	
					Guthrie		44.0	252	
					Guthrie*		61.0	293	
					Guthrie*		68.0	287	WNW
					Guthrie*		77.0	289	
					Chiricahua*		53.0	269	
					Chiricahua *		45.0	269	
					Chiricahua *		46.0	269	W
					Chiricahua *		40.0	269	
41	2/14/90	11:15:00	374.1	6	Bonita	8.3	18.6	199	
					Bonita	9.3	20.8	203	
					Bonita	12.0	26.8	223	SW
					Bonita	9.5	21.3	263	
					Guthrie*		68.0	207	

Acc. No.	Date	Time	Average MP	No. of vehicles	Met station	Wind speed m/s	(mph)	Wind direction	Direction of source
					Guthrie*		79.0	214	
					Guthrie*		70.0	219	SW
					Guthrie*		75.0	239	
42	3/5/90	14:40:00	377.4	16	Bonita	7.9	17.7	211	
					Bonita	8.7	19.5	226	
					Bonita	12.5	28.0	227	SW
					Bonita	10.2	22.8	241	
					Guthrie*		64.0	190	
					Guthrie*		69.0	205	
					Guthrie*		66.0	233	SW
					Guthrie*		65.0	243	
43	4/1/90	11:53:00	379.1	4	Bonita	3.5	7.8	89	
					Bonita	4.8	10.7	163	
					Bonita	5.5	12.3	149	SSE
					Bonita	5.8	13.0	151	
					Guthrie*		20.0	201	
					Guthrie*		23.0	208	SSW
					Guthrie*		20.0	282	
					Guthrie*		25.0	123	
44	11/11/93	15:37:00	379.8	6	Bonita	6.4	14.3	232	
					Bonita	6.9	15.4	220	
					Bonita	12.3	27.5	255	WSW
					Bonita	13.9	31.1	265	
					Guthrie*		59.0	219	
					Guthrie*		58.0	243	
					Guthrie*		61.0	229	SW
					Guthrie*		51.0	291	
45	3/25/94	14:35:00	379.9	3	Bonita	8.7	19.5	222	
					Bonita	9.6	21.5	220	
					Bonita	10.8	24.2	230	SW
					Bonita	11.6	25.9	235	
					Guthrie*		51.0	231	
					Guthrie*		51.0	241	
					Guthrie*		65.0	232	SW
					Guthrie*		51.0	218	

APPENDIX C

ARIZONA CLIMATE

[Reproduced from Marcus, Melvin, et al., "Evaluation of Highway Dust Hazards Along Interstate Route 10 in the Casa Grande-Eloy Region." Final Report (Chapter 3) prepared for the ADOT Highways Division, by the Center for Environmental Studies, Arizona State University, October 29, 1976.]

CENTER FOR ENVIRONMENTAL STUDIES

Arizona State University

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Final Report Prepared for

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3. CLIMATE AND DUST STORMS

CHAPTER 3

CLIMATE AND DUST STORMS

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INTRODUCTION

The relationships among soil surface conditions, land use types, blowing dust potentials, and dust accidents were enumerated in the previous chapter. This chapter discusses meteorological and climatological characteristics associated with blowing dust events; that is, general storm types, wind flow regimes, and other conditions that cause blowing dust and reduced visibility in the Casa Grande-Eloy area. Major dust-producing storm mechanisms and related climatic elements are discussed, analyzed, and related to specific accident events.

METHODOLOGY AND CONSTRAINTS

Discussions and conclusions reached in this chapter are based on literature review and on analysis of climatological and meteorological data readily available from several stations flanking the Casa Grande/Eloy area. No pertinent meteorological information is available for the immediate study area (e.g., wind speed and direction, visibility). Thus, weather and climate conditions are inferred from nearby stations--in particular, Phoenix Sky Harbor Airport, Davis Monthan AFB, and Luke AFB. Data from several other stations are also employed in analyzing the 1975 dust accident record. These stations are listed in Table 3.1 and shown in Figure 3.1.

Historical wind data were used to construct wind regime summaries and dust event frequencies. Fortunately, wind records for 1975 are available for several stations near Eloy. From

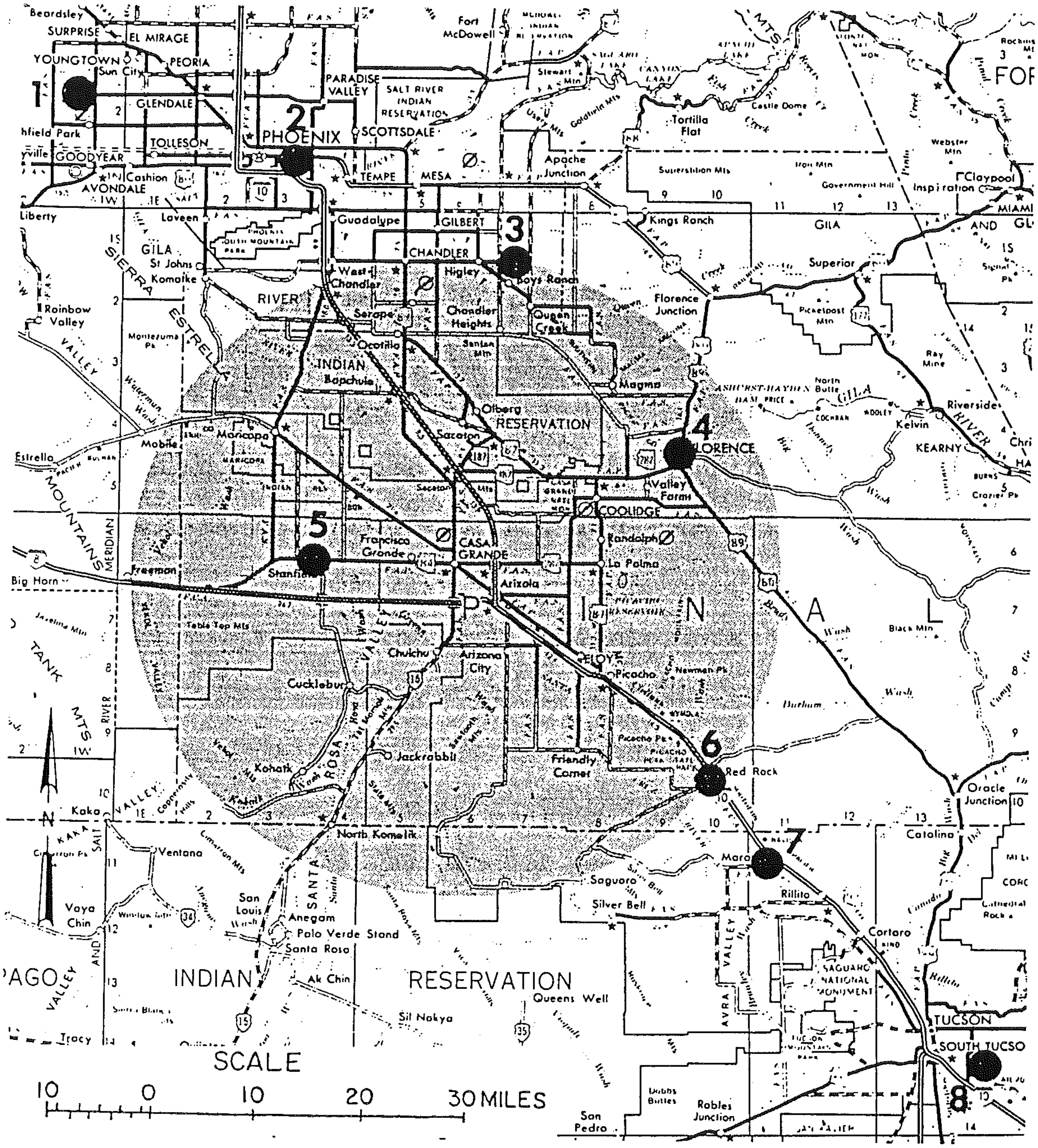
TABLE 3.1

METEOROLOGICAL AND CLIMATOLOGICAL DATA SOURCES

Station	Record Used	Elements Analyzed
Luke Air Force Base	December 1941-March 1952	Wind speed, wind direction, precipitation, dust occurrences, thunderstorm activity
Davis Monthan Air Force Base	August 1941-January 1946; March 1948-August 1953	Wind speed, wind direction, precipitation, thunderstorm activity
Marana	September 1942-June 1944	Wind speed, wind direction, thunderstorm activity, precipitation, dust occurrences
Sky Harbor International Airport (NWS)	1935-1974	Thunderstorm activity
Tucson Municipal Airport	1935-1974	Thunderstorm activity
Red Rock (Arizona Public Service - Saguaro Plant)	1975	Wind speed, wind direction
Stanfield (Pinal County Air Pollution Control District)	1975	Wind speed, wind direction
Williams Air F Force Base	1975	Wind speed, wind direction
Florence (Conoco Oil Co.)	1975	Wind speed, wind direction

FIGURE 3.1

LOCATION OF METEOROLOGICAL STATIONS NEAR THE STUDY AREA



METEOROLOGICAL STATIONS

1. LUKE AFB
2. SKY HARBOR AIRPORT
3. WILLIAMS AFB
4. CONOCO, FLORENCE
5. STANFIELD AIR CONTROL
6. ARIZONA PUBLIC SERVICE, REDROCK
7. MARANA AIR PARK
8. DAVIS MONTHAN AFB

Shaded area represents an area 30 miles in radius from Casa Grande.

these a detailed storm/accident inventory is presented in Appendix 2. These sites are Red Rock (APS), Stanfield (Pinal County Air Pollution Control District), Williams AFB, and Florence (Conoco Oil Company). This information is invaluable, because it provides additional sites for the construction (hour-by-hour) of wind fields for the dust accident cases in 1975.

In addition to the listed surface observations, daily weather maps and, in one case, GOES (Geostationary Environmental Satellite) imagery were analyzed to support the 1975 accident analysis.

Although no meteorological data exists for the exact accident study area, sufficient data and pertinent literature exists for a general meteorological discussion of the blowing dust problem. Because most of the accidents occur during storms (which for the most part are detectable at nearby stations where meteorological records are available), it is felt that the following analysis is based on reasonable spatial and temporal relationships.

