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Evaluation of Measures to Promote Desert Bighorn Sheep Highway Permeability: U.S. Route 93

Arizona Department of Transportation Research Center

ADOT

Evaluation of Measures to Promote Desert Bighorn Sheep Highway Permeability: U.S. Route 93

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Prepared by:
Jeffrey W. Gagnon, Norris L. Dodd, Scott Sprague, Chad Loberger, Rob Nelson, Susan Boe, and Raymond E. Schweinsburg
Arizona Game and Fish Department
Research Branch
5000 West Carefree Highway
Phoenix, AZ 85068

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16. Abstract

This study evaluated desert bighorn sheep–highway relationships from 2008 to 2010 along a 17-mi stretch of U.S. Route 93 (U.S. 93), in northwestern Arizona. Highway reconstruction between mileposts (MP) 2.3 and MP 17.0 was completed in October 2010. The research objectives were to:

- Assess sheep movements, highway crossing patterns, distribution, and determine permeability.
- Investigate spatial and temporal patterns of sheep highway crossings and relationships to traffic volume.
- Investigate spatial and temporal sheep-vehicle collision patterns.
- Assess the impact of highway reconstruction activities on sheep movements, habitat use, and permeability.
- Establish baseline data for pre- and during-reconstruction movements, highway crossing and passage rates, and sheep-vehicle collisions against which to conduct a sound post-reconstruction assessment.

Researchers instrumented 38 desert bighorn sheep (*Ovis canadensis*) with GPS collars. Sheep crossed the highway 340 times. U.S. 93 constituted a significant barrier to sheep passage, as passage rates averaged just 0.07 crossings/approach. Passage rates varied by season, with summer rates higher than winter and spring rates given that sheep exhibited increased tolerance to traffic during summer when crossing U.S. 93 in pursuit of water. Sheep exhibited minimal response to consistently high traffic volume encountered during the daytime hours when they were predominantly active.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^0F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^0C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^0C	Celsius	1.8C+32	Fahrenheit	^0F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

° F	degrees Fahrenheit
χ^2	chi square
AADT	average annual daily traffic
ADOT	Arizona Department of Transportation
AGFD	Arizona Game and Fish Department
ANOVA	analysis of variance
ATR	automatic traffic recorder
BACI	before-after–control-impact (experimental design)
CANAMEX	Canada to Mexico (Trade Corridor)
df	degrees of freedom
EIS	environmental impact statement
FHWA	Federal Highway Administration
ft	foot
GIS	geographic information system
GPS	Global Positioning System
hr	hour
I-17	Interstate 17
K-S	Kolmogorov-Smirnov (statistical test)
lb	pound
MCP	minimum convex polygon (home range)
mi	mile
mi^2	square mile
MP	milepost
P	probability
Reclamation	Bureau of Reclamation
SDI	Shannon diversity index
SE	standard error
SR	State Route
US	United States
U.S. 93	U.S. Route 93
VHF	very high frequency
WVC	wildlife-vehicle collision
yr	year

LIST OF SPECIES

Animals

Bobcat	*Lynx rufus*
Burro (feral)	*Equus asinus*
Coyote	*Canis latrans*
Desert bighorn sheep	*Ovis canadensis*
Elk	*Cervus elaphus*
Gray fox	*Urocyon cinereoargenteus*
Mountain goat	*Oreamnos americanus*
Mountain lion	*Puma concolor*
Mule deer	*Odocoileus hemionus*
Pronghorn	*Antilocapra americana*
White-tailed deer	*Odocoileus virginianus*

Plants

Bursage	*Ambrosia dumosa*
Catclaw acacia	*Acacia greggii*
Cheesebush	*Hymenoclea salsola*
Creosotebush	*Larrea tridentata*
Galleta grass	*Pleuraphis rigida*
Honey mesquite	*Prosopis grandulosa*
Mormon tea	*Ephedra nevadensis*
Range ratany	*Krameria parvifolia*

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We sincerely thank the Arizona Desert Bighorn Sheep Society for its financial support of the project and for its committed volunteers who assisted during sheep capture efforts.

Lastly, the technical advisory committee made many suggestions toward improving the project's effectiveness and applicability. The committee's tremendous support, oversight, and commitment throughout the duration of the project are appreciated.

EXECUTIVE SUMMARY

The research team assessed desert bighorn sheep-highway relationships from 2008 to 2010 along an 18-mile stretch (mileposts [MPs] 0−18.0) of U.S. Route 93 (U.S. 93) southeast of Hoover Dam and 70 miles northwest of Kingman, Arizona. U.S. 93 is the primary transportation route between Phoenix, Arizona, and Las Vegas, Nevada. This highway corridor has been congressionally designated as one leg of the CANAMEX (Canada to Mexico) Trade Corridor and future Interstate 11. The study section of the highway cuts through the northern extent of the Black Mountains where nearly 30 percent of the state's total desert bighorn sheep population resides. Desert bighorn has long been a focal species of concern in planning for the Hoover Dam Bypass project (MP 0−2.2) begun in 2002 and for highway reconstruction between MP 2.3 and MP 17.0 from a two-lane highway to four-lane divided highway.

The environmental analysis for the highway widening project addressed the impact of the widening on desert bighorn sheep travel corridors and habitat fragmentation, as well as the potential for increased sheep-vehicle collisions. Extensive prior desert bighorn research supported the implementation of a comprehensive set of measures to maintain wildlife connectivity as part of highway reconstruction, including three wildlife overpasses and ungulate-proof fencing.

Highway reconstruction was initiated in April 2009 and was completed in November 2010. The integration of overpasses and other measures warrants assessing—in a rigorous, experimental context—the efficacy of such measures in promoting sheep highway permeability. This research study was intended to establish additional pre-reconstruction baseline data to facilitate post-reconstruction comparisons. This study also included investigating the impact of reconstruction activities on critical habitat-use patterns of desert bighorn, especially regarding water demand (summer) and lambing activities (spring). The objectives of this research project were to investigate (1) desert bighorn movements, highway crossing patterns, distribution, and highway permeability before and during highway reconstruction; (2) relationships of sheep highway crossing and distribution patterns to traffic volume; and (3) sheep-vehicle collision patterns. This study established pre- and during-reconstruction baseline data for future comparison with data obtained from a post-reconstruction assessment.

Desert Bighorn Sheep Movements and Highway Permeability

The research team determined the number of highway crossings and calculated crossing and passage rates for desert bighorn using Global Positioning System (GPS) telemetry. Passage rates, which served as the team's relative measure of highway permeability, were derived from the proportion of sheep highway crossings to sheep highway approaches within 0.15 mi of U.S. 93. The team assessed mean daily sheep crossing and passage rates spatially at various temporal scales and compared pre-reconstruction and during-reconstruction results among highway stretches.

Researchers captured and fit 38 desert bighorn sheep with GPS collars that collected 137,195 total GPS animal positions. Collared sheep crossed U.S. 93 340 times, 77 times before reconstruction commenced and 263 times during reconstruction, with mean crossing rates of 0.02 and 0.03 crossings/day,

respectively. The spatial distribution of crossings did not occur in a random manner. U.S. 93 constituted a significant barrier to sheep passage. The average passage rate was low (0.07 crossings/approach) between MP 2.3 and MP 17.0. The sheep highway passage rate varied by season, with the summer rate (0.25 crossings/approach) significantly higher than the winter and spring rates, though not significantly different from the fall rate (0.19 crossings/approach). The demand for water during the extreme summer months likely accounts for the higher passage rates, given that sheep exhibited increased tolerance to traffic when crossing U.S. 93 in pursuit of permanent water sources. The relatively high fall passage rate coincided with the sheep breeding season when male sheep exhibit extensive movements.

There was no difference between pre- and during-reconstruction sheep crossing and passage rates, partly because of the consistent impact of high traffic volume and because the reconstructed highway still functioned as a "small" two-lane roadway until traffic was allowed on all four lanes. The measures intended to promote sheep highway permeability are anticipated to have a beneficial impact on overall highway permeability, given that prior studies have shown dramatic improvements to permeability with the use of passage structures and fencing.

Traffic Relationships

The research team measured traffic volume using a permanent automatic traffic recorder programmed to record hourly traffic volumes at MP 18.0. Traffic and GPS data were combined to correlate the traffic volume each animal experienced in the hour before observed movement. The researchers examined how the proportion of sheep GPS fixes at different distances from the highway varied with traffic volume by calculating the proportion of GPS fixes in each 330-ft distance band (out to a maximum of 1980 ft). Though the average annual daily traffic (AADT) averaged 8720 vehicles/day, during the diurnal period when desert bighorn sheep were most active (0600 hours−1800 hours), the AADT-equivalent volume approached 12,000 vehicles/day—the highest volume documented among the studies of five Arizona highways and species.

The researchers found a static distribution of desert bighorn sheep relocations among 330-ft distance bands outward from U.S. 93 across all traffic volumes. This limited response reflected the constant exposure to high traffic volume that sheep encountered when active. At such high volumes, vehicular traffic serves as a "moving fence" that physically renders highways impermeable to wildlife and results in a "noise effect zone" extending away from the highway. Mean monthly sheep crossing and passage rates were both associated with monthly traffic volume, all of which were highest during summer. These associations likely reflected the seasonal tolerance by sheep to high traffic volume while seeking out water sources during the hot, dry summer months. Conversely, sheep highway crossings were negatively associated with daily traffic volume.

Based on research along five highways in northern and central Arizona, including U.S. 93, the research team found a very strong negative association between mean passage rates for five wildlife species and active-period AADT-equivalent traffic volumes. This association accounted for three-quarters of the variation in passage rates, and it better describes a seemingly universal impact of traffic volume across

highways and wildlife species, both nocturnal and diurnal, than the association with highway AADT. Across these highways and species, passage rates averaged 0.49 crossings/approach for species with active-period AADT-equivalent volumes up to 4000 vehicles/day but averaged a mere 0.04 crossings/approach for AADT-equivalent volumes above 4000 vehicles/day.

The research team anticipates that the U.S. 93 wildlife overpasses, bridges, and fencing will help mitigate the impact of high traffic volume, similar to the outcome documented for elk and white-tailed deer along State Route 260. A key to the success of State Route 260 wildlife underpasses in promoting permeability was the relatively minor influence of traffic volume on passage rates when elk and deer used the below-grade passage structures rather than at-grade crossings. Post-reconstruction evaluation should show whether or not this is the case for desert bighorn and the new U.S. 93 wildlife overpasses.

Construction Disturbance Impact on Desert Bighorn Sheep

The research team took a comprehensive, multiscale approach to its assessment of potential U.S. 93 reconstruction impacts on desert bighorn. Reconstruction appeared to have no impact on mean sheep crossing and passage rates, though the rates were consistently low for both pre- and during-reconstruction datasets. However, there was a significant difference in the spatial distribution of U.S. 93 crossings by sheep, with a 50 percent increase in crossings observed on the old realignment section (MP 0−2.2) and a 96 percent decline in crossings between MP 5.0 and MP 9.0 during reconstruction.

Researchers found little difference in the probabilities of sheep distribution outward to 1980 feet away from the highway among the different disturbance-level classes associated with reconstruction. Desert bighorn appeared tolerant of heavy equipment and bridge construction activities. However, researchers did find that with very high disturbance (blasting), desert bighorn exhibited a dramatic shift away from the highway. At a broader scale, during the lambing period, the researchers found a significant difference in the distribution of female GPS relocations among distance bands from U.S. 93 both before and during reconstruction. Compared to pre-reconstruction data from a previous study, 68 percent fewer sheep were located within 0.31 mi of the highway and 50 percent fewer located within 0.62 mi of the highway during reconstruction.