ATMOSPHERIC CONDITIONS AND BLOWING DUST

Strong surface winds that lead to blowing dust generally are produced by large horizontal pressure gradients in the atmosphere. Pressure differences that occur over hundreds of kilometers normally produce typical synoptic scale wind patterns, such as those associated with frontal passages and/or a series of thunderstorm cells; while pressure differences over tens of kilometers are associated with local scale events, such as individual thunderstorm cells. Local scale pressure differences produce events such as dust devils, but generally do not account for any but microscale blowing dust phenomena.

Topography acts to channel wind flow so that considerable variation in the wind field and preferred local storm tracks may occur. This, in turn, may produce substantial dust-loading and visibility variations from place to place. Differences in blowing dust are not, however, a simple matter of horizontal wind flow variations. Aerodynamic roughness properties of the ground surface can dictate the nature of the near-surface wind profile, thus affecting the magnitude of vertical momentum transfer operating to saltate and suspend surface materials. In addition to these factors, sediment types and particle sizes are significant factors that explain atmospheric dust load variations from place to place. Light scattering characteristics of suspended dust also produce variations in driver visibility during a storm.

Although all these factors are important in relation to potential accidents, the major atmospheric events that initiate reduced driver visibility and lead to accidents are the dust storms that frequent Central Arizona, particularly in summer months. The term "dust storm" is not synonomous with "thunderstorm," although most frequently in the drier portions of the state a blowing dust event does coincide with the development of thunderstorms.

Large dust storms are the direct result of atmospheric perturbations that produce winds strong enough to lift soil material from the earth's surface. The nature of these dust storms and the atmospheric conditions that produce them have a cyclical rhythm that follows the seasons. During the cooler half of the year, the enlarged circumpolar vortex spreads southward sufficiently to cover the study area. Embedded in the vortex are fronts and lines of convergence, as well as other disturbances. Associated with the fronts are atmospheric temperature differences which lead to vertical eddy exchanges that lift dust into the air. Weak low pressure troughs pass across the area, and as they pass and the Pacific High builds in behind them, rather large horizontal pressure gradients develop. Synoptic situations of this kind bring strong westerly winds which produce dust over large portions of the state. Additionally, at times when a high pressure center forms over the Colorado Plateau-Great Basin area and remains there, air may spill over the Mogollon Rim and blow with great force across the lowlands to the south, creating dust hazards in the central part of the state.

In summer, the circumpolar vortex is reduced in size, and frontal systems and associated troughs pass north of the state. At the earth's surface a thermal low pressure center develops over southwestern Arizona that frequently extends northwestward into California. At this time of year the Bermuda High expands and shifts westward over the southeastern United States, bringing moist tropical air into the southwestern

United States. Within these moist air masses thunderstorms develop that produce winds of sufficient velocity to lift dust into the air.

Spring and Fall are transition periods during which the basic flow patterns of the previous season change to the patterns of the next season. Accordingly, during these seasons flow patterns of either summer or winter may be present.

Table 3.2 gives the number of dust-related accidents between Mileposts 170 and 240 by month and indicates that 27 of the 32 accidents from 1968 to 1975 occurred during the summer. This time of year is the thunderstorm season--a time when dust storms are generated by thunderstorm activity. Thus, the major mechanism that produces reduced visibility due to blowing dust is the development, intensification, and dissipation of thunderstorm activity associated with an influx of moist, unstable air into Southern and Central Arizona in summer months.

Since these events are critical to dust-related accident potentials, a considerable portion of this chapter focuses on the definition, seasonal and diurnal variations, and origins of various thunderstorm activities that take place in summer in Central Arizona. An understanding of the climatology of these storms is essential to the eventual management of the dust hazard.

Ultimately, the blowing dust problem must be viewed on a local scale. That is, a discussion of the problem must be presented for the specific study area. Subsequent sections of

TABLE 3.2

FREQUENCY OF DUST-RELATED HIGHWAY ACCIDENTS ALONG I-10 BY MONTHS (1968-75)

I-10 Milepost	Month												
	J	F	M	A	M	J	J	A	S	O	N	D	Total
170.0 - 179.9		3			1			1	1				6
180.0 - 189.9													0
190.0 - 199.9					2	2		1					5
200.0 - 209.9						2	3	1	5				11
210.0 - 219.9		1						2	4				7
220.0 - 229.9							1	1					2
230.0 - 239.9			1										1
Total	0	4	1	0	3	4	4	6	10	0	0	0	32

this chapter analyze surface wind and precipitation data for the study area; and Appendix 2 presents a detailed meteorological inventory of several dust-related accidents in 1975, utilizing all available meteorological data from sites near the study area.

THE CLIMATOLOGY OF ARIZONA DUST STORMS

Dust Storm Processes

Major dust storms affect Phoenix and its environs about four times each summer and lower horizontal visibility to 0.8 km (1/2 mi) or less (Ingram, 1972a). Dust is generated by both wind shifts and strong winds associated with the outflow of cold air from thunderstorms.

Shifting of winds before and after thunderstorms are difficult to predict; however, Byers (1959) has given a general rule of thumb:

> Early in the cumulus stage there is a gentle inward turning of the surface wind, forming an area of weak lateral convergence under the updraft. As the cell grows and a downdraft develops, the surface winds become strong and gusty as they flow outward from the downdraft regions. The outward flowing cold air underruns the warmer air which it displaces, and a discontinuity in the wind and temperature fields is established (the pseudo-cold front). The discontinuity moves outward, pushed by the downdraft, resulting in strong horizontal divergence.

As a thunderstorm approaches, winds will tend to blow more or less directly toward the storm. As the pseudo-cold front passes, winds will suddenly reverse direction, blowing directly from the storm, and be strong and gusty. Simultaneously, the temperature will fall several degrees. There are four possible dust-producing actions present under these circumstances: (1) the sudden shifting of the wind, (2) strong winds in the outdraft, (3) thermal turbulence created by air temperature differences, and (4) mechanical turbulence due to topography.

The cold dome of outflowing downdraft air spreading behind the pseudo-cold front has a simplified form illustrated in Figure 3.2a. In this sketch, the thunderstorm cell is considered to be moving from left to right. The cold air may be thought of as having spread laterally considerably farther on the downwind side of the cell than on the windward side, as would be expected in a moving system. After the storm has passed over a point, precipitation from the storm, if it reaches the surface, will moisten the surface, thereby helping to prevent the continuance of blowing dust. As a consequence, airborne dust is most prevalent on the forward side of a moving thunderstorm, where the wind shear is greatest; weaker along the sides perpendicular to the direction of motion of the storm, and very rarely present in the rear of the storm.

In a mature thunderstorm, falling rain exerts a frictional drag upon the surrounding air, inducing a downdraft in the cloud. Evaporation of rain droplets further cools the air, adding to the speed of the downdraft. Additional cooling occurs as a result of contact with the relatively cold raindrops; this also adds to the speed of the downdraft. If hail is also present in the cloud, its influences are similar to those of water droplets. In most cases, falling rain and cold air from the thundercloud reach the ground at approximately the same time (Petterssen, 1956).

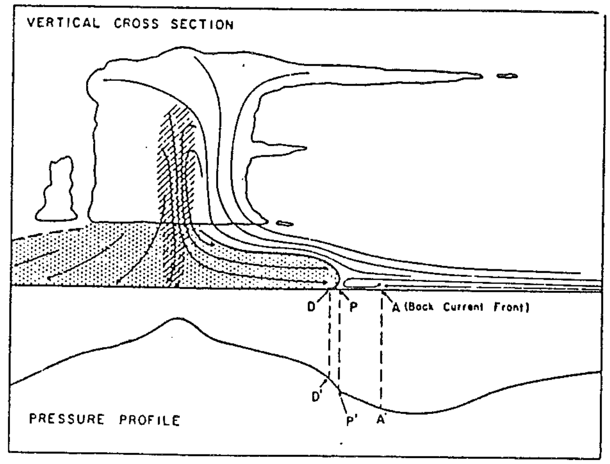


Figure 3.2a Schematic model of the low-level airflow inside and outside of thunderstorm outflows (from Fujita, 1960).

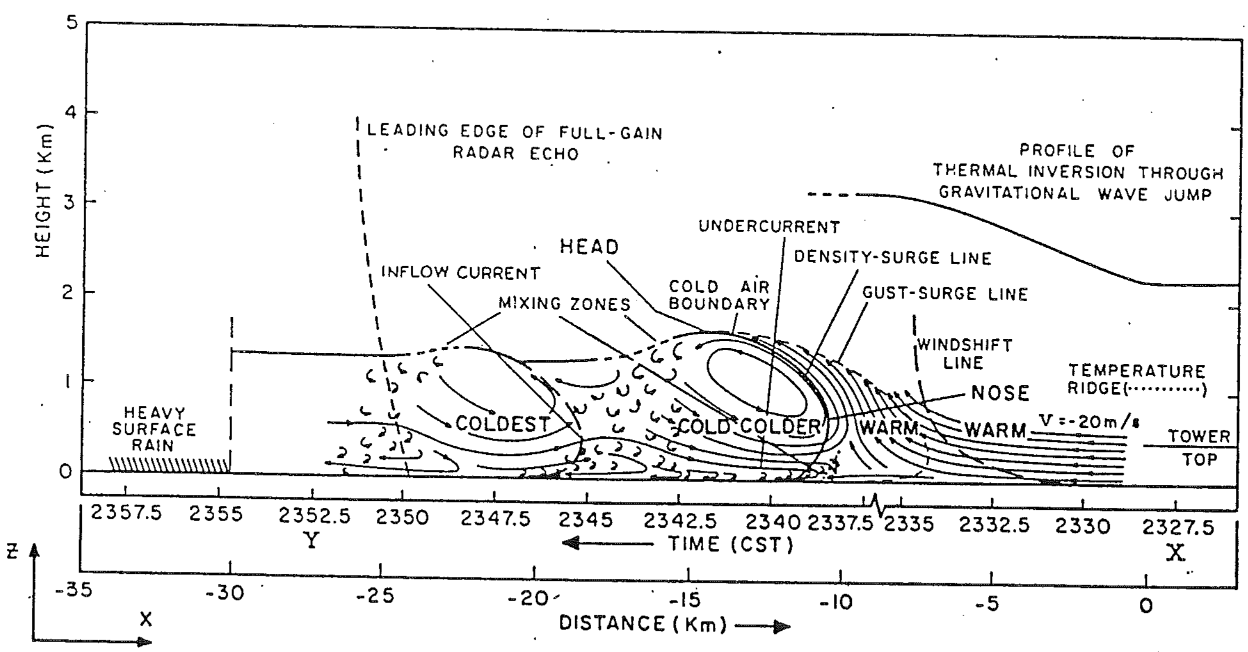


Figure 3.2b Schematic structure of a windshift-pressure jump and gust front (from Charba, 1974).

Of course, if the base of the thunderstorm is sufficiently high, the falling rain may be evaporated before reaching the ground, leading to the descriptive term "dry thunderstorm." A cold downdraft from the storm, however, will continue to descend until the surface is reached, whereupon it may still be sufficiently strong to raise surface dust particles into the air. Also, the advancing cool air will provide a local circulation acceleration which tends to lift dust into the air. Note in Figure 3.2a the "Back Current Front" ahead of the pseudo-cold front. This zone of convergence marks an area where rapid changes in wind speed and direction occur. Figure 3.2b is an enlargement of the pseudo-cold front region. An extremely complex gust front structure is indicated which indeed needs more field study before definitive relationships can be established among dust loads, land use effects, and atmospheric flow characteristics. Blowing dust processes occurring in advance of the density head may be just as hazardous to motorists as the dust wall passage itself.

Figure 3.3 shows a panorama and side view of the dust wall of a macro-lobe that is produced during a typical dust storm. The structure near the surface to 300 m (984 ft) or so is lobate, resembling a density current head that can be replicated in tank experiments with fluids of different densities (Charba, 1974). The contrast is that of cold air pulsing to the surface and protruding into warmer air. This turbulent process produces a rolling dense dust wall which is extremely hazardous. Furthermore, considerable variations

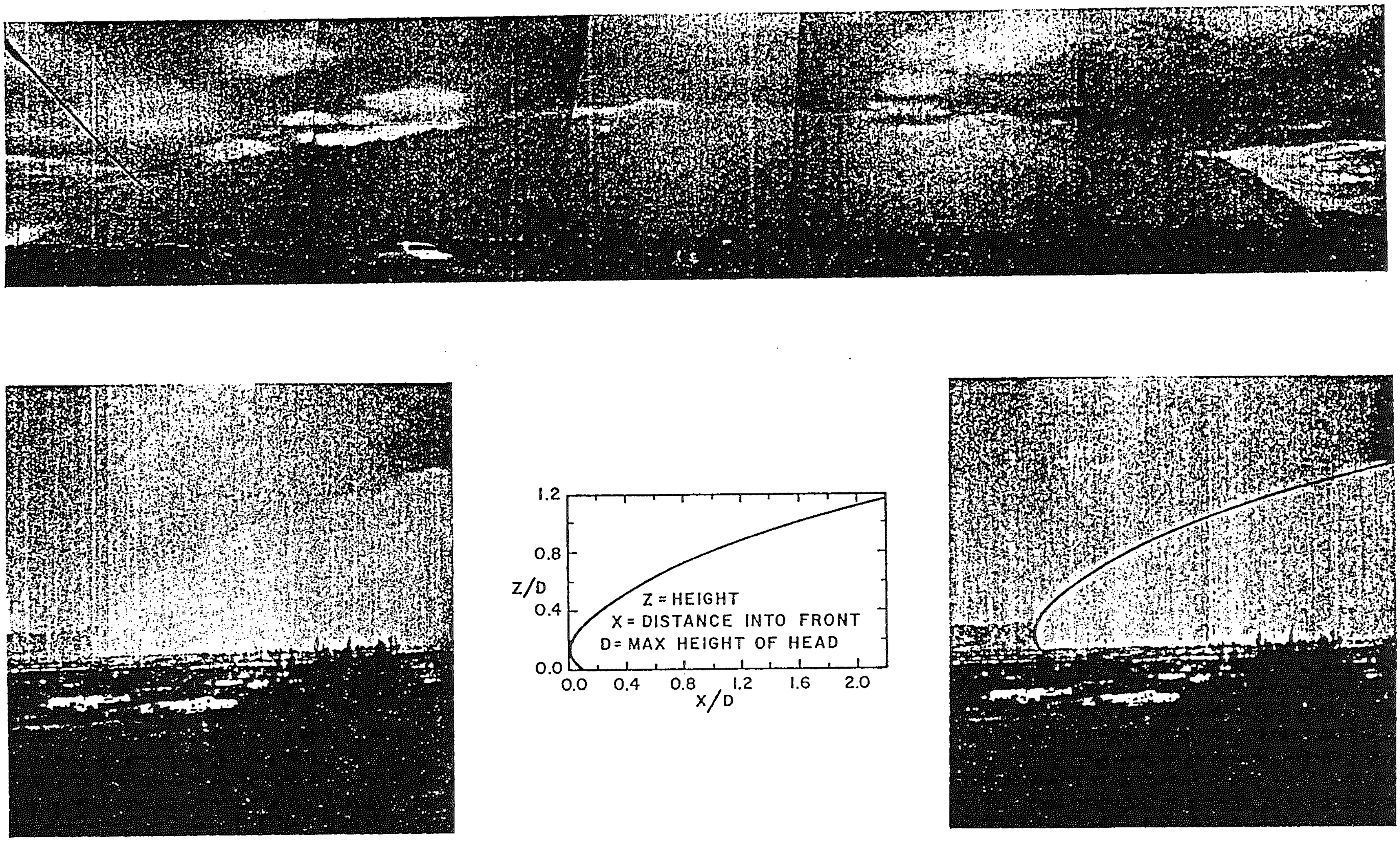


Figure 3.3 Dust wall associated with passage of a pseudo-cold front in a thunderstorm. Upper figure shows a frontal view of a macro-lobe. The two pictures below show a cross-sectional view. The diagram illustrates general shape of the density head (after Idso, 1972).

in driver visibility may occur within the dust cloud due to successive outflows.

Thunderstorm Origins and Types

If vertical gradients of temperature and humidity are such that the air becomes convectively unstable, a thunderstorm may result, provided a mechanism is available to release the instability. Such a mechanism can be the lifting of warmer air by colder air along a cold front. Another mechanism is surface heating along mountain slopes, which renders the air column more unstable. During winter the atmosphere is usually not convectively unstable enough to produce thunderstorms by either of these mechanisms (see Table 3.3 for the monthly average number of thunderstorms). Thus, thunderstorms are

TABLE 3.3

AVERAGE NUMBER OF THUNDERSTORMS BY MONTH
FOR PHOENIX AND TUCSON

Month	Phoenix	Tucson
Jan	*	*
Feb	1	*
Mar	1	*
Apr	1	1
May	1	1
Jun	1	2
Jul	6	14
Aug	7	13
Sep	3	5
Oct	1	2
Nov	1	*
Dec	1	*
Annual	24	40

*Less than 0.5

Source: National Climatic Center, 1974, Local Climatological Data for Phoenix, Arizona, and Tucson, Arizona, Environmental Data Service, NOAA, Asheville, NC, 28801.

most frequent in July and August. Winter dust storms, although infrequent, are normally caused by frontal systems, rather than by thunderstorm development (see Case Study Number 1 of Appendix 2 for example).

In summer, the Bermuda High expands northward and extends a ridge of high pressure westward into Arizona above 1500 m (5000 ft) mean sea level. Circulation around this pressure center normally advects moisture from the Gulf of Mexico into Arizona. At other times, the source of moist air entering the state may be the Gulf of California or the Pacific Ocean.

With strong solar heating of the surface the air becomes unstable, especially on the east mountain slopes in late morning and western mountain slopes in the afternoon (Ingram, 1972a). If the air is sufficiently unstable and enough water vapor is available, thunderstorms may result. Source regions for thunderstorms are numerous, but three tend to dominate: (1) the Sierra Madre or Sonora; (2) the Mogollon Rim; and (3) the Gulf of California.

Sierra Madre or Sonora Type Thunderstorms

Generally, these thunderstorms originate over mountains of north central Mexico in Sonora. By early afternoon the storms drift with high level steering currents away from the mountains northwestward into Arizona. These storms often move across the Casa Grande/Eloy area in late afternoon or evening hours. An example of a storm of this type is the storm of 16 July 1971, a day on which dust-related accidents occurred on I-10 at 1700 and 1800 MST. This dust storm was associated with thunderstorm activity which originated over the Sierra Madre Mountains and moved northwestward over Tucson toward Phoenix. As described by Idso, et al (1972):

> During this season of the year, the Bermuda High often extends westward into eastern Arizona, and during the afternoon, some of the Mexican (thunderstorm) activity has been seen to move northwestwards, steered by variations in the easterly flow (possibly easterly waves) on the bottom side of the lobe of the Bermuda High.

This particular storm formed southeast of Tucson and began moving northwestward. It passed Tucson at 1530 MST, moved into the Santa Cruz Valley, and continued on toward Phoenix. As deduced from meteorological reports from several sites along its path, the mean speed of its advance was 47 kph (29 mph). Sustained winds in the cold air outdraft of the thunderstorm were 53 kph (33 mph). It is estimated that the storm arrived in the area between Eloy and Casa Grande about 1730 MST.

The general characteristics of this particular event are summarized in Table 3.4 below (Idso, et al, 1972).

TABLE 3.4

GENERAL DUST STORM EFFECTS--16 JULY 1971

	Wind Speed kph (mph)	Temperature (^{o}C)	Relative Humidity (%)	Visibility km (miles)
Before	11 (7)	38	33	48 (30)
After	53 (33)	25	74	<0.8 (<0.5)

The primary visibility hazard of the dust storm is the very sudden decrease in horizontal visibility as the wall of dust along the leading edge of the cool air mass passes over the highway. However, there may also be local gusts and blowing dust ahead of the major dust wall which may be just as hazardous.