At its broadest scales, researchers found limited blasting-activity impacts on sheep movements and distribution. There was no difference in the proportions of sheep GPS relocations within 0.6-mi distance bands outward from the blast sites on the days before and days after blasting. They also found no difference in the mean distance from blasting sites between the day before and the day after blasting for sheep located within 6 mi of the highway. However, when examined over a week, the researchers found a strong association between days after blasting and mean distance from blasting sites, which suggests a delayed desert bighorn response to blasting. All blasting activities occurred in an eight-month period that excluded the summer months, thereby avoiding any potential adverse impacts on sheep's accessing water sources during the critical hot and dry months.

Desert Bighorn Sheep–Vehicle Collision Relationships

The research team documented six sheep-vehicle collisions during the study, including five during 2009 and 2010, which is an average of 2.5/yr or 0.16/mi/yr. However, these averages underestimate the actual long-term pre-reconstruction incidence of collisions involving desert bighorn. Between September 2001 and October 2010, the study stretch of U.S. 93 was closed to commercial truck traffic as a precautionary measure to protect the Hoover Dam following the September 11, 2001, terrorist attacks (9/11). Also, between 2003 and November 2010, active highway construction further affected pre-reconstruction traffic and driving patterns. Thus, the team established a more representative pre-reconstruction baseline for post-reconstruction comparison from a prior study for the period 1989−1990. During this period an average of 11.0 sheep-vehicle collisions/yr (0.69 collisions/mi/yr) were documented. This rate is more than four times the rate of collisions documented by the research team for 2009 and 2010.

The research team anticipates that the combination of passage structures and fencing integrated into the U.S. 93 reconstruction project, which was completed in November 2010, will dramatically reduce the incidence of U.S. 93 wildlife-vehicle collisions. The portions of U.S. 93 fenced with ungulate funnel fencing, between MP 0 and MP 17, correspond to the location of 92.5 percent of all pre-reconstruction sheep highway crossings.

This research study, when combined with other similar studies along other Arizona highways, provided an opportunity to further investigate highway barrier effects on wildlife permeability for varying levels of traffic volume and highway size. GPS telemetry is an invaluable tool that has facilitated an increased understanding of the importance of wildlife-highway relationships in promoting safer and ecologically sensitive transportation systems.

This study has established pre- and during-reconstruction baseline data, which will allow for a rigorous post-reconstruction evaluation based on a sound before-after–control-impact experimental design. Such post-reconstruction evaluation is critical to assessing desert bighorn and other wildlife use of the three wildlife overpasses and other structures, as well as for determining relationships to different design characteristics (e.g., width), placement, and fencing for application in future projects. Post-reconstruction evaluation is especially important for assessing the efficacy of all the measures in promoting sheep highway permeability and reducing sheep-vehicle collisions.

CHAPTER 1. INTRODUCTION

BACKGROUND

Highways constitute one of the most significant forces altering natural ecosystems in North America (Noss and Cooperrider 1994; Trombulak and Frissell 2000; Farrell et al. 2002; Forman et al. 2003). Forman (2000) and Forman and Alexander (1998) estimated that highways have affected more than 20 percent of the US land area through habitat loss and degradation. Wildlife-vehicle collisions (WVCs) are a serious and growing threat to both wildlife populations and humans; WVCs are responsible for the direct mortality of wildlife and contribute to human deaths, injuries, and property damage (Schwabe and Schuhmann 2002; Bissonette and Cramer 2008). Over 38,000 human deaths attributable to WVCs occurred in the United States between 2001 and 2005, and the economic impact exceeds $8 billion/year (Huijser et al. 2008). Aside from wildlife mortality effects, the most pervasive impact of highways on wildlife is barrier and fragmentation effects, which diminish habitat connectivity and permeability (Noss and Cooperrider 1994; Forman et al. 2003). Highways constitute barriers to wildlife movement that fragment populations and habitats and that limit juvenile dispersal (Beier 1995; Proctor et al. 2012). Recent evidence has demonstrated that highways limit genetic interchange and isolate subpopulations of wildlife (Epps et al. 2005; Riley et al. 2006; Sprague 2010).

The degree of highway barrier effects varies by wildlife species, highway type and standard, and traffic volume (Jaeger et al. 2005). Increasing traffic volume can magnify the impact of roads and highways on ungulates, including altered habitat use (Rowland et al. 2000; Wisdom et al. 2005), restricted movements and fragmented populations (Epps et al. 2005; Proctor et al. 2012), and increased mortality through collisions with vehicles (Groot Bruinderink and Hazebroek 1996; Gunson and Clevenger 2003). The magnitude of these highway impacts increases with increasing traffic volume and highway standard, though traffic volume exerts the greatest impact according to modeling by Jaeger et al. (2005). Theoretical models suggest that highways with an average annual daily traffic (AADT) of 4000–10,000 vehicles/day present strong barriers to wildlife passage, but that highways with an AADT above 10,000 vehicles/day create impermeable barriers to wildlife passage (Mueller and Berthoud 1997; Seiler 2003; Iuell et al. 2003).

Only recently have studies yielded quantitative data relative to assessing highway impacts on permeability. Several studies have used before-after–control-impact (BACI) experimental designs (Underwood 1994; Hardy et al. 2003; Roedenbeck et al. 2007) that elucidate highway reconstruction permeability impacts and the influence of passage structures in promoting permeability (Dodd, Gagnon, Boe, et al. 2007; Olsson 2007; Gagnon et al. 2011). Arizona researchers have stressed the value of a quantifiable and consistent metric of permeability. They have calculated highway passage rates from Global Positioning System (GPS) telemetry for several species to derive comparable estimates of permeability and to assess traffic impacts on Arizona highways (Dodd et al. 2007a; Dodd et al. 2012; Dodd et al. 2011; Gagnon, Theimer, Dodd, and Schweinsburg 2007; Gagnon et al. 2010). Collectively, these studies have used comparable methodologies and metrics to assess multiple species and highways

with different traffic patterns and have thus added substantially to the understanding of highway impacts and traffic relationships to wildlife permeability.

The integration of structures designed to reduce WVCs and promote wildlife passage across highways in transportation projects has increased in the past decade (Bissonette and Cramer 2008). Passage structures have proven beneficial in promoting crossings by a variety of species (Farrell et al. 2002; Clevenger and Waltho 2003; Dodd, Gagnon, Boe et al. 2007; Gagnon et al. 2011) and, in conjunction with fencing, have dramatically reduced WVC incidences (Clevenger et al. 2001; Dodd et al. 2006; Olsson et al. 2008; Gagnon et al. 2010). Whereas early passage structures were typically used as single-species mitigation measures to address WVCs (Reed et al. 1975), the focus today is on preserving ecosystem connectivity and permeability benefiting multiple species (Clevenger and Waltho 2000). Such assessments, along with assessments of genetic interchange, help justify the high cost of passage structures (Corlatti et al. 2009). Few studies have quantified during-reconstruction impacts on wildlife movement and permeability, especially where such impacts potentially limit or impede access to important habitats (Singer and Doherty 1985; Dodd, Gagnon, Boe, et al. 2007; Olsson 2007).

Along with structural characteristics, proper location and placement of wildlife crossing structures are vital considerations to maximizing wildlife use (Reed et al. 1975; Foster and Humphrey 1995; Clevenger and Waltho 2000, 2003; Dodd, Gagnon, Manzo, et al. 2007; Gagnon et al. 2011). Spacing between passage structures is also an important consideration, and Bissonette and Adair (2008) recommended passage structure spacing for several species that is tied to isometric scaling of home ranges. Their spacing recommendations, when used with other criteria such as WVC hotspots, were intended to help maintain landscape connectivity. The availability of information on wildlife movements and highway crossings, along with WVC data, is valuable in developing and evaluating comprehensive strategies and locating passage structures such that their success is maximized in promoting wildlife permeability and highway safety.

DESERT BIGHORN SHEEP AND HIGHWAYS

Desert bighorn sheep are adapted to the arid, mountainous desert habitats that occur throughout much of northern Mexico and the southwestern United States. Sheep populations are distributed in naturally fragmented groups in isolated mountain ranges separated by relatively flat, unsuitable habitats (Krausman and Leopold 1986; Bleich et al. 1990, 1996; Andrew et al. 1999; Epps et al. 2007). At one time in the 19th century, 1,000,000 sheep were estimated to inhabit the western United States, with 35,000 in Arizona alone (Buechner 1960). Sheep populations declined precipitously following European settlement of the western United States due to overhunting and the introduction of domestic livestock that exposed desert bighorn to exotic diseases and competed for limited forage in desert ranges (Russo 1956).

Through aggressive management, including reintroductions of desert bighorn sheep to historical ranges, the state's sheep population has dramatically recovered (Cunningham et al. 1993). However, fragmentation of habitats and isolation of populations associated with anthropogenic influences tied to

human growth and development present continued challenges (Leslie and Douglas 1979). The rapid human population growth in the Southwest, especially in Arizona, has brought increased barrier threats from new and improved highways, canals, fences, housing developments, and off-highway vehicles (Gionfriddo and Krausman 1986; Epps et al. 2007). This fragmentation now threatens many of the state's sheep populations, most of which number fewer than 100 animals and are isolated (Krausman and Leopold 1986). Berger (1990) concluded that desert bighorn populations with fewer than 50 individuals tend to go extinct, but that extirpation of populations is not necessarily caused by food shortages, weather, predation, or interspecific, or between species, competition (e.g., with cattle, burros, mule deer).

While no specific population size ensures population persistence (Thomas 1990), small desert bighorn populations occupying marginal or comparatively poor habitat or small patches of suitable habitat may require management intervention to ensure long-term persistence (Berger 1990; Gross et al. 1997; Wehausen 1999; McKinney et al. 2003; Epps et al. 2007). Habitat patch size may be the primary correlate of desert bighorn population performance and persistence (Gross et al. 1997; Singer et al. 2001; McKinney et al. 2003), but factors other than patch size may influence extinction and colonization (Fleishman et al. 2002). As such, desert bighorn conservation efforts should emphasize preventing further habitat fragmentation and restoring connectivity (Krausman et al. 1993; Fahrig 1997; Berger 1999; Epps et al. 2007).

The importance of traditional movement corridors to desert bighorn in maintaining connectivity—especially for males, which are more likely than females to make long-distance movements between mountain ranges—is well documented (Epps et al. 2007); these traditional corridors are tied to areas exhibiting adequate steep and broken escape-terrain attributes (Geist 1971; Cunningham and Hanna 1992; Epps et al. 2007). Loss or obstruction of such traditional travel corridors and fragmentation of habitats can have significant implications for long-term population persistence and can lead to genetic isolation of subpopulations (Geist 1971; Epps et al. 2005, 2007).A landmark assessment of the barrier effect of highways and resulting impact on desert bighorn genetic diversity among 27 southern California populations found that highways indeed limit gene flow (Epps et al. 2005). The degree of reduced genetic diversity was tied to years of isolation attributable to highways, and continued isolation poses a severe threat to the persistence of naturally fragmented sheep populations (Epps et al. 2005).