Mogollon Rim Type Thunderstorm

This type of thunderstorm appears to occur when moisture is advected upslope to the Mogollon Rim from either the Gulf of Mexico or Baja California. Upper level (3000-6000 m/ 10,000-20,000 ft) steering winds, normally above 19 kph (11.9 mph from the southeast or northeast, push the storm across the I-10 dust storm area (Ingram, 1972a). When steering winds are light and from the southeast, the thunderstorms tend to propagate toward the supply of moisture; in this case, the deeper moist layers are toward the southwest. In general, thunderstorm activity is initiated during late morning hours; in early afternoon, the storms move southwesterly away from the mountains.

Summertime thunderstorms may originate over the Mogollon Rim under a variety of circumstances. Bryson and Lowry (1955a and b) have indicated that the moisture source for summertime thunderstorm activity is the Pacific Ocean during June; while in July the primary source of moisture is the Gulf of Mexico. The warm, humid, convectively unstable air enters Arizona from the southeast and south and floods across the state. By 1000 to 1100 MST surface heating along the Mogollon Rim can cause instability, resulting in strong cumulus buildup and subsequent thunderstorms. Hales (1972) points out that:

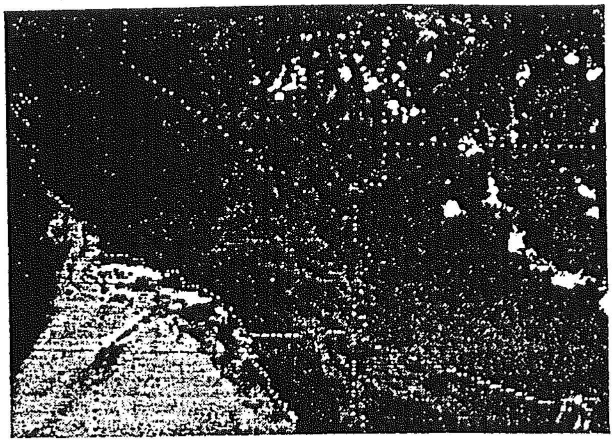
> The prevailing high level, or steering winds, are south or southeast during July and August, and therefore nearly parallel to the Mogollon Rim. These winds tend to keep thunderstorm activity from drifting toward lower elevations and keep it concentrated along the higher terrain.

Occasionally, Rim thunderstorms do seem to move southwestward over the desert floor. The unusual feature of such a movement is that it is nearly perpendicular to the direction of the mean steering level winds from the southeast. Reasons for this movement are not yet entirely clear.

A series of GOES satellite pictures taken on 25 July 1975 (Figure 3.4), illustrates the development of airmass thunderstorms along the Mogollon Rim and their subsequent movement toward the southwest. Examination of the photographs shows the development of thunderstorms over the Rim, and their departure from the Rim about 1845 MST. By early evening the storms were near the study area. Several dust-related automobile accidents were reported during the afternoon hours on this date along I-10, US-60, and State Route 84.

Gulf of California Type Thunderstorm

During periods of deep southwesterly flow, moisture is advected over Arizona from the Gulf of California. It comes in strong surges of tropical air that produce widespread rains over the state. Strong surface heating, especially over hills, will trigger thunderstorm activity in the convectively unstable air. Resulting storms drift northeasterly, steered by upper level flow.



(a) 1845 MST

(b) 1945 MST

(c) 2045 MST

(d) 2145 MST

(e) 2245 MST

Figure 3.4 GOES satellite photographs illustrating thunderstorm formation along the Mogollon Rim on 25 July 1975. Note 1845 MST development of puffy cumulus clouds along the Mogollon arc and the 2245 MST movement of large thunderstorm clouds to the southwest of the Rim.

General Dust Storm Conditions

Data from Phoenix's Sky Harbor Airport indicate that dust storms may last from one to three hours (Ingram, 1972a). With the arrival of a dust storm, the air temperature may drop 5°C (9°F), while the dew point temperature remains fairly constant. The wind direction may change by as much as 180°, while the wind speed may increase by 16 kph (10 mph) or more. Visibility will usually drop from 50 km (31 mi) to 0.8 km (0.5 mi) or less. Changes in meteorological elements with the arrival of a dust storm at Phoenix are summarized in Table 3.5.

TABLE 3.5

MEAN CHANGES IN SEVERAL METEOROLOGICAL ELEMENTS WITH THE ARRIVAL OF A DUST STORM AT PHOENIX, ARIZONA

Reduction of Visibility	Pressure Drop (3 hrs)	Air Temp Drop	Dew Point Drop	Wind Direction Change	Wind Speed Increase
50 km	2 mb	5°C	~0°C	~90°	16+ kph
31 mi	.06 in	9°F	~0°F		10+ mph

Examples of changes in winds and visibilities as recorded at Sky Harbor Airport (Phoenix) and Williams AFB (Chandler) during passages of pseudo-cold fronts are tabulated (Tables 3.6 and 3.7). It must be borne in mind that Sky Harbor, in particular, is surrounded by an urban scene; therefore, wind speeds will be reduced, and in general visibilities will be better than in the study area. Furthermore, due to different land use patterns,

TABLE 3.6

SIERRA MADRE DUST STORMS

Recording Station	Date	Time MST	Visibility km (miles)	Wind Direction	Wind Speed kph (mph)
Phoenix	6/28/70	1655	40 (25)	320	11 (07)
		1756	40 (25)	260	16 (10) Gusts to 29 (18)
		1955	0.8 (0.5)	160	32 (20) Gusts to 45 (28)
Phoenix	8/14/70	1855	56 (35)	270	16 (10)
		1955	24+ (15+)	230	14 (09)
		2023	0.8 (0.5)	150	32 (20) Gusts to 47 (29)
Phoenix	8/9/71	2055	24+ (15+)	250	16 (10)
		2246	16 (10)	120	31 (19)
		2255	1.6 (1)	140	29 (18) Gusts to 42 (26)
Phoenix	7/16/71	1656	56 (35)	240	19 (12)
		1755	56 (35)	260	13 (08)
		1855	0.8 (0.5)	170	29 (18) Gusts to 63 (39)
Phoenix	9/17/72	2055	24+ (15+)	240	5 (03)
		2157	24+ (15+)	210	5 (03)
		2221	5 (3)	150	31 (19) Gusts to 35 (22)
Phoenix	9/1/72	1855	56 (35)	230	11 (07)
		1955	24+ (15+)	220	11 (07)
		2055	24+ (15+)	160	10 (06)
		2132	1.6 (1)	160	(22) Gusts to 43 (27)

TABLE 3.7

RIM ORIGIN DUST STORMS

Recording Station	Date	Time MST	Visibility km (miles)	Wind Direction	Wind Speed kph (mph)
Chandler	7/11/75	1455	48 (30)	290	10 (6)
		1555	32 (20)	300	10 (6) Gusts to 19 (12)
		1644	4 (2.5)	030	48 (30) Gusts to 55 (34)
Phoenix	7/25/75	1816	16 (10)	290	16 (10)
		1835	16 (10)	340	6 (4)
		1855	40 (25)	130	10 (6)
		1917	10 (6)	070	32 (20) Gusts to 48 (30)
Chandler	9/4/75	1455	32 (20)	270	13 (8)
		1555	24 (15)	280	13 (8)
		1600	0.5 (0.3)	020	42 (26) Gusts to 55 (34)
Chandler	9/5/75	1455	48 (30)	---	C (Calm)
		1558	0.4 (0.25)	12	35 (22) Gusts to 45 (28)

visibilities at Williams AFB are expected to be better than those experienced in the study area.

Table 3.6 shows wind and visibility changes experienced with the passage of a dust storm (associated with thunderstorms of Sierra Madre or Sonora origin). Table 3.7 gives wind and visibility changes associated with thunderstorms of Mogollon Rim origin.

Seasonal and Diurnal Distribution of Thunderstorms

Seasonal and diurnal distributions of thunderstorms can be derived from data recorded at Luke AFB and Davis Monthan AFB. This section defines the dominance of the summer-early fall thunderstorm season, as well as the late afternoon-evening preponderance of thunderstorms.

The monthly percentage frequency of occurrence of thunderstorms at Luke AFB is shown in Table 3.8. It is seen that thunderstorms occur at Luke AFB during all months except May, with the highest probability of occurrence during July. Generally, the thunderstorm season at Luke AFB may be considered to extend from July through October.

The diurnal percentage frequency of occurrence, by hour, of thunderstorms at Luke AFB during the thunderstorm season is presented in Table 3.9. It is apparent that minimal thunderstorm activity occurs during mid-morning, with peak activity at 2200 and 2300 MST.

TABLE 3.8

PERCENTAGE FREQUENCY OF OCCURRENCE OF THUNDERSTORMS, BY MONTH, AT LUKE AFB, ARIZONA

Month	Total Observations	Thunderstorm Observations	% Frequency of Occurrence
Jan	4464	1	0.02
Feb	3743	1	0.03
Mar	3720	2	0.05
Apr	3600	4	0.11
May	4464	0	0.00
Jun	4320	1	0.02
Jul	4464	41	0.92
Aug	4464	31	0.69
Sep	4320	20	0.46
Oct	4464	12	0.27
Nov	3959	3	0.08
Dec	4461	5	0.11

TABLE 3.9

THE DIURNAL PERCENTAGE FREQUENCY OF OCCURRENCE OF THUNDERSTORMS AT LUKE AFB

Hour	Jul	Aug	Sep	Oct	Sum	% Frequency of Occurrence (July-Oct)
01	4	3	0	1	8	1.08
02	2	2	0	0	4	0.54
03	0	4	1	0	5	0.68
04	2	3	1	1	7	0.95
05	1	2	1	1	5	0.68
06	2	1	1	0	4	0.54
07	0	1	0	0	1	0.14
08	1	0	0	0	1	0.14
09	0	0	0	0	0	0.00
10	0	1	0	0	1	0.14
11	0	0	2	0	2	0.27
12	0	1	1	0	2	0.27
13	1	0	1	1	3	0.41
14	1	0	0	1	2	0.27
15	0	0	0	1	1	0.14
16	0	2	1	0	3	0.41
17	0	1	1	0	2	0.27
18	1	0	2	1	4	0.54
19	1	1	1	1	4	0.54
20	6	1	1	0	8	1.08
21	2	2	2	0	6	0.81
22	5	3	2	2	12	1.63
23	7	2	1	1	11	1.49
24	5	1	1	1	8	1.08
Total	41	31	20	12	104	0.59
Total Obs./Hr.	186	186	180	186	738	

Table 3.10 presents the percentage frequency of occurrence, by month, of thunderstorms at Davis Monthan AFB, Arizona. Thunderstorms occur during all months except January at Davis Monthan AFB with the highest probability during July. The thunderstorm season at Davis Monthan AFB is considered to extend from July through September.

TABLE 3.10

PERCENTAGE FREQUENCY OF OCCURRENCE OF THUNDERSTORMS, BY MONTH, AT DAVIS MONTHAN AFB, ARIZONA

Month	Total Observations	Thunderstorm Observations	% Frequency of Occurrence
Jan	7439	0	0.00
Feb	6096	1	0.02
Mar	7439	8	0.11
Apr	7200	17	0.24
May	7440	3	0.04
Jun	7199	28	0.39
Jul	7440	211	2.84
Aug	8183	224	2.74
Sep	7200	174	2.42
Oct	7440	47	0.63
Nov	7199	4	0.06
Dec	7440	5	0.07

The diurnal percentage frequency of occurrence of thunderstorms, by hour, at Davis Monthan AFB, during the defined thunderstorm season, is shown in Table 3.11. It is seen that

TABLE 3.11

THE DIURNAL PERCENTAGE FREQUENCY OF OCCURRENCE OF THUNDERSTORMS AT DAVIS MONTHAN AFB, TUCSON

Hour	Jul	Aug	Sep	Sum	% Frequency of Occurrence (July-Sept)
01	8	7	1	16	1.68
02	6	5	1	12	1.26
03	3	4	1	8	0.84
04	3	5	0	8	0.84
05	3	3	2	8	0.84
06	2	4	2	8	0.84
07	4	4	1	9	0.95
08	6	3	1	10	1.05
09	0	2	0	2	0.21
10	0	1	0	1	0.11
11	2	0	0	2	0.21
12	2	1	1	4	0.42
13	2	2	0	4	0.42
14	8	6	6	20	2.10
15	6	19	4	29	3.05
16	14	15	9	38	4.00
17	23	21	11	55	5.78
18	26	21	18	65	6.83
19	20	25	12	57	5.99
20	18	22	9	49	5.15
21	21	21	6	48	5.05
22	17	12	4	33	3.47
23	9	7	2	18	1.89
24	8	14	2	24	2.52
Total	211	224	93	528	2.31
Total Obs/Hr	310	341	300	951	

minimum thunderstorm activity occurs during late morning hours, and maximum activity occurs from 1700 to 2100 MST during the thunderstorm season. It is expected that thunderstorm activity in the study area should be minimal during the winter months through June, and maximum activity is expected to occur during July and August.

The above statistics on observations of thunderstorm activity for Luke AFB and Davis Monthan AFB are good indices of the potential seasonal and diurnal periods for dust storms.

Figure 3.5 illustrates the diurnal variation of rain and drizzle and thunderstorm activity at Tucson. It is seen that the development of thunderstorm activity (most frequent at 1700 to 2000 MST) is earlier than at Luke AFB. Also, a lag effect can be observed between the observation of strong winds, lightning, etc. and subsequent rainfall (the lag is on the order of about 2 hours). This pattern is also suggested for Phoenix dust storms by Ingram (1972b). This lag is significant because the strong outflow motion from thunderstorms precedes rain; thus, the surface would normally be dry at the time of strong downdraft motion. Dust-loading takes place prior to rainfall and visibility is reduced at sunset hours or shortly thereafter.

This average diurnal pattern coincides with the timing of many dust-related accidents. For example, 19 of 23 accidents occurred during late afternoon and early evening (Table 3.12). Fourteen of these occurred in the pre-rainfall period of the

FIGURE 3.5

DIURNAL VARIATION OF THUNDERSTORMS AND PRECIPITATION AT
DAVIS MONTHAN AFB, TUCSON

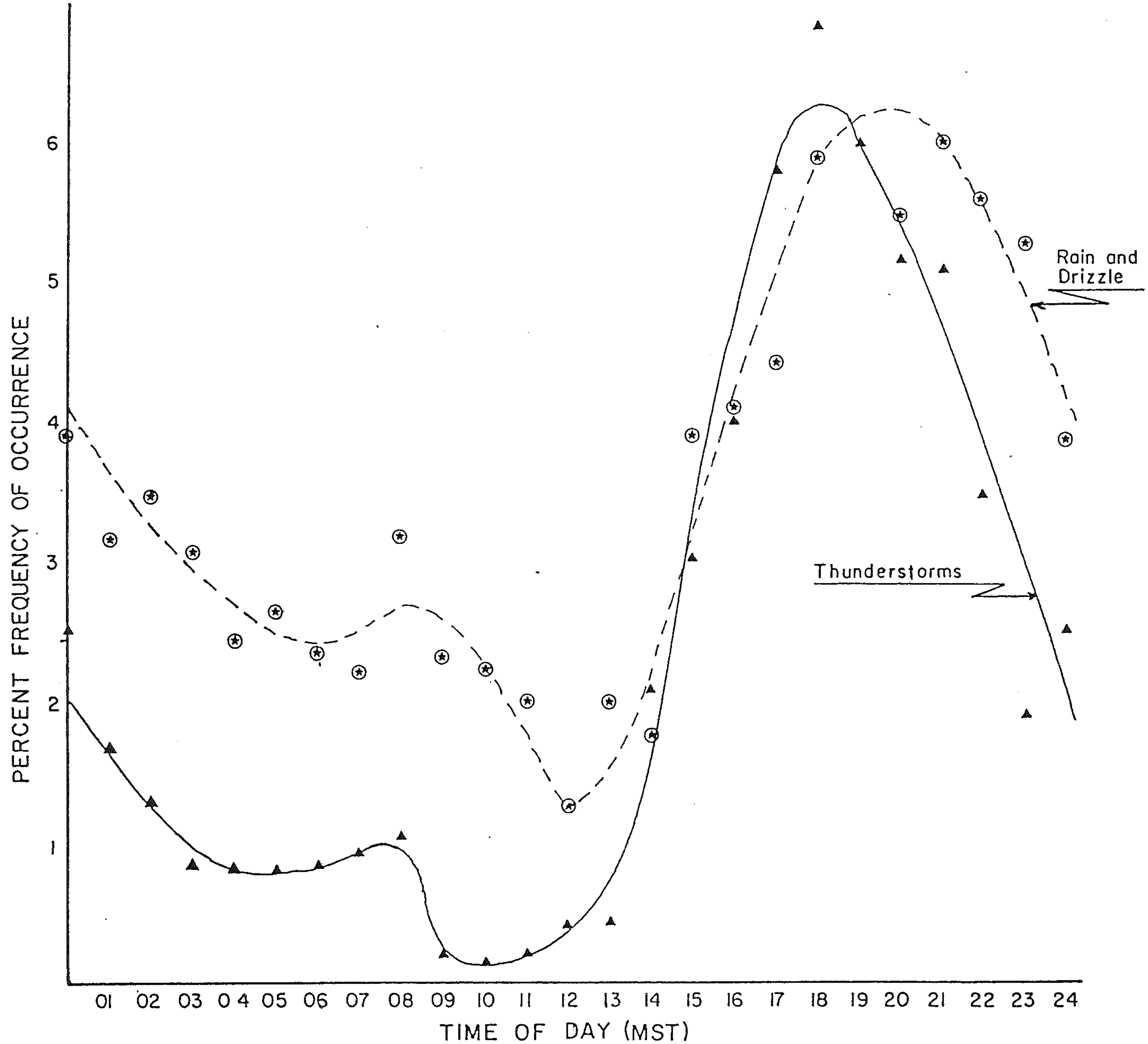


TABLE 3.12

HOURLY DISTRIBUTION OF DUST-RELATED ACCIDENTS ON I-10 BETWEEN MILEPOST 190 AND MILEPOST 220

Time of Day (MST)	1400-1500	1500-1600	1600-1700	1700-1800	1800-1900	1900-2000	2000-2100	2100-2200	2200-2300	2300-2400
Frequency	0	2	2	8	4	3	1	1	1	1
Total: 23										

thunderstorm--the time of maximum downdraft when the dust wall travels in front of the storm.

ANALYSIS OF SURFACE WINDS, PRECIPITATION, AND BLOWING DUST

Wind and moisture interact locally with land use and topography to produce the specific dust hazard of a given area. Using data from sites as near the I-10 study area as possible (Luke AFB, Phoenix Sky Harbor Airport, and Davis Monthan AFB), interrelationships between wind, precipitation, and visual observations of blowing dust were derived. This analysis provides a base from which the construction of forecasts for the specific study area ultimately may be made.

Analysis of Surface Wind and Blowing Dust

As stated earlier, at least two conditions must exist before blowing dust can occur: (1) availability of fine grained soil surface particles (average diameter between 10 and 100 microns) loosely aggregated in sufficiently large quantities;

and (2) sufficient wind speed to dislodge the dust particles from the earth's surface and lift them into the air. In this discussion only meteorological parameters are considered; other factors were discussed in the preceding chapter.

Wind

To determine wind speeds required to raise dust, percentage frequencies of occurrence of dust as a function of wind speed for all months were tabulated. These values are shown in Table 3.13 and in graphic form in Figure 3.6. From Figure 3.6 it appears that dust in the study area becomes airborne at winds of approximately 16 kph (10 mph), although two cases of dust were noted (out of 2215 observations) in the wind speed class of 6-11 kph (4-7 mph). About 5% of the winds at 29 kph (18 mph) contain dust, while 25% of the winds at 40 kph (25 mph) contain dust. A threshold wind speed of about 16 kph (10 mph) appears necessary for the production of dust at Luke AFB.