Traditional management techniques such as habitat protection, improvement, and maintenance of dispersal corridors, are important in the conservation of desert bighorn sheep populations (Schwartz et al. 1986). However, Beier and Loe (1992) warned that the preservation or reestablishment of natural wildlife movement corridors in the absence of appropriate scientific foundations may not adequately preserve connectivity. Though wildlife passage structures have been widely used in North America to enhance permeability and reduce WVCs for a range of wildlife species, limited information exists on the efficacy of passage structures in promoting highway permeability for desert bighorn. One notable example in efforts to promote sheep connectivity, though yielding mixed results, is along State Route (SR) 68 in northeastern Arizona, at the southern end of the Black Mountains. Here, the widening of 14 miles of the highway from two to four lanes incorporated three wildlife underpasses to facilitate sheep

passage. Bristow and Crabb (2008) evaluated the efficacy of these underpasses in promoting sheep passage using GPS telemetry and camera monitoring. Bristow and Crabb found that only 12 percent of the GPS-collared sheep, all of which were males, used the underpasses for highway crossing. In 20 months of camera monitoring, Bristow and Crabb (2008) documented 25 instances where desert bighorn crossed under SR 68, all of which, again, were male-only crossings; the highest use occurred during the breeding season. Use of the three underpasses varied considerably, with one structure with poor approach sighting and another situated in relatively flat, unsuitable desert bighorn habitat exhibiting limited or no documented sheep use; 88 percent of crossings occurred at the third structure located in the most rugged terrain (Bristow and Crabb 2008). They stressed the importance of locating sheep passage structures along existing travel corridors to maximize success, as well as the role of fencing to funnel animals to the structures.

Recent landscape-scale assessments reflect the increased awareness and critical need to promote desert bighorn connectivity (Epps et al. 2007), including in transportation contexts. The Arizona Wildlife Linkages Workgroup (2006) identified 152 linkage zones across the state that warrant maintaining and promoting wildlife connectivity across highways, including just over half (78) where desert bighorn sheep is a species of concern. For several of the priority linkages in this assessment, refined linkage design assessments have been developed that focus on identifying and developing specific strategies to promote desert bighorn connectivity (e.g., Beier et al. 2008).

U.S. ROUTE 93 AND DESERT BIGHORN SHEEP

Planning efforts for constructing the U.S. Route 93 (U.S. 93) Hoover Dam Bypass and approaches, including constructing a new bridge over the Colorado River at milepost (MP) 0 and widening the two-lane highway to a four-lane divided highway from MP 0 to MP 17, began in the 1960s. This long-term planning culminated with the formal initiation of an environmental impact statement (EIS) and public scoping in 1990 by the Bureau of Reclamation (Reclamation). The Arizona Game and Fish Department (AGFD) and other entities raised concern over the impact of highway widening on desert bighorn travel corridors and habitat fragmentation, as well as the potential for increased sheep-vehicle collisions and the impact on sheep population viability in the Black Mountains. A major focus of the environmental analysis was evaluating the impact of various proposed approach alignments, of which three passing through desert bighorn habitat were given serious consideration. Reclamation initiated the EIS for the Hoover Dam Bypass project (MPs 0–2.2) but withdrew from the project as the lead agency in 1993; the project was put on hold in 1995. In 1997, the Federal Highway Administration (FHWA) took over as lead agency. The final EIS and Record of Decision were issued in 2001, with the Sugarloaf Mountain Alternative selected as the bypass alignment and bridge crossing (FHWA 2001). Construction on the Arizona approach from MP 0 to MP 2.2 began in 2003, and construction of the new bridge crossing in 2004, with both completed in October 2010.

Early in the environmental analysis process for the Hoover Dam Bypass and highway reconstruction, Cunningham and Hanna (1992) made an intensive two-year assessment of desert bighorn movements and habitat use in the Black Mountains adjacent to the U.S. 93 corridor; this assessment was critical to

selecting the Sugarloaf Mountain alignment alternative. They tracked 49 sheep fitted with very high frequency (VHF) telemetry collars to determine areas of importance, movement corridors, habitat use, and behavioral responses to the highway. Cunningham and Hanna (1992) identified three separate ewe (female sheep) groups and use areas near the highway; the ewe groups exhibited significantly different habitat use and home ranges, with relatively little ewe interchange among the groups. Unlike the ewes, the rams (male sheep) wintered predominantly west of the highway, and many moved considerable distances to the northeast across the highway during the breeding season; Cunningham and Hanna (1992) documented 15 of the 18 collared rams (83 percent) crossing U.S. 93. All three of the bypass alignment alternatives bisected one or more of the ewe groups' home ranges, and the primary ewe group was the only one to be potentially affected by all three alignments. Cunningham and Hanna (1992) were particularly concerned with the sheep's continued use of the existing sewage ponds located near Sugarloaf Mountain for water sources, especially given the ponds' proximity (0.3 mi) to the bypass alignment. They recommended developing alternative water sites to mitigate the potential impact of construction.

Cunningham and Hanna (1992) recorded nearly 600 sheep highway crossings, with the majority between MP 2.1 and MP 3.0. The ewes from the primary group crossed an average of 30 times each during the study, typically at breaks in guardrails and with minimal hesitancy, which suggested that U.S. 93 was not a barrier to their passage compared to ewes in the other two groups. Cunningham and Hanna (1992) identified two periods in which bypass and highway reconstruction activities would have the most effect on desert bighorn sheep: spring (lambing) and summer (peak water demand); they mapped critical lambing and water areas. Most of the highway crossings by the primary ewes occurred during those two periods, as well as most of the 24 documented sheep-vehicle collisions. They reported that 31.4 percent of collisions occurred on the bypass stretch (MP 1.0–2.2), 29.2 percent between MP 2.9 and MP 4.0, and 29.2 percent beyond MP 5.0. Cunningham and Hanna (1992) also expressed concern for potential damage to bighorn sheep health from construction-generated dust, given that bighorn sheep deaths tied to dust-induced bronchopneumonia had been documented elsewhere (Spraker et al. 1984).

As the U.S. 93 bypass construction progressed between MP 0 and MP 2.2, impacts on sheep were visually monitored (844 observations) between 2003 and 2008 (Douglas and McMahon 2009). The primary ewe group continued to use the Sugarloaf Mountain sewage ponds during reconstruction, though use of the Sugarloaf Mountain hot springs was minimal due to reduced flows associated with drought conditions (Douglas and McMahon 2009). Active dust abatement appeared to effectively prevent dust-related impacts on desert bighorn, and the bypass construction and new highway did not appear to have fragmented the population, partly due to sheep passage under the completed 900-ft-long Sugarloaf Mountain Bridge at MP 0.7.

Concurrent with bypass construction and as refined planning progressed for reconstruction of U.S. 93, McKinney and Smith (2007) conducted an assessment of desert bighorn sheep movements relative to the proposed reconstruction plans between MP 2.3 and MP 17. They focused on identifying potential locations for passage structures to enhance highway permeability for sheep and to reduce WVC

incidences. McKinney and Smith (2007) instrumented 36 desert bighorn sheep with GPS receiver collars from 2004 to 2006 and obtained over 73,000 relocations. They recorded 345 sheep highway crossings, including 232 between MP 0 and MP 3 and 113 crossings between MP 3 and MP 17; 59 percent of their collared sheep did not cross U.S. 93. They documented five continuous, linear, elevated guideways corresponding to ridgelines where sheep concentrated their movements and crossings; 82 percent of the sheep crossings between MP 3 and MP 17 occurred at three of these locations for which McKinney and Smith (2007) recommended passage structures to promote highway permeability and ensure genetic heterogeneity and vigor: MP 3.3, MP 5.1, and MP 12.2 (Table 1; Figure 1). During the course of their study, McKinney and Smith (2007) recorded only one WVC involving desert bighorn, far fewer than the incidences reported by Cunningham and Hanna (1992); they attributed this decline in collisions to lower vehicle speeds due to construction and the restriction of commercial truck traffic on U.S. 93 after the September 11, 2001, (9/11) terrorist attacks.

Table 1. U.S. 93 Bridge and Wildlife Crossing Structures Implemented with Highway Reconstruction between Mileposts 3 and 17.

Structure Name	Structure Type	Milepost	Length (ft)
Wildlife Crossing #1	Overpass	12.2	202.0
Devils Wash Bridge Northbound	Bridge	8.0	290.0
Devils Wash Bridge Southbound	Bridge	8.0	268.8
Wildlife Crossing #2	Overpass	5.1	202.0
White Rock Canyon Bridge Southbound	Bridge	4.2	216.5
White Rock Canyon Bridge Northbound	Bridge	4.2	213.8
Wildlife Crossing #3	Overpass	3.3	202.0

Source: ADOT 2008.

The Arizona Department of Transportation (ADOT) subsequently commissioned a technical advisory committee to address the recommendations for promoting sheep highway permeability developed by McKinney and Smith (2007), as well as to evaluate preliminary bridge designs as part of a bridge selection analysis (ADOT 2008). In addition to the Sugarloaf Mountain Bridge (MP 0.7) and the Kingman Wash Traffic Interchange Bridge (MP 2.1) completed under the bypass project, the bridge selection report and final plans for MPs 3−17 included two new paired mainline bridges and three new wildlife crossing structures (overpasses) corresponding to the priority sites identified by McKinney and Smith (2007: Table 1).