This is consistent with values given by Bagnold (1941) and Cooke and Warren (1973). In a tightening pressure gradient situation, surface wind speeds are increasing. At a certain wind speed, blowing dust will begin to be observed. Two effects are noticed at this threshold wind speed: (1) Only small amounts of finer particles are removed and visibility is not significantly reduced; and (2) Larger soil particles are left in place.

At wind speeds above the threshold value, several effects may be observed. If the soil particles are uniform in size and shape and a copious supply is available, large quantities

TABLE 3.13

THE PERCENTAGE FREQUENCY OF OCCURRENCE AT LUKE AFB OF DUST AS A FUNCTION OF WIND SPEED CLASS, BY MONTH AND ANNUALLY

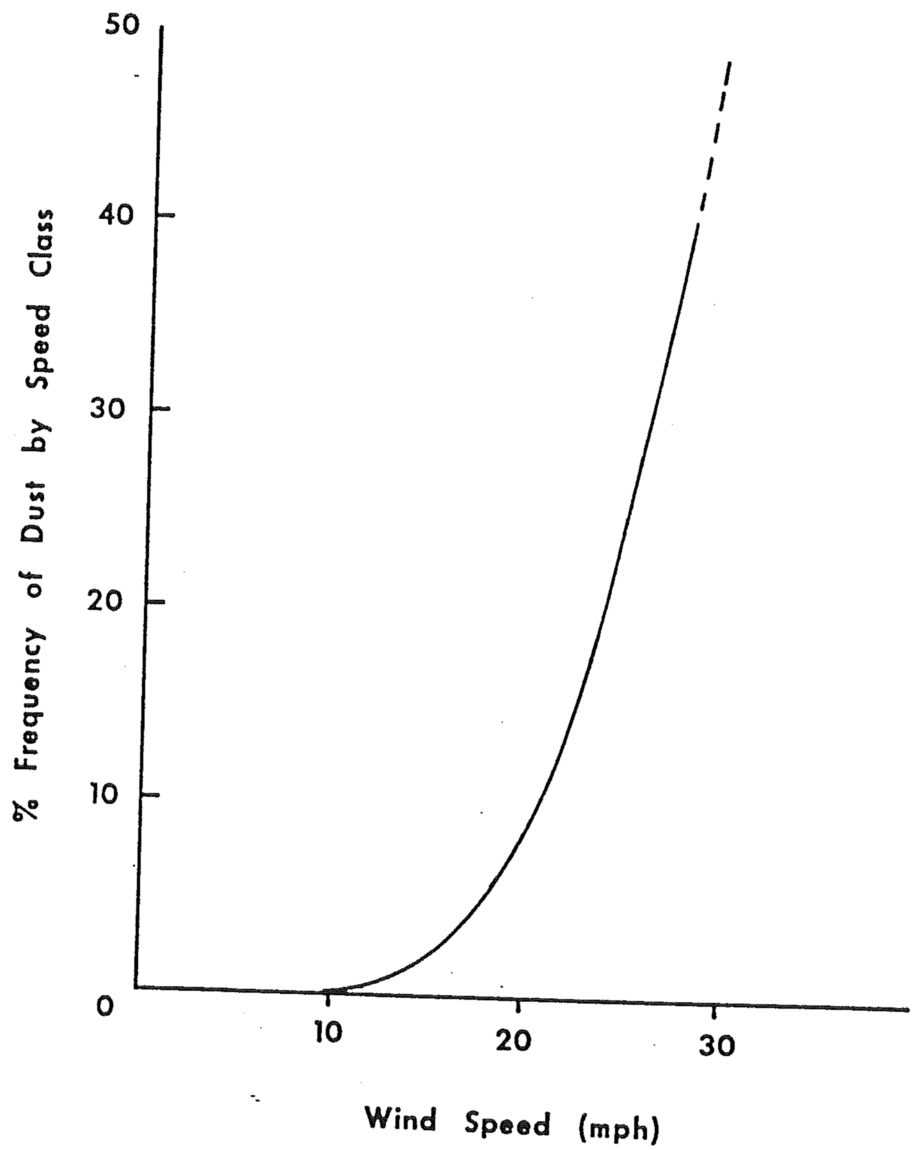
Month	Wind Speed Class: kph (mph)							
	0.6-5 (1-3)	6-11 (4-7)	12-19 (8-12)	20-29 (13-18)	30-39 (19-24)	40-50 (25-31)	51-61 (32-38)	62-74 (39-46)
Jan	0	0	0	0	0	---	----	---
Feb	0	0	0	2.21	4.35	36.36	---	---
Mar	0	0*	0.95	1.44	15.00	66.67	50.00	---
Apr	0	0	0	1.13	8.16	40.00	---	---
May	0	0*	0	0.54	4.35	0	---	---
Jun	0	0	0.39	1.63	6.25	0	---	---
Jul	0	0	0.92	7.33	41.18	80.00	0	0
Aug	0	0	0	4.76	8.33	33.33	100.00	---
Sep	0	0	0.40	0	33.33	---	---	---
Oct	0	0	0	2.13	0	0	---	---
Nov	0	0	0.42	5.06	33.33	---	---	---
Dec	0	0	0	0	11.11	0	---	---
Ann	0	0	0.09	2.02	11.90	40.42	40.00	0

* = Less than 0.005

--- = No dust events observed

FIGURE 3.6

BLOWING DUST FREQUENCY VERSUS WIND SPEED AT LUKE AFB



of dust will be stirred up, reducing visibility substantially. If the particles are multi-sized, some of the smaller particles, left after removal of surface fine particles during lighter winds, will now begin saltating, again stirring up large quantities of dust and resulting in reduced visibilities. This process proceeds until only larger particles are left on the surface, which will then impede further removal of smaller particles under the surface layers (Loewe, 1943, Cooke and Warren, 1973). As wind speeds subside, dust particles will settle out of the air, falling on and between larger particles on the surface, with a corresponding increase in visibility. If the surface supply of dust particles is limited, all particles will be removed quickly, and no further dust problem will be observed.

During large horizontal pressure gradient conditions, the wind direction will remain fairly constant or change only slowly. Significant quantities of dust may then be deposited downwind of obstacles, such as large rocks and bushes. As long as the wind direction remains constant, this accumulated dust will remain undisturbed. Should a sudden wind shift occur as with a frontal passage, however, large amounts of dust become available to be blown again into the air. Greatly reduced visibilities will now accompany the advancing wind shift line. Reduced visibilities will persist as long as any of the previously accumulated dust supplies remain and are exposed to wind.

In preparing the data for Table 3.12, it was noted that during some months a given wind speed class would produce dust while the same wind speed class during another month would not.

In addition, during a given month a certain wind speed class would be accompanied by dust while a higher wind speed class would not. One may speculate on reasons for this behavior. For example, dust may not be observed if wind were blowing over a moist surface, but might over a dry surface. Alternatively, a strong wind may blow over a hard, crusted surface and not raise dust whereas a lighter wind could stir dust from freshly broken land.

Thus, conditions that must exist to create blowing dust involve more than just air motion. As discussed in earlier chapters an understanding of the total environmental system in the I-10 study area is essential before steps can be taken to ameliorate the dust storm hazard.

Dust and Strong Winds

A wind speed of approximately 16 kph (10 mph) has been shown to be required to raise dust in the study area. The percent frequency of occurrence of all wind speeds of 19 kph (12 mph) or more, by month, shown in Table 3.14, was superimposed upon the percent frequency of occurrence of dust (see Figure 3.7). It is immediately apparent that the highest frequency of winds greater than 19 kph (12 mph) shows little relationship to dust occurrence. Similarly, the percentage frequency of occurrence of dust for each month of the year (Table 3.15) does not clearly relate to mean wind speed (Figure 3.7). This illustrates the low correlations that can exist between wind and dust due to the importance of other factors such as land use.

TABLE 3.14

FREQUENCY OF WINDS 19 KPH (12 MPH) BY MONTH

AT LUKE AFB

Month	Frequency of Winds >19 kph (12 mph)	Total Observations	% Frequency of Occurrence Winds >19 kph
Jan	37	3719	0.99
Feb	197	3407	5.78
Mar	260	3719	6.99
Apr	325	3600	9.03
May	393	3719	10.57
Jun	262	3600	7.28
Jul	175	3720	4.70
Aug	142	3719	3.82
Sep	54	3600	1.50
Oct	50	3720	1.34
Nov	80	3598	2.28
Dec	122	3719	3.28

Source: U.S. Department of Commerce, no date, Job Number CL5079, U.S. Weather Bureau, Washington, D.C., Period & Record: July 1951-June 1956.