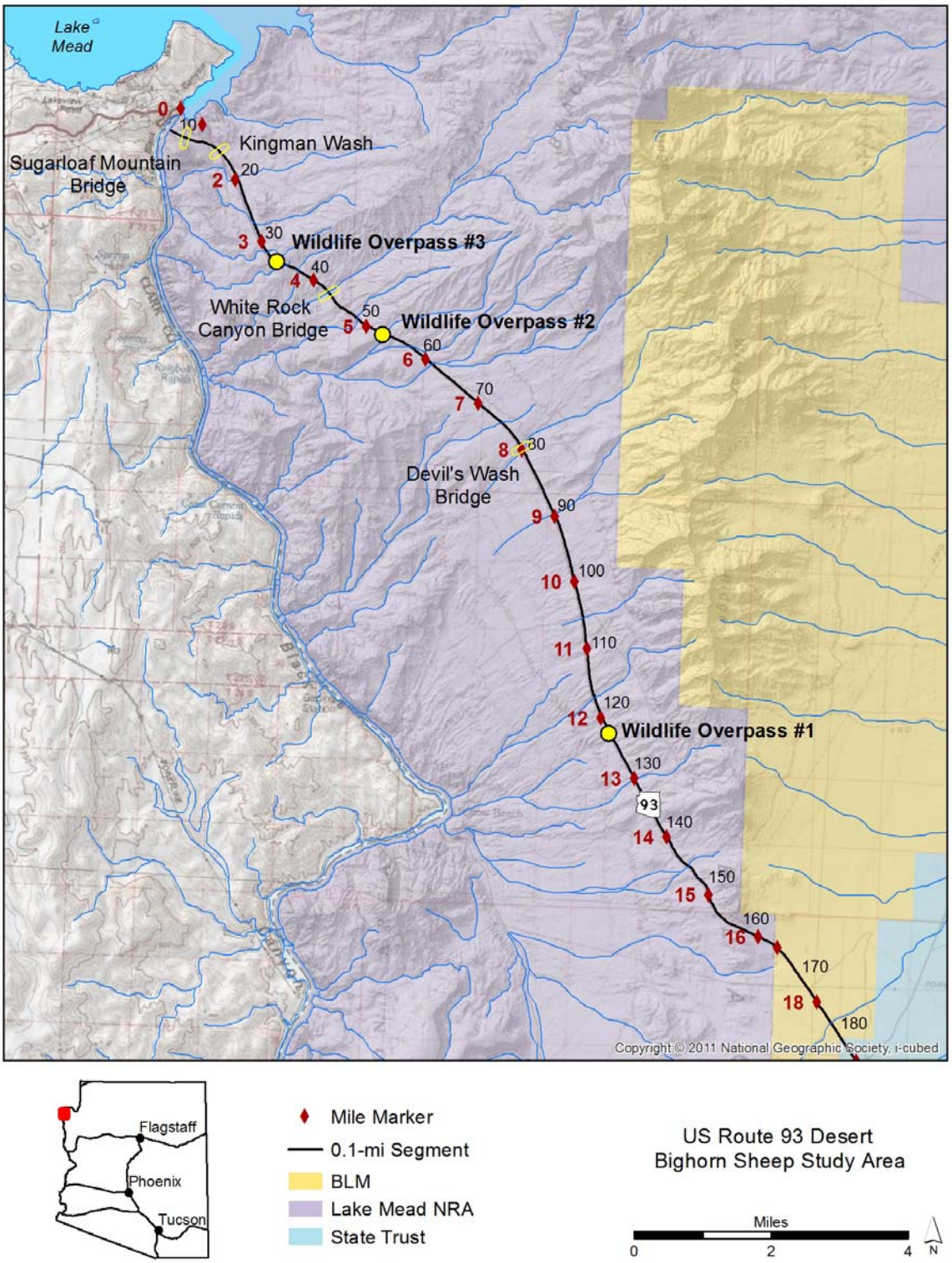


Figure 1. U.S. 93 Study Area Showing Landownership, Mileposts (red numbers), 0.1-mi Segments (black numbers), and Location of Bridges and Wildlife Overpasses.

RESEARCH JUSTIFICATION AND OBJECTIVES

Over the past two decades, various agencies, including ADOT, Reclamation, and FHWA, have been committed to addressing and mitigating the impacts of the U.S. 93 bypass and highway reconstruction on the Black Mountains desert bighorn population; this commitment has included funding extensive desert bighorn research and monitoring (Cunningham and Hanna 1992; McKinney and Smith 2007; Douglas and McMahon 2009) and implementing comprehensive measures to maintain connectivity (FHWA 2001). In fact, the three wildlife overpasses now in place, along with fencing and other measures, represent one of the most aggressive efforts intended to promote desert bighorn connectivity in North America. Given these commitments and innovations associated with the wildlife crossings, it is critical to evaluate—in a rigorous, experimental context—the efficacy of these crossings in promoting desert bighorn highway permeability and population connectivity (Hardy et al. 2003; Roedenbeck et al. 2007). The fact that extensive pre-reconstruction research has been completed facilitates post-reconstruction evaluation under a BACI experimental design (Cunningham and Hanna 1992; Underwood 1994; McKinney and Smith 2007; Roedenbeck et al. 2007). Furthermore, with concerns expressed by Cunningham and Hanna (1992) and McKinney and Smith (2007) and in the project EIS (FHWA 2001) regarding during-reconstruction impacts on desert bighorn, during-reconstruction evaluation is warranted to elucidate the degree to which reconstruction affects critical habitat-use patterns of desert bighorn, especially water demands during the summer and lambing activities during the spring (Cunningham and Hanna 1992).

The research team has advocated assessing wildlife highway permeability under a BACI experimental design measuring permeability to determine the efficacy of measures to promote permeability and connectivity (Dodd, Gagnon, Boe, et al. 2007; Dodd et al. 2007a). Highway passage rates have been consistently calculated by GPS telemetry for five species on five Arizona highways to derive comparable estimates of permeability and to assess traffic impact (Dodd, Gagnon, Boe et al. 2012; Dodd et al. 2011; Dodd and Gagnon 2011; Gagnon, Theimer, Dodd, and Schweinsburg 2007; Gagnon et al. 2010; Gagnon et al. 2011). Unfortunately, the pre-reconstruction assessment of McKinney and Smith (2007) was not designed to yield information sufficient to calculate sheep passage rates and thus provided limited insights into U.S. 93 pre-reconstruction sheep highway permeability. As such, the team's study was structured to collect both pre- and during-reconstruction GPS telemetry data sufficient to calculate sheep passage rates, allowing for comparison of permeability across all reconstruction phases; post-reconstruction evaluation has been ongoing since late 2010. Such a comparison will add to the growing understanding of wildlife-highway relationships and passage structure efficacy amassed from continued studies on additional wildlife species and highways, thereby expanding experimental conditions where permeability has been assessed (Jaeger et al. 2005).

The specific objectives of this U.S. 93 research study include the following:

- Assess and compare pre- and during-reconstruction desert bighorn movements, highway crossing patterns, and distribution and determine permeability across the highway corridor.
- Investigate the spatial and temporal relationships of sheep highway crossing and distribution patterns to traffic volume.
- Investigate spatial and temporal sheep-vehicle collision patterns.
- Assess the impact of U.S. 93 highway reconstruction activities (e.g., blasting, heavy equipment operation) on sheep movements, permeability, and use of critical seasonal habitats and develop mitigation strategies to minimize these impacts on future projects.
- Establish pre- and during-reconstruction desert bighorn movements, highway crossing and passage rates, and sheep-vehicle collision baselines for comparison with a post-reconstruction assessment.

CHAPTER 2. STUDY AREA

U.S. 93 is the primary transportation route between Phoenix, Arizona, and Las Vegas, Nevada, and has been congressionally designated as one leg of the CANAMEX (Canada to Mexico) Trade Corridor along which commercial and noncommercial traffic is projected to increase dramatically in the future. U.S. 93 AADT volumes on the new bridge over the Colorado River as part of the Hoover Dam Bypass project were forecast at 9300 vehicles/day in 1997 and are anticipated to increase by 76 percent to almost 16,400 vehicles/day by 2017 (FHWA 2001). Since mid-October 2010, U.S. 93 traffic has crossed the Colorado River on the new bypass bridge at MP 0 instead of at the Hoover Dam overpass, 70 miles northwest of Kingman, Arizona, and 20 miles southeast of Las Vegas (see Figure 1). The research team's focal study area extended between MP 0 and MP 17 (latitude 35°50′–36°00′N, longitude 114°34′–114°44′W; see Figure 1). Bypass construction between MP 0 and MP 2.2 was largely completed by 2004, though paving was completed in 2010. Active reconstruction activities between MP 2.3 and MP 17 were initiated in April 2009 to widen the existing two-lane highway to a four-lane divided highway with a standard median width (108 ft centerline to centerline; Figure 2). Reconstruction activities were completed and the highway opened to traffic in November 2010.

The U.S. 93 study area cuts through the northern extent of the Black Mountains, while SR 68 bisects the southern extent. Both fragment desert bighorn habitat and population interchange across the Black Mountains bounded by Lake Mead to the north, the Colorado River to the west, and Interstate 40 to the south (Figure 3). Landownership within the study area includes Bureau of Land Management, National Park Service (Lake Mead National Recreation Area), and Reclamation holdings near Hoover Dam (see Figure 1).

Elevations within the study area range from 637 ft at the Colorado River to 4957 ft on Mount Wilson, the dominant physiographic feature within the study area (Figure 4). The topography adjacent to U.S. 93 well suits desert bighorn and includes rugged mountainous terrain with steep talus slopes and cliffs grading into foothills through which ephemeral dry washes cut (Cunningham and Hanna 1992; McKinney and Smith 2007; Figure 4).

Vegetation across the study area is characteristic of the arid and sparse Mohave Desertscrub biotic community (Turner 1994) and is dominated by the creosotebush-bursage association (Figure 4). Along washes where more moisture collects, catclaw acacia, cheesebush, and mesquite are prevalent (Cunningham and Hanna 1992; McKinney and Smith 2007), while range ratany, Mormon tea, and galleta grass occur at the higher elevations (Cunningham and Hanna 1992).

Figure 2. Reconstruction of U.S. 93 (between Mileposts 2.3 and 17) from a Two-lane Highway to Four-lane Divided Highway.

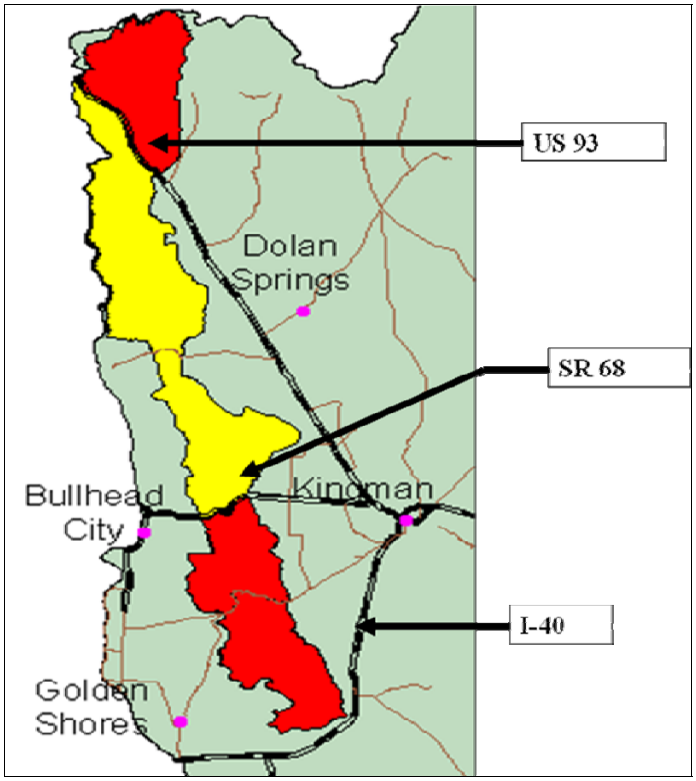


Figure 3. Black Mountains of Northwest Arizona, Which Are Divided into Three Subunits by U.S. 93 and SR 68.

Figure 4. Mountainous Desert Bighorn Habitat within the U.S. 93 Study Area: Rugged Cliff Habitats South of the Highway near Fortification Hill (top) and Mount Wilson and Foothill Habitats North of the Highway (bottom).

The climate during the hot summer months (June–August) has an overwhelmingly pervasive influence on the flora and fauna of the area; average high temperatures at the Willow Beach Recording Station all exceed 105 degrees Fahrenheit (° F) (Figure 5). The annual high and low mean temperatures are 86.8° F and 58.5° F, respectively. Precipitation occurs almost entirely by rainfall and averages 5.6 inches per year. Nearly half the precipitation occurs during January−March and is associated with frontal storms emanating from the Pacific Ocean (Figure 5). Summer precipitation during June is negligible but increases during July−September in the form of scattered thunderstorms (Figure 5).

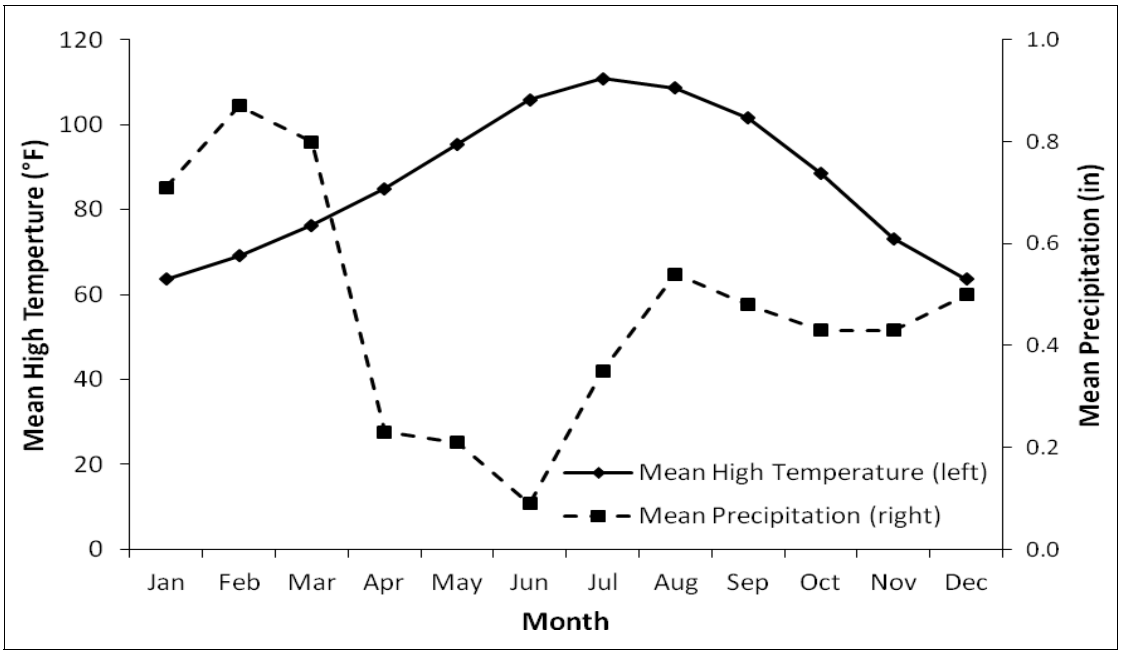


Figure 5. Mean Monthly High Temperatures (left axis) and Precipitation (right axis) Recorded in 1967−2009 at the Willow Beach Recording Station near U.S. 93.

Desert bighorn sheep has been a focal species of concern throughout all planning efforts for the Hoover Dam Bypass and U.S. 93 reconstruction (FHWA 2001). The desert bighorn population adjacent to the study area is a subunit of the largest extant desert bighorn sheep population of the 32 identified populations in Arizona (Figure 3). This population has been estimated to number as many as 2000 animals, though drought conditions caused a 54 percent reduction of the herd from 2001 to 2004 (McKinney and Smith 2007). The desert bighorn population encompassing the Black Mountains accounts for nearly 30 percent of the state's total population, and it has served as an important source herd for numerous sheep reintroductions into historical habitat for the Nelson subspecies (*Ovis canadensis nelsoni*) throughout northern Arizona and Utah. This desert bighorn population provides wildlife viewing opportunities for hikers and tourists in the study area and along the Colorado River, as well as providing permitted recreational hunting opportunities; 15 hunting permits were authorized in 2011.

Other large wildlife residing in the study area include low densities of mule deer and predators including bobcat, coyote, gray fox, and mountain lion. Domestic livestock were absent from the study area, but feral burros were present though uncommon.

The 2009−2010 AADT for U.S. 93, measured at the automatic traffic recorder (ATR) installed at MP 18.0 in late 2008, was 8720 vehicles/day (interpolated to account for data missing for two months—May 2009 and July 2010). This AADT reflected that there had been no commercial truck traffic allowed on this stretch of U.S. 93 to limit the threat to Hoover Dam since the 9/11 terrorist attacks; commercial traffic was rerouted over the Colorado River on SR 68 to the south. There was considerable variation in average traffic volume by month, ranging from 194,562 vehicles/month in January to 324,698 vehicles/month in July at the height of the summer tourist season (Figure 6). There also was considerable variation in traffic by day, with traffic volume on Fridays and Sundays 26 percent higher than on other days (Figure 6). Hourly traffic volume varied considerably from the nighttime low between midnight and 0400 hours averaging only 59 vehicles/hr, to the afternoon peak volumes between noon and 1500 hours of 648 vehicles/hr, or an AADT equivalent (648 vehicles/hr × 24 hr) of 15,552 vehicles/day. The average U.S. 93 AADT-equivalent hourly traffic volume exceeded the 10,000 vehicles/hr threshold at which Seiler (2003) and Iuell et al. (2003) hypothesized highways become impermeable barriers to wildlife between 0900 hours and 1800 hours, or most of the diurnal period when desert bighorn are active. Commercial truck traffic was restored to U.S. 93 once the Hoover Dam Bypass was opened on October 19, 2010. The daily traffic volume for that month jumped 28 percent from an average of 7853 vehicles/day to 10,076 vehicles/day.

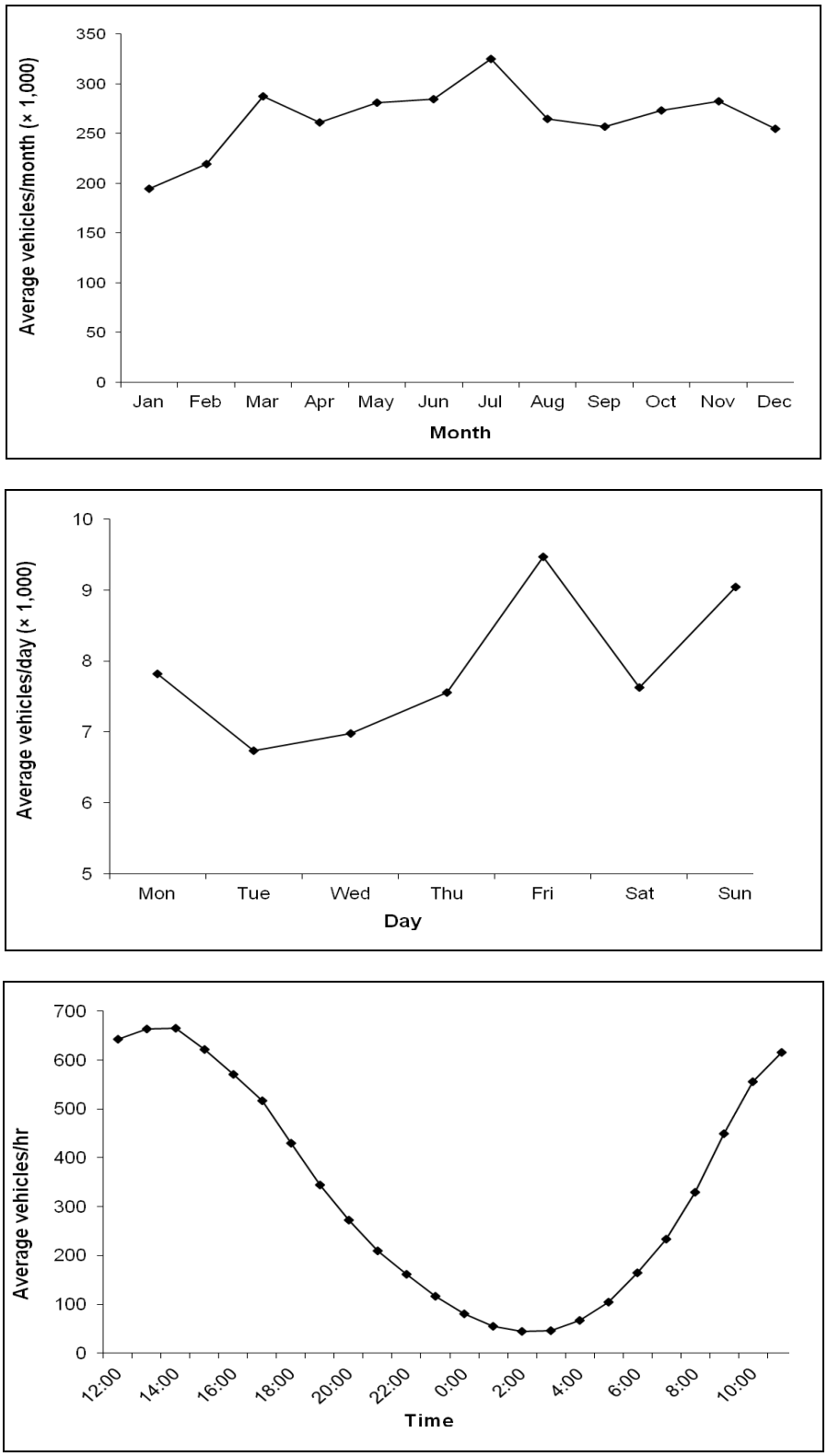


Figure 6. Average U.S. 93 Traffic Volume by Month (top), Day (middle), and Hour (bottom) Determined by the Automatic Traffic Recorder at Milepost 18.0 in 2009–2010.

CHAPTER 3. METHODS

WILDLIFE CAPTURE, GPS TELEMETRY, AND DATA ANALYSIS

Desert Bighorn Sheep Capture

The research team captured desert bighorn using a net gun fired from a helicopter (Firchow et al. 1986; Figure 7). A fixed-wing aircraft and numerous ground spotters using optics equipment were employed during the sheep-searching efforts to minimize helicopter searching. Desert bighorn sheep were captured during the fall (September–November) to minimize heat-related stress on them, as well as deleterious effects on females that could occur if captured later in their pregnancies. The team's capture objectives were to (1) instrument as nearly as possible an equal number of sheep on each side of U.S. 93, (2) spread the collars among as many different herds as possible along the length of the study area, and (3) capture sheep within 5 mi of U.S. 93.

Upon capture, sheep were immediately blindfolded, hobbled, and untangled from the capture net. Sheep were fitted with GPS collars and marked with a numbered, colored ear tag (Figure 7). Basic information about each sheep, such as sex, approximate age, and other characteristics, were recorded. The team instrumented them with GPS satellite uplink receiver collars (Globalstar satellite tracking collars, Model NSG-D; North Star Science and Technology, LLC, King George, VA) programmed to receive seven GPS fixes/day, with one relocation every 2 hr between 0600 hours and 1800 hours; GPS units had a battery life of up to 23 months. All collars had VHF beacons, mortality sensors, and programmed release mechanisms to facilitate recovery.

Figure 7. Capture of Desert Bighorn near U.S. 93, Showing Net Gunning from a Helicopter (left) and Blindfolded Male Sheep Affixed with an Ear Tag and GPS Satellite Collar (right).

GPS Analysis of Desert Bighorn Sheep Movements

Once the researchers recovered the GPS collars and downloaded data, they employed geographic information system (GIS) software (ArcGIS® Version 8.3, ESRI, Redlands, California) to analyze GPS data similar to the analyses of Dodd et al. (2007a) for elk. The team calculated individual minimum convex polygon (MCP) home ranges by connecting the outermost GPS fixes to encompass all fixes (White and Garrott 1990) and assessed differences in means between sexes and reconstruction treatments using *t* tests for independent samples.

Calculation and Analysis of Crossing Rates

The team divided the study area into 180 sequentially numbered 0.1-mi segments corresponding to the units used by ADOT for tracking WVCs and highway maintenance (see Figure 1)—an approach identical to that of Dodd, Gagnon, Boe, et al. (2007). The researchers calculated the number and proportion of GPS fixes within 0.15, 0.30, and 0.60 mi of U.S. 93 for each sheep.

To determine highway crossings, the team drew lines connecting all consecutive GPS fixes and inferred highway crossings where lines between fixes crossed U.S. 93 through a given segment (Dodd, Gagnon, Boe, et al. 2007; Figure 8). The team used Animal Movement ArcView Extension (Version 1.1) software to help determine sheep crossings (Hooge and Eichenlaub 1997). The research team compiled individual sheep crossings by highway segment, date, and time. They calculated crossing rates for individual sheep by dividing the number of crossings by the days a collar was worn.

To account for the number of individual sheep that crossed each U.S. 93 highway segment, as well as evenness in approach frequency among individuals, the research team calculated a Shannon diversity index (SDI; Shannon and Weaver 1949) for each segment using this formula:

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

To calculate SDI (or H') for each highway segment, the researchers calculated and summed all $-(p_i \ln p_i)$ for each animal that crossed in the segment, where each p_i is defined as the number of crossings by individual collared sheep within each segment divided by the total number of respective crossings in the segment. The team used SDI to calculate weighted crossing frequency estimates for each segment, multiplying uncorrected crossing frequency by the SDI. Weighted highway crossings better reflect the number of sheep that cross and the equity in distribution among collared sheep (Dodd, Gagnon, Boe, et al. 2007; Dodd et al. 2011).

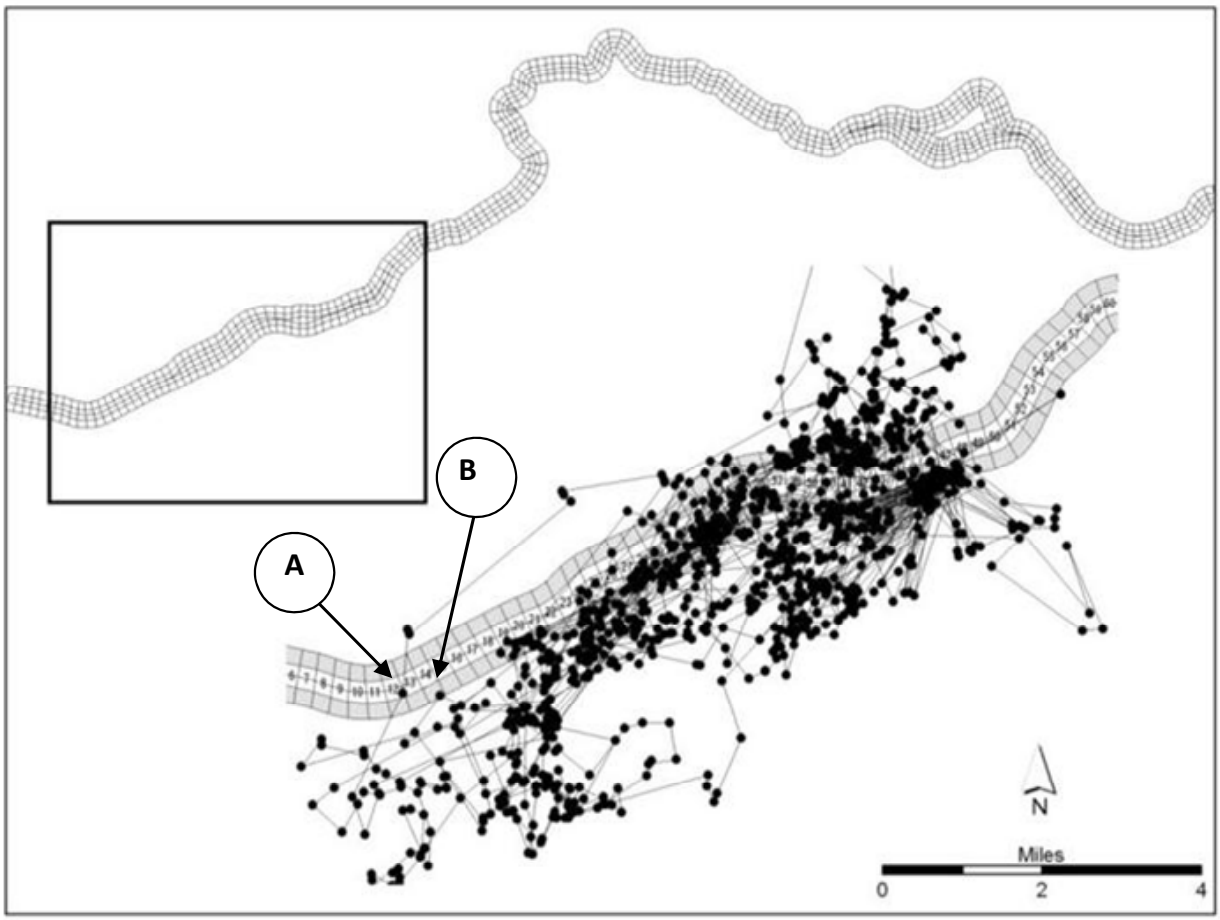


Figure 8. GPS Locations and Lines between Successive Fixes to Determine Highway Approaches and Crossings in 0.1-mi Segments.

(Note: The expanded section shows GPS locations and lines between successive fixes to determine approaches to the highway [shaded band] and crossings. Example A denotes an approach and crossing; Example B denotes an approach without a crossing.)

Though McKinney and Smith (2007) programmed their sheep collars to receive GPS relocations every 5 hr, precluding the calculation of highway passage rates, the research team nonetheless used daily relocation data from their 2007 report to calculate comparable pre-reconstruction sheep crossing rates for 2004 to 2006. The team used analysis of variance (ANOVA) to compare mean sheep crossing rates among these reconstruction-phase classes:

- Pre-reconstruction: 2004−2006 (McKinney and Smith 2007).
- Pre-reconstruction: November 2008−March 2009.
- Combined pre-reconstruction: April 2004−March 2009.
- During-reconstruction: April 2009−October 2010.

Analysis of Spatial Crossing Patterns

The researchers tested the hypothesis that the observed spatial crossing distribution among 0.1-mi segments did not differ from a discrete randomly generated distribution using a Kolmogorov-Smirnov (K-S) test (Clevenger et al. 2001; Dodd et al. 2007a). The team compiled the percentage of sheep crossings made within four stretches of U.S. 93 to compare the distribution within each stretch between pre-reconstruction (both 2008–2009 and 2004–2009) and during-reconstruction phases. The team used chi-square (χ^2) tests to compare observed (during-reconstruction) distributions with expected (pre-reconstruction baseline) distributions of sheep crossings (percentages) within these U.S. 93 stretches:

- MPs 0−2.2: existing highway alignment.
- MPs 2.3−5.0: stretch with Overpass #3.
- MPs 5.1−9.0: stretch with Overpass #2.
- MPs 9.1−18.0: stretch with Overpass #1.

Calculation and Analysis of Passage Rates

The team calculated passage rates for collared sheep, which served as the relative measure of highway permeability, for direct comparison with passage rates determined on other projects throughout Arizona (Dodd, Gagnon, Boe, et al. 2007). An approach was considered to have occurred when an individual sheep traveled from a point outside the 0.15-mi buffer zone to a point within 0.15 mi of U.S. 93, determined by successive GPS fixes (Figure 8). The approach zone corresponded to the road-effect zone associated with traffic-related disturbance (Rost and Bailey 1979; Forman et al. 2003), which was previously used for elk, mule and white-tailed deer, and pronghorn (Dodd et al. 2007a; Dodd, Gagnon, Boe, et al. 2012; Dodd, Gagnon, Sprague et al. 2012; Gagnon et al. 2011). Individual sheep that directly crossed U.S. 93 from a point beyond 0.15 mi were counted as an approach and a crossing. The research team calculated passage rates as the proportion of highway crossings to approaches for those sheep that had at least five approaches to U.S. 93. The research team compared mean sheep highway passage rates between these two reconstruction-phase classes using *t* tests:

- Pre-reconstruction: November 2008−March 2009.
- During-reconstruction: April 2009−October 2010.

Researchers derived values for individual desert bighorn approaching and crossing U.S. 93 and pooled them by reconstruction phase. Researchers tested the null hypothesis that no differences in mean sheep crossing and passage rates existed as a function of highway reconstruction class. Where the team obtained significant ANOVA results among classes for sheep crossing rates, they conducted post hoc pairwise comparisons using a Tukey test for unequal sample sizes (Statsoft Inc. 1994). The researchers applied arcsine transformations to the raw crossing and passage rate data to allow comparison of proportions and ensure normality in the datasets (Neter et al. 1996).

Researchers compared crossing and passage rates at various temporal scales, including time of day, day of week, month, and season. They used 2-hr intervals for comparing crossing and passage rates

corresponding to the GPS relocation interval, and they used the same seasons as those used in other Arizona highway assessments (Dodd, Gagnon, Boe, et al. 2007; Dodd and Gagnon 2011):

- Winter: December−February.
- Spring: March−May.
- Summer: June−August.
- Fall: September−November.

Spring corresponded to the peak Black Mountains desert bighorn population lambing period, and summer corresponded to the peak water demand period along U.S. 93 (Cunningham and Hanna 1992). The researchers used chi-square tests to compare observed versus expected frequencies of sheep crossings by time, day, and month, and they used linear regression to assess the association between mean crossing and passage rates and mean corresponding traffic volume by time, day, and month. The researchers used ANOVA to compare mean crossing and passage rates aggregated by season and used *t* tests to compare mean sheep passage rates between sexes by reconstruction class.

Given the strong reliance on water sources (Cunningham and Hanna 1992), including the Colorado River, during the summer months, the research team assessed the association between water sources and sheep highway passage rates. In addition to comparing seasonal passage rates, the team also used linear regression to assess the association between mean monthly sheep highway passage rates and the mean monthly high temperature and precipitation. In addition, the research team addressed spatial association by aggregating sheep highway approaches and crossings into six sequential 0.6-mi (1.0 km) distance classes based on the distance of 0.1-mi highway segments from the Colorado River. Passage rates were derived for each class ranging from 0−0.6 mi to 3.2−3.7 mi, and rates for all locations farther than 3.7 mi from the river were combined. The research team used linear regression to assess the association between mean highway passage rates and distance from the river (using class midpoints).

TRAFFIC AND DESERT BIGHORN SHEEP DISTRIBUTION RELATIONSHIPS

The research team measured traffic volume using a permanent ATR programmed to record hourly traffic volumes. ADOT's Multimodal Planning Division Data Team provided data collected from an ATR installed near the southern end of the study area in 2008 (MP 18.0).

The researchers examined how the proportion of desert bighorn GPS fixes at different distances from the highway varied with traffic volume by calculating the proportion of fixes in each 330-ft distance band, out to a maximum of 1980 ft. As was done in other Arizona highway-permeability studies for other species, the researchers combined traffic and GPS data by assigning traffic volumes for the previous hour to each GPS location using ArcGIS Version 9.1 software and Microsoft Excel® spreadsheets (Gagnon, Theimer, Dodd, and Schweinsburg 2007). This allowed them to correlate the traffic volume each animal experienced in the hour before movement to a particular point within 1980 ft of the road, regardless of distance traveled. To avoid bias due to differences in the number of fixes for individual animals, the proportion of fixes occurring in each distance band for each sheep was used as the sample

unit rather than total fixes. The team calculated a mean proportion of fixes for all animals within each 330-ft distance band from U.S. 93 at nine sequential 100-vehicle/hr traffic volume classes between 0−100 and 901−1000 vehicles/hr (Gagnon, Theimer, Dodd, and Schweinsburg 2007).

Researchers also used linear regression to examine the association between traffic volume and mean sheep highway crossings and passage rates by month, day, and hour.

CONSTRUCTION DISTURBANCE IMPACT ON DESERT BIGHORN SHEEP

In addition to the comparisons of mean pre- and during-reconstruction sheep highway crossing and passage rates and spatial crossing distributions, researchers addressed reconstruction-related impacts on U.S. 93 desert bighorn in several manners.

Desert Bighorn Sheep Distribution by Construction Disturbance Class

First, the team assessed the probability that desert bighorn GPS relocations occurred within 330-ft distance bands outward from U.S. 93 to 1980 ft in association with four general reconstruction disturbance classes (Figure 9 is a good example of high disturbance):

- No disturbance: construction finished or idle.
- Low-moderate: fence and guardrail installation and bridge construction.
- High: roadway alignment work and heavy-equipment operation.
- Very high: blasting.

Figure 9. Male Desert Bighorn Sheep Adjacent to U.S. 93 during Highway Reconstruction.
(Photo courtesy of FNF Construction)

Researchers used chi-square tests to compare observed versus expected (no-disturbance baseline) probabilities of sheep GPS relocations occurring within aggregated distance bands (0–330 ft; 331–990 ft; 991–1320 ft; 1321–1980 ft) for the various reconstruction disturbance levels; for analysis, the team converted probabilities to percentages.

Female Desert Bighorn Distribution during Peak Lambing Period

Due to concerns that highway construction-related disturbance could limit or alter female sheep access to traditional lambing sites (Cunningham and Hanna 1992), the research team compared its distribution of female GPS relocations during the spring lambing period (March−May) to those determined from similar data gathered during the study by McKinney and Smith (2007); the team's study did not cover

the pre-reconstruction spring period. The proportion of relocations for those females for which at least 10 percent of all spring relocations occurred within 0.6 mi (1 km) of U.S. 93 were calculated for three distance bands from U.S. 93: 0–0.3 mi, 0.3–0.6 mi, and 0.6–1.2 mi. The researchers used chi-square tests to compare observed (during-reconstruction) female distribution versus expected female distribution (pre-reconstruction baseline [McKinney and Smith 2007]). The team also used a *t* test to compare the mean distances from U.S. 93 for females during the lambing period.

Blasting Disturbance Analysis

Blasting created the highest degree of potential disturbance that could limit or alter sheep access to traditional lambing sites and critical water sources (Cunningham and Hanna 1992). Between September 2009 and May 2010 (230 days), 38 blasting events occurred predominantly at four sites: MP 3.4 (21 blasts averaging 6867 lb of explosive/blast), MP 8.0 (5 blasts averaging 18,653 lb/blast), MP 12.2 (6 blasts averaging 11,372 lb/blast), and MP 16.5 (3 blasts averaging 13,746 lb/blast). Blasting periods ranged from 13 (MP 16.5) to 107 days (MP 3.4), with an average of 6.1 days between blasting periods. The team's analysis of blasting impacts on desert bighorn focused on blasting events at the MP 3.4 and MP 8.0 sites, which accounted for over three-quarters of all blasts and affected the core study area.

The research team compared the mean difference in desert bighorn GPS daily minimum relocation distances on the day before and day after blasting within several distance bands from the blasting sites—0−2 mi, 2−3 mi, 3−4 mi, 4−5 mi, and >5 mi—the team used *t* tests to determine the significance of the differences for each distance band. The research team compared the proportions of sheep GPS relocations occurring within 0.6-mi distance bands out to 4.2 mi from U.S. 93, and for 4.2−6.0 mi combined, on the day before and day after blasting. the research team used chi-square tests to compare the expected (day before) distribution to observed (day after) distribution of relocation proportions. For both analyses, the team compared desert bighorn relocation differences from the blast sites and proportions of relocations within distance bands with similar "control" GPS relocation data recorded one year prior at MP 3.4 and six months prior at MP 8.0 (no GPS-collared animals were present here before then); comparisons between blasting period and control data were accomplished with *t* testing and chi-square testing.

To assess the potential for a delayed impact from blasting on desert bighorn sheep, researchers assessed the mean daily minimum distance from blast sites over a period of a week following blasting using GPS relocations. The team also assessed potential cumulative impacts from repeated blasting at the sites by computing the mean minimum daily distance from blast sites by the number of days that a blast occurred after the prior blast event. The team used linear regression to assess the association between distances from blast sites by days after blasting and days that a blast occurred after the prior blast event.

DESERT BIGHORN SHEEP–VEHICLE COLLISION RELATIONSHIPS

Previous studies have documented WVC incidences involving desert bighorn along U.S. 93 and have identified such incidences as a concern regarding the sheep population (Cunningham and Hanna 1992; Figure 10). This current study used two methods to document the incidence of sheep-vehicle collisions. First, the research team relied on forms submitted by agency personnel, primarily Department of Public Safety highway patrol officers and ADOT maintenance personnel, to determine the incidence of collisions during the study. Second, the team augmented these agency-submitted records by conducting regular searches of the highway corridor for evidence of WVCs.

Figure 10. Male Desert Bighorn Killed in a Sheep-Vehicle Collision along U.S. 93.

The database compiled from the consolidated (nonduplicate) records included the date, time, and location (to the nearest 0.1 mi) of the sheep-vehicle collisions, sex of the individual sheep involved (where known), and the reporting agency. The research team compiled and summarized the WVC records by year.

CHAPTER 4. RESULTS

WILDLIFE CAPTURE, GPS TELEMETRY, AND DATA ANALYSIS

Desert Bighorn Sheep Capture and Movements

The research team used helicopter net gunning to capture desert bighorn along U.S. 93 on two occasions. The initial capture occurred on November 7–8, 2008, during which 29 sheep (13 females and 16 males) were caught and fitted with GPS collars. A follow-up capture occurred on September 30, 2009, to redeploy recovered collars, during which 1 female and 8 males were captured and fitted with GPS collars. GPS collars were affixed to desert bighorn for an average of 419.0 days (±39.5 standard error [SE]) spanning both pre- and during-reconstruction phases (Table 2). The 38 sheep GPS collars accrued 137,195 GPS fixes (Figure 11) for a mean of 3429.9 fixes/sheep (±243.6); 15.9 percent (547.1 fixes/sheep ±84.7) were recorded within 0.6 mi of U.S. 93, and 7.4 percent (252.2 fixes/sheep ±41.9) were within 0.15 mi of the highway. Desert bighorn traveled an average of 624.0 ft (±26.3) between GPS relocations, with no difference in the distance traveled by female (605.6 ft ±23.0) and male (679.2 ft ±33.3) sheep. Desert bighorn MCP home ranges averaged 36.2 mi^2 (±5.4); mean male home ranges (48.9 mi^2 ±7.9) were nearly three times larger than female home ranges (17.2 mi^2 ±2.4; t = 3.19, df = 38, P = 0.003). The research team found no difference between pre- reconstruction (22.2 mi^2 ±5.3) and during-reconstruction (28.5 mi^2 ±4.2) mean MCP home ranges (P = 0.350).

Highway Crossing Frequencies and Rates

Collared sheep crossed U.S. 93 340 times, 77 times before reconstruction commenced and 263 times during reconstruction (Table 2; Figures 12 and 13). Only 12 of the 28 collared sheep (42.9 percent) crossed U.S. 93 during the pre-reconstruction phase, ranging from 1 to 26 crossings and averaging 2.8 crossing/sheep (±1.1; Table 2). Nearly half (16) of the 33 sheep collared during reconstruction crossed the highway a range of 1–81 times, averaging 8.0 crossings/sheep (±3.2; Table 2). Researchers found no differences between female crossings/sheep (3.3 ±2.2) and male crossings/sheep (2.3 ±1.4) before reconstruction or between female crossings/sheep (10.8 ±7.9) and male crossings/sheep (6.3 ±4.2) during reconstruction.

Though the research team recorded more during- reconstruction than pre-reconstruction sheep crossings of U.S. 93, the mean crossing rates did not differ between the phases—0.03 (±0.02) crossings/day during reconstruction versus 0.02 (±0.01) crossings/day before reconstruction (Table 2). Furthermore, as shown in Table 2, the team's mean pre- and during-reconstruction sheep crossing rates did not differ from the mean crossings/day rate (0.02 ±0.02) determined from pre-reconstruction data (McKinney and Smith 2007).

Table 2. Comparison of Highway Crossing Frequencies, Mean Crossing Rates, and Mean Passage Rates for GPS-collared Desert Bighorn Sheep across U.S. 93 Highway Reconstruction Phases.

	Research Phase			
Parameter	**Pre-reconstruction (2004–2006)**	**Pre-reconstruction (2008–2009)**	**Combined Pre-reconstruction (2004–2009)[a]**	**During Reconstruction (2009–2010)**
No. of collared desert bighorn	34	28	62	33
No. of highway crossings	377	77	454	263
Mean days desert bighorn collared (±SE)	507.8 (±40.2)	129.8 (±6.6)	337.0 (±21.6)	289.2 (±32.9)
Mean crossings/desert bighorn (±SE)	11.1 (±3.6)	2.8 (±1.1)	7.3 (±2.6)	8.0 (±3.2)
Mean crossing rate (crossings/day) (±SE)	0.02 (±0.02) A	0.02 (±0.01) A	0.02 (±0.02) A	0.03 (±0.02) A
Mean passage rate (crossings/approach) (±SE)	N/A	0.07 (±0.03) A	N/A	0.07 (±0.02) A
No. of collared desert bighorn approaching highway (for passage rate calculation)	N/A	22	N/A	28

Note: Letter "A" denotes differences among crossing and passage rate means by reconstruction phase from ANOVA.
[a] Data from McKinney and Smith's (2007) study.

Spatial Crossing Patterns

Researchers calculated SDI-weighted crossings reflecting the number of different sheep crossing at the 0.1-mi segments and equity in their crossing frequency (Figures 12 and 13). The team found that before reconstruction (2008−2009), 12 different desert bighorn sheep crossed at 36 U.S. 93 segments, with an average of 1.4 different sheep crossing/segment (range = 1−3). As such, total weighted crossings (33.4) actually were lower than uncorrected crossings (77), particularly between MP 0 and MP 2.2 (Figure 12). Conversely, when the team combined its pre-reconstruction sheep crossing data with crossing data from McKinney and Smith (2007), weighted crossings increased threefold over uncorrected crossings (Figure 14); an average of 2.9 different sheep (range = 1−8) crossed at each of 72 segments. The combined pre-reconstruction weighted crossing distribution underscored the basis of the recommendation by McKinney and Smith (2007)for passage structures at MP 3.3 and MP 5.1 (Figure 14). The 16 sheep that crossed U.S. 93 during reconstruction crossed at 52 different 0.1-mi segments, with an average of 2.2 different sheep crossing/segment; total weighted crossings (254.5) differed little from uncorrected crossings (263). Weighted crossings between MP 0 and 2.2, where an average of 3.4 different sheep crossed/segment, increased 16.9 percent (Figure 13), while weighted crossings between MP 9.0 and 18.0 were 78.5 percent lower than uncorrected crossings, owing to all but two crossings having been made by a single sheep (Figure 13).

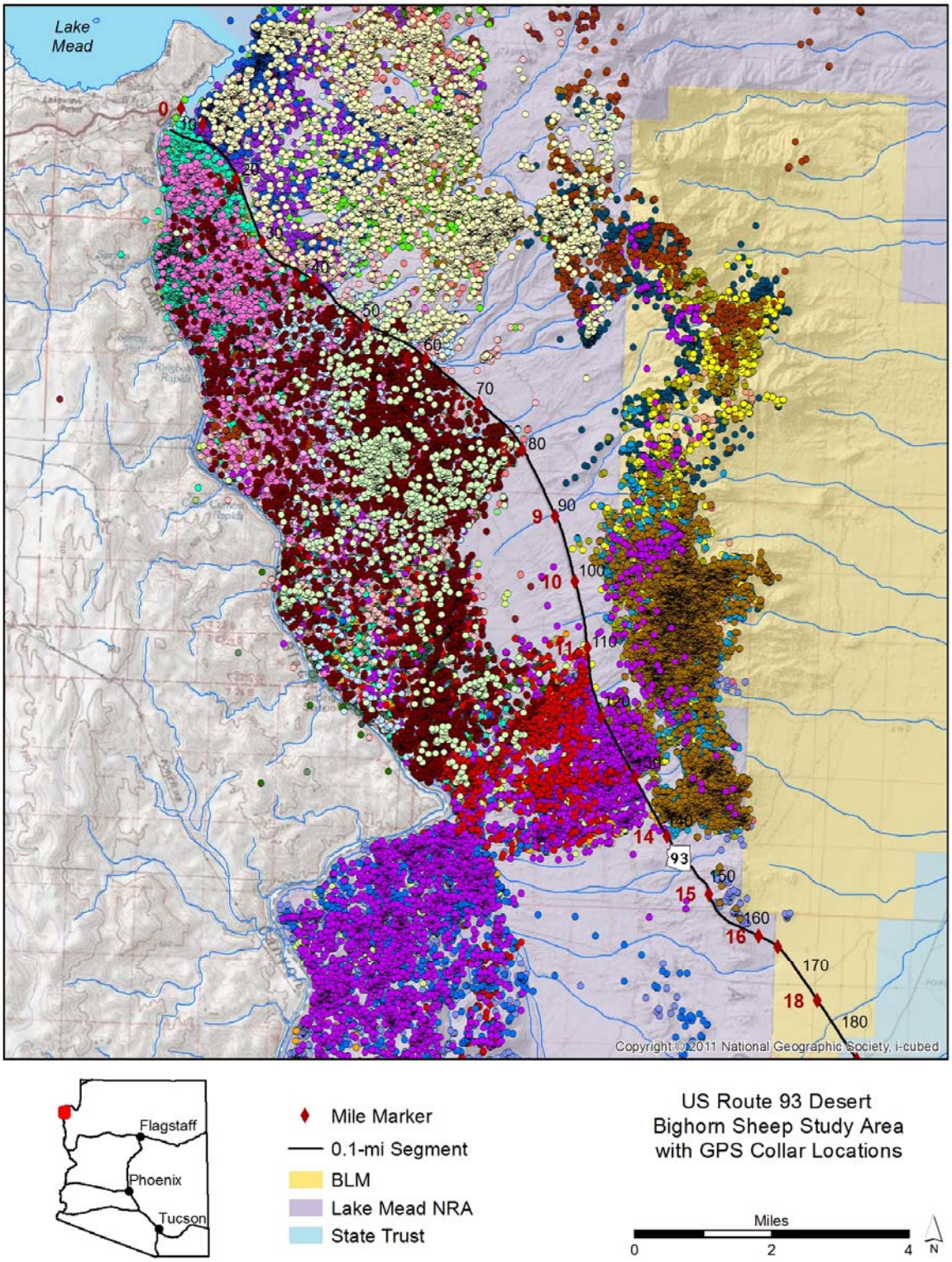


Figure 11. Distribution of GPS Relocations for Individual Desert Bighorn Sheep Collared along U.S. 93 between 2008 and 2010.

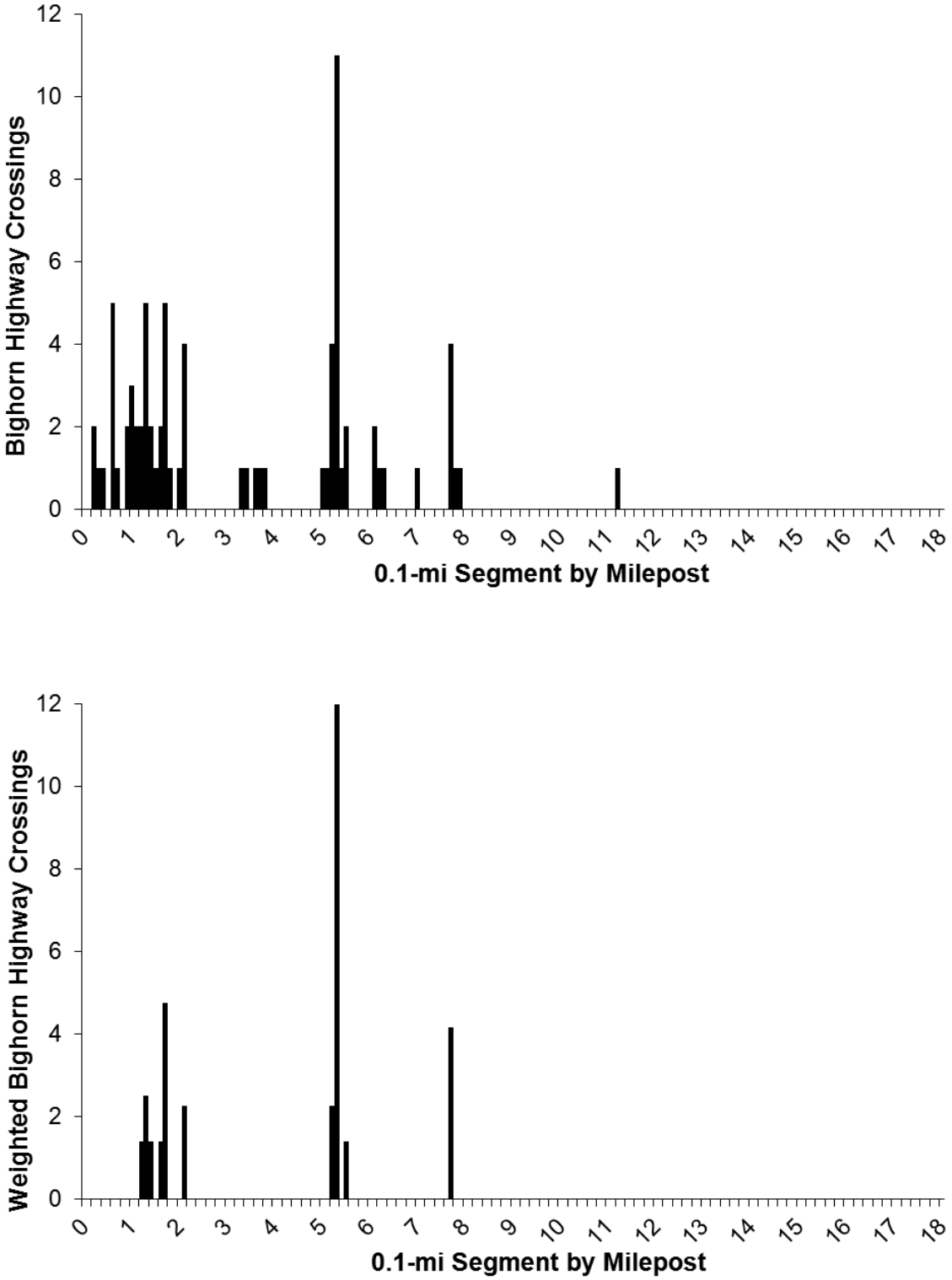


Figure 12. U.S. 93 2008–2009 Pre-reconstruction Desert Bighorn Sheep Highway Crossings (top) and Weighted Highway Crossings (bottom) by 0.1-mi Segment.

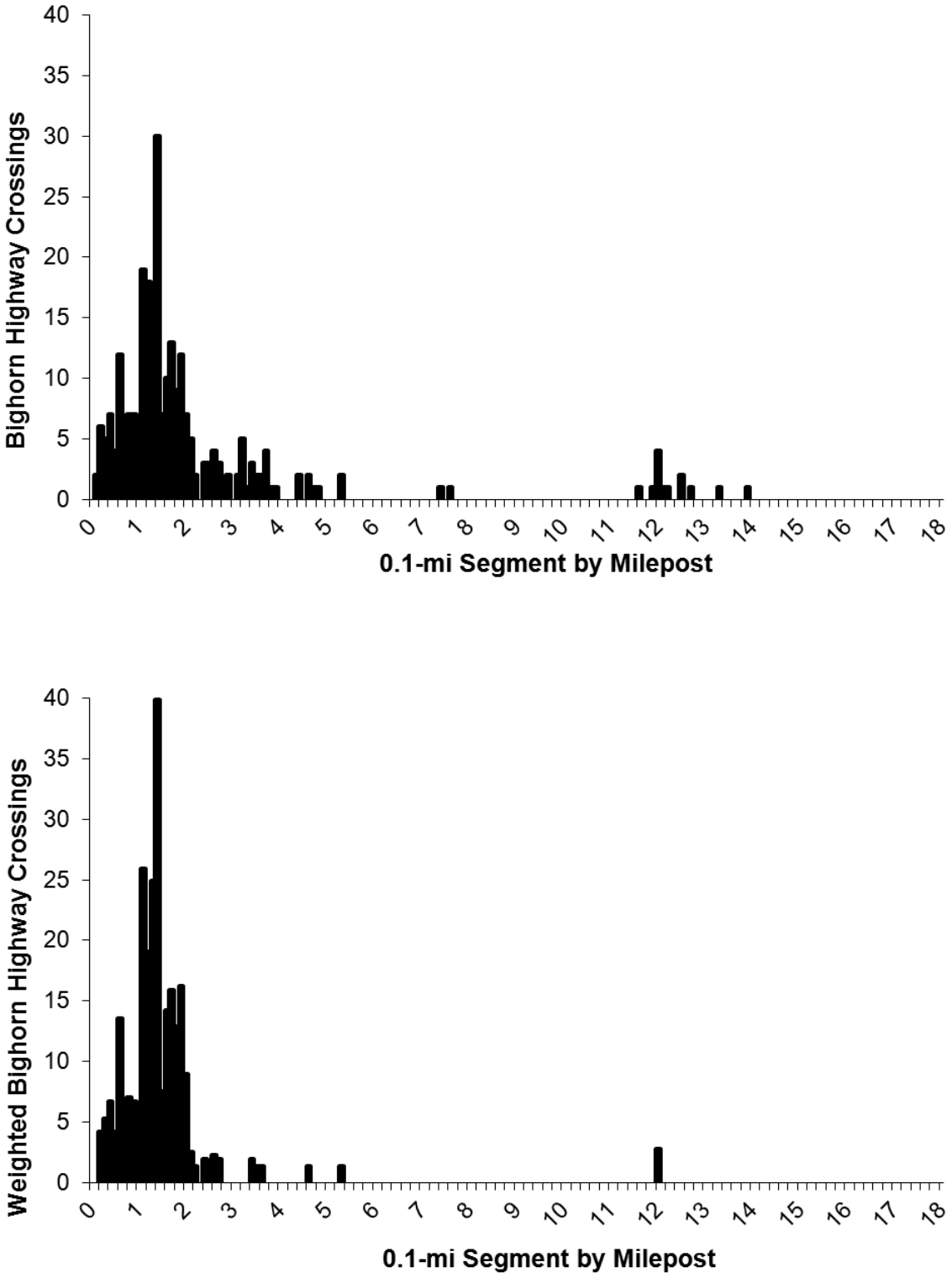