FIGURE 3.7

MONTHLY WIND CHARACTERISTICS AND DUST FREQUENCIES AT LUKE AFB

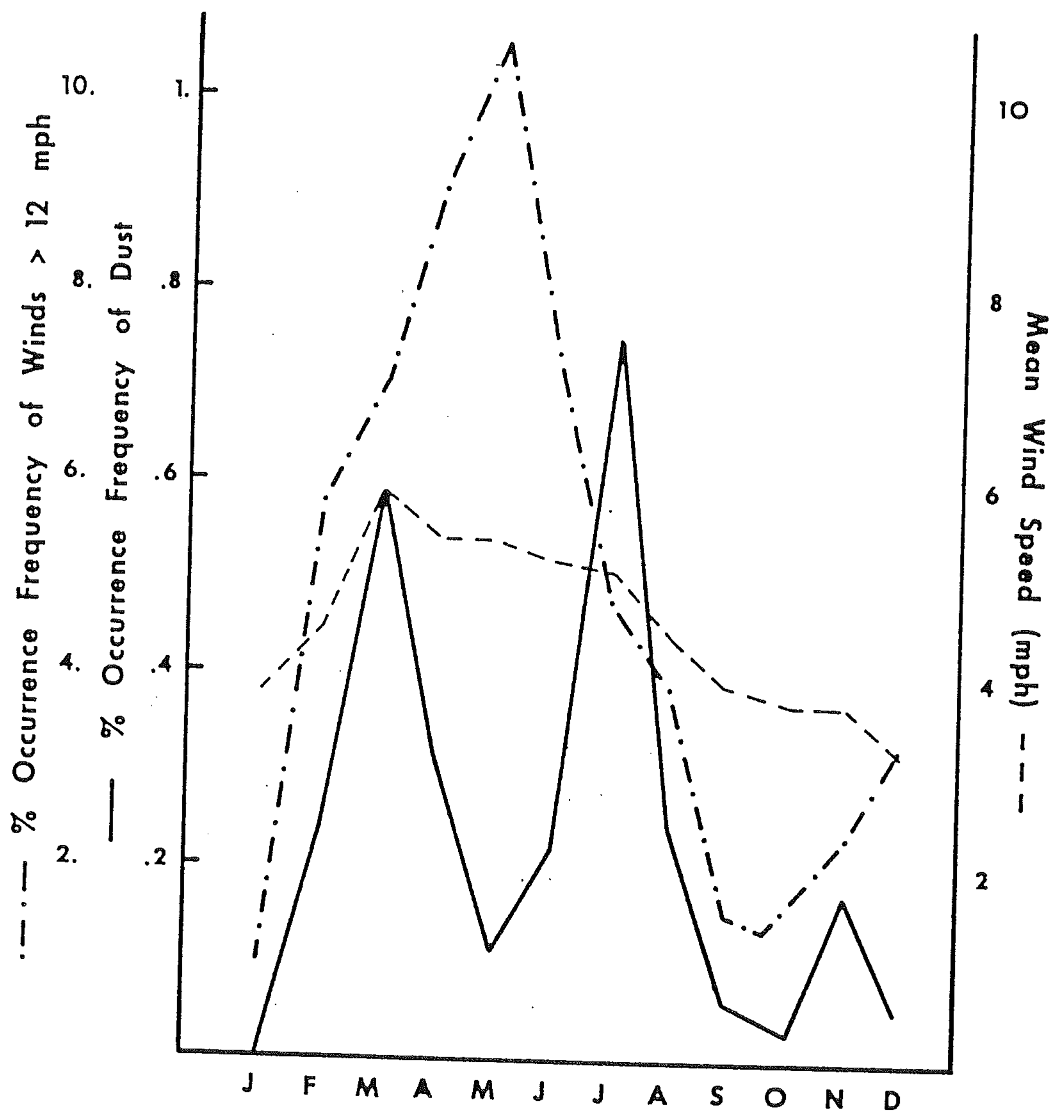


TABLE 3.15

THE PERCENTAGE FREQUENCY OF DUST, BY MONTH,

AT LUKE AFB, ARIZONA

Month	Dust Observations	Total Observations	% Time Dust Observed
Jan	0	3719	0.00
Feb	8	3407	0.23
Mar	22	3719	0.59
Apr	11	3600	0.31
May	4	3719	0.11
Jun	8	3600	0.22
Jul	28	3720	0.75
Aug	9	3719	0.24
Sep	2	3600	0.06
Oct	1	3720	0.03
Nov	6	3598	0.17
Dec	2	3719	0.05

Monthly mean wind speeds (Table 3.16) are greatest in March (9.6 kph/5.9 mph) and July 8.2 kph/5.1 mph). May, a month of low dust probability, has an average wind speed of 8.7 kph (5.4 mph) intermediate between March and July. Clearly, the frequency of dust occurrences cannot be explained by average wind speeds.

TABLE 3.16

MEAN MONTHLY WIND SPEEDS IN KILOMETERS PER HOUR (MILES PER HOUR), AT LUKE AFB, ARIZONA

Month	Mean Wind Speed kph (mph)	Month	Mean Wind Speed kph (mph)
Jan	6.1 (3.8)	Jul	8.2 (5.1)
Feb	7.2 (4.5)	Aug	7.1 (4.4)
Mar	9.6 (5.9)	Sep	6.3 (3.9)
Apr	8.7 (5.4)	Oct	6.0 (3.7)
May	8.7 (5.4)	Nov	6.0 (3.7)
Jun	8.4 (5.2)	Dec	5.1 (3.2)

Wind Roses

The percentage frequency distribution of wind speed classes greater than 19 kph (12 mph) by direction at Luke AFB and Davis Monthan AFB were calculated for alternate months. These results are shown by wind roses (Figures 3.8 and 3.9). High wind frequencies do not exceed three percent, except during March and May, at either location. From March through September, the prevailing direction of these winds is southwesterly at Luke AFB and southwesterly to northwesterly at Davis Monthan AFB. Winds in excess of 39 kph (24 mph) are confined to the spring months at Luke AFB; at Davis Monthan AFB they occur in all months.

The summer wind roses for Davis Monthan AFB (July to Sept.) indicate that high winds (39 kph) are not predominant from only one direction, but occur with some consistency from opposite directions. This is probably due to very rapid changes that take place prior to, during, and after thunderstorms move across the area. Thus, wind rose analysis used in conjunction with land use analysis is somewhat restrictive in terms of conclusive relationships, since high winds are quite variable in direction.

FIGURE 3.8

WIND ROSES FOR SELECTED MONTHS AT DAVIS MONTHAN AFB

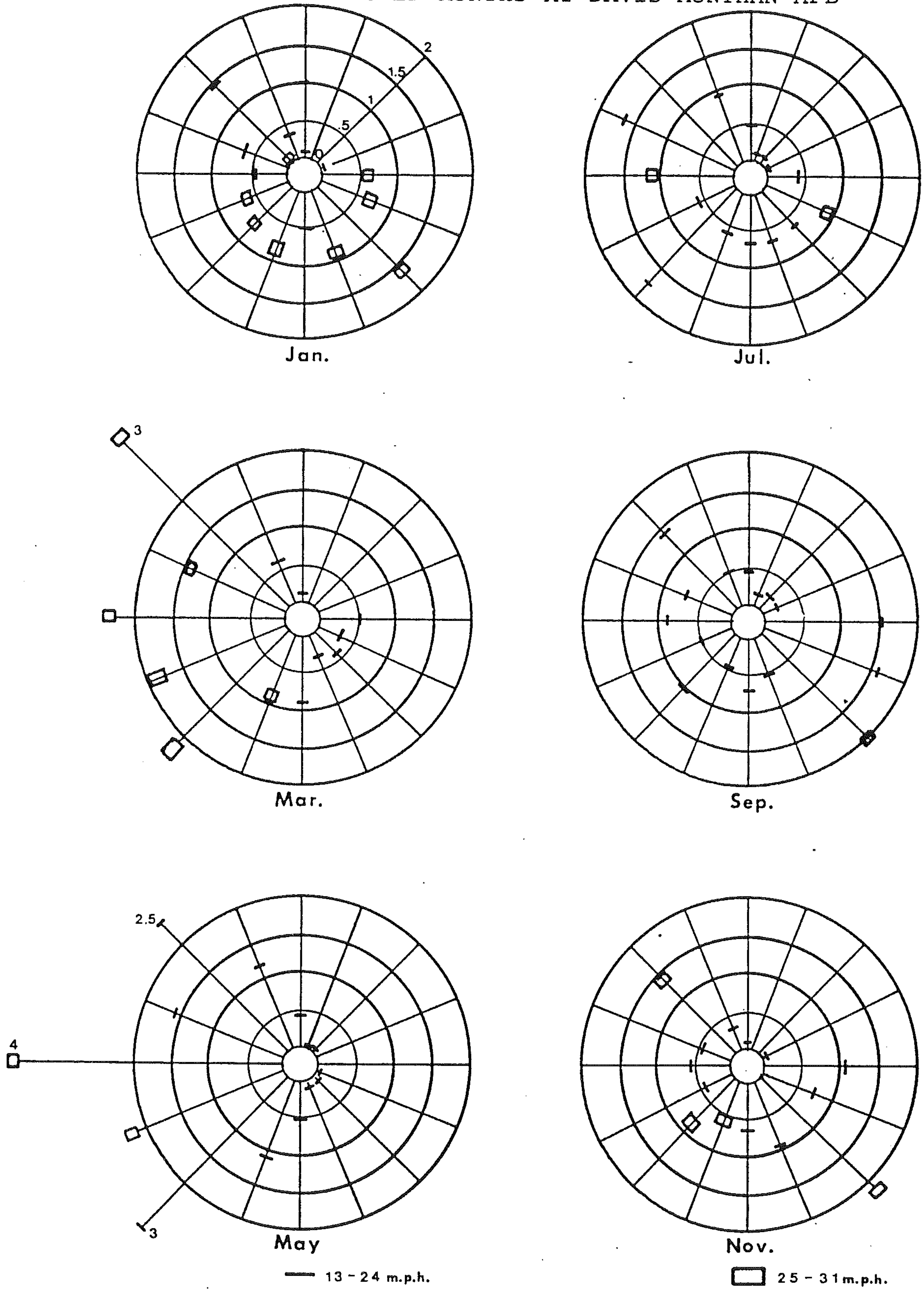
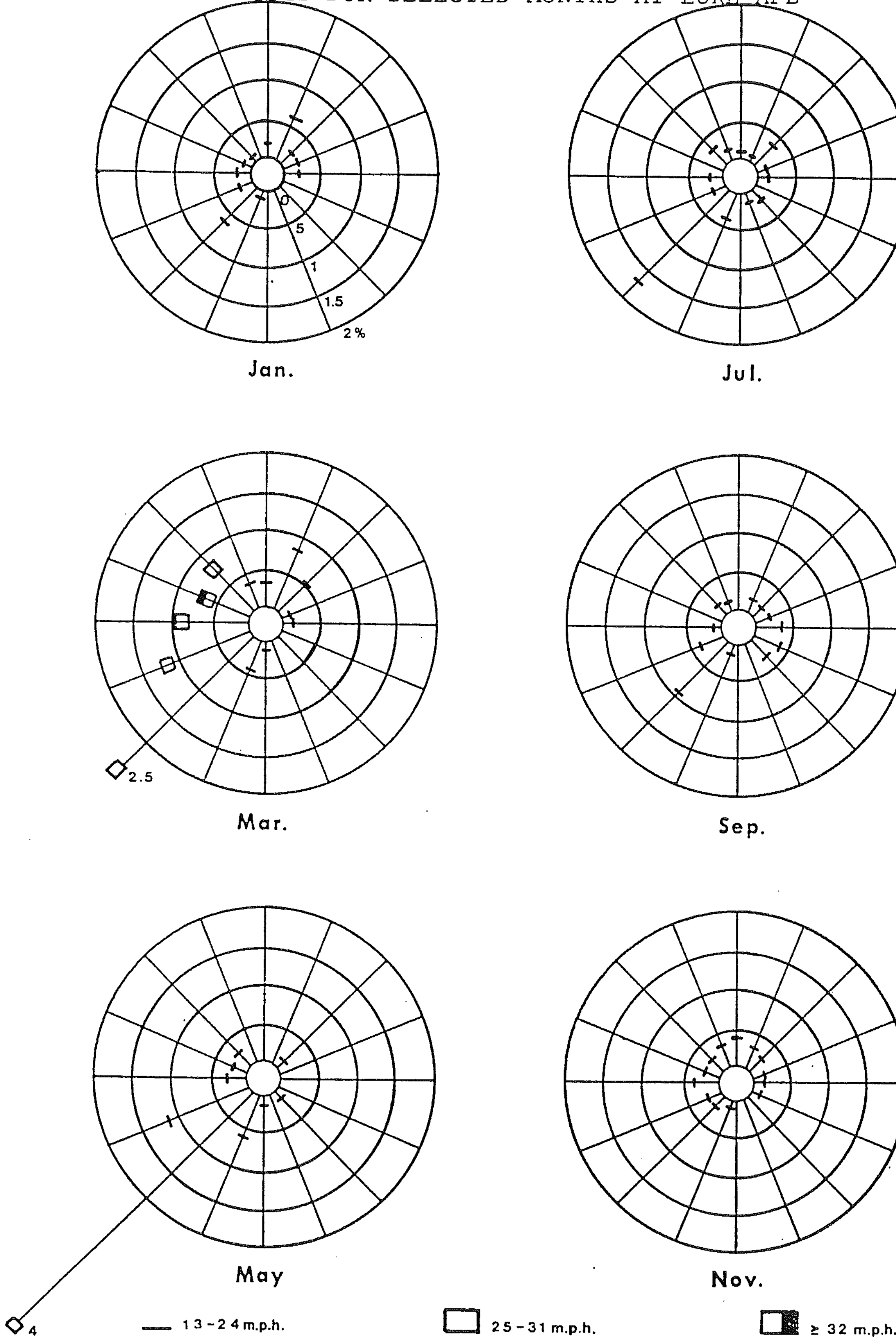


FIGURE 3.9

WIND ROSES FOR SELECTED MONTHS AT LUKE AFB



Precipitation and Dust

Although the greatest frequency of thunderstorms occur in July-September, the number of days with relatively heavy rain (greater than 6.4 mms/0.25 in.) are few (Table 3.17). Also, the mean number of days between thunderstorm precipitation events is quite high (see again Table 3.17).

On the other hand, there are 3-4 days of measurable rainfall in the study area for every day of relatively high rainfall (greater than 6.4 mm (0.25 in.).

Because it has been suggested that a dampened soil surface will inhibit dust storms, it is worth relating this possibility to the above precipitation data. Given the assumption, for example, that more than 6.4 mm (0.25 in.) of rain on one day will be required to present a wet surface on the following day, dust formation will be prevented. Table 3.17 is based on this assumption and it is clear that there are few days indeed when dampened soil would reduce the dust storm potential. As stated earlier, the precipitation associated with thunderstorms follows the windblown dust wall. It is concluded that rains from one thunderstorm are not usually an effective dust suppressor for the succeeding storm, unless they cause the surface to become "crusty" so that the particles are "cemented" to the ground.

TABLE 3.17

PRECIPITATION CHARACTERISTICS AT
LUKE AFB AND DAVIS MONTHAN AFB*

Month	Luke AFB		Davis Monthan AFB	
	Mean # Days 6.4 mm (0.25")	Mean # Days Between Rains 6.4 mm (0.25")	Mean # Days 6.4 mm (0.25")	Mean # Days Between Rains 6.4 mm (0.25")
Jun	0.00	----	0.30	100**
Jul	1.67	18.5	2.50	12.4
Aug	1.50	21.7	2.10	14.8
Sep	0.83	36.1**	1.30	23.1
Oct	0.33	93.9**	0.08	----

*Data based on approximately 20 years of record.

**Indicates number of consecutive days in that month from one year to the next. So, for example, for Luke AFB in October there would be no rain for 3 years in a row exceeding 0.25". Or, in other words, once every 3 years Luke AFB would experience a rain >0.25".

CONCLUSIONS AND RECOMMENDATIONS

Conclusions regarding climate and dust storms in the I-10 study area are as follows:

1. Analysis of wind speed classes and observations of blowing dust indicate that blowing dust is associated with winds over 16 kph (10 mph). Rarely is blowing dust observed below this threshold velocity. This conforms with Bagnold (1941) and Cooke and Warren (1973).

2. Winds associated with thunderstorms appear to cause the greatest amount of blowing dust and the most accidents.

3. The highest frequency of winds over 19 kph (12 mph) appears to be from the Southwest at Luke AFB and Northwest to Southwest at David Monthan AFB. However, winds associated with storms that cause blowing dust-related accidents are commonly from many other directions at these two sites. Winds in excess of 40 kph (25 mph) -- those winds associated with major dust storms -- are very infrequent (generally less than 0.10%) with no preferred direction.

4. There are three thunderstorm regimes; (a) Sierra Madre Origin, (b) Mogollon Rim Origin, and (c) Gulf of California Origin. Each type generates a well-defined pseudo-cold front along which a dense wall of dust develops. For 1975, thunderstorms of the Mogollon Rim origin caused the greatest number of dust-related accidents. Ingram (1972a) states that Sierra Madre

thunderstorms are the most frequent type for Phoenix. However, it is not known whether these storms cause proportionately more accidents than Rim storms in the study area.

5. Dust-related accidents occur most frequently between 1700-1900 MST. This is the most frequent time for summer thunderstorm activity in the study area. Other factors leading to accidents late in the day may be heavy highway useage, driver fatique, and proximity to sunset with consequent degradation of general driver visibility.

6. Even though the heaviest rainfall is received in summer, this natural moisture supply is insufficient to eliminate the dust hazard in the Casa Grande/Eloy area. Rainfall is too infrequent and/or too meager to maintain a continually moist surface or to adequately maintain a protective surface crust.

7. The 1975 accident record reviewed in Appendix 2 reveals a definite association in the timing of dust-related accidents and the passage of storms with associated blowing dust. Processes developing ahead of, within, and behind the dust wall front need to be studied in more detail.

8. Thunderstorms have a definite synoptic antecedence. Sierra Madre Origin storms appear to require a deep southeasterly wind current above 3,000 m (10,000 ft.), whereas Rim origin storms require a light north to northeasterly steering current at that level. General predictability of these storms appears feasible; however, additional forecasting techniques using radar,

upper air winds, GOES satellite imagery, and surface observations need to be developed to enhance prediction of blowing dust events for the specific study area.

Recommendations specific to the meteorological and climatological aspects of blowing dust are as follows:

1. There is a real need to develop a better meteorological and dust observational network in Central Arizona, so that more accurate dust observations and subsequent forecasts can be provided for the study area. At least one weather station should be established in the Casa Grande/Eloy area to monitor the following elements: (a) wind speed, (b) wind direction, (c) temperature, (d) humidity, (e) visibility, (f) precipitation, and (g) air pressure.

2. It would be advantageous to establish a research micrometeorological station to analyze the critical momentum and moisture parameters related to saltation, suspension, and subsequent reduced visibility by blowing dust. Detailed on-site sediment loading measurements would be included.

3. The combined weather network and micrometeorological station should improve forecasting ability for dust storms. Ideally, the station data should be "real time"; that is, its data should be available hour-by-hour to a central office, where they can be integrated with other meteorological data; e.g., satellite data and radar observations

4. There are a variety of warning systems that could be employed to detect imminent dust events. Which is most appropriate depends on the precise nature of the immediate cause of most dust-related accidents. The final chapter of this report considers several of these in more detail.

APPENDIX D

ASSESSMENT OF SATELLITE IMAGERY

Wind erosion is relatively easy to see on satellite images in the absence of clouds. For example, MRI obtained the pictures in Figures 1 and 2 to determine the areas affected by a wind storm in March 1989. Figure 1 is a GOES image in the visible spectral band. Figure 2 is a GOES image in the infrared band. As can be seen, the visible spectrum photo shows clouds better than dust, while the infrared photo better illustrates the dust storm over Kansas. The two images work well together to display dust storms. Satellite images are distributed from various sites through the Internet as images are acquires (routinely taken every 15 min). These images are available from the Internet addresses, http://www.wisc.edu/data/g8/latest_g8ir.gif and http://www.wisc.edu/data/g8/latest_g8vis.gif. These GIF images (1024x900 pixels) files are from the GOES-8 imager that has a five band multi-spectral capability with 10 bit precision and high spatial resolution. Three windows are especially useful for characterizing dust storms: (1) visible spectrum (0.52-0.72 μm); (2) shortwave infrared (3.78-4.03 μm); and (3) infrared window (11.5-12.5 μm). The GOES-8 geostationary satellite is a NOAA device launched in April 1994 that is a major component of the NOAA/National Weather Service modernization program. The University of Wisconsin, Space Science and Engineering Center, is a global leader in the analysis of geostationary satellite data. They have special image analysis capability which can be used to derive special products for Arizona from GOES-8 and GOES-9 satellites.

The usefulness of satellite images to determine the location of dust storms along Highway I-10 is questionable at this time. First, the images are distributed only once every 30 min. Highway patrolman observations and reports are likely to be a faster way to obtain and distribute useful information on dust storms. Secondly, a connection to an appropriate Internet site, such as www.wisc.edu, would have to be made a routine occurrence, essentially dedicating a computer with a large monitor to this task and requiring an experienced observer of satellite images. Thirdly, the resolution of GOES images may not be sufficient to identify dust storms from small area/sources.

Fourthly, adjust events associated with a thunderstorm will be obscured by the thunderstorm on a satellite image. A satellite view of a significant dust storm caused by a frontal passage that has a duration of several hours and affects many miles of highway would be useful in determining locations of dust sources.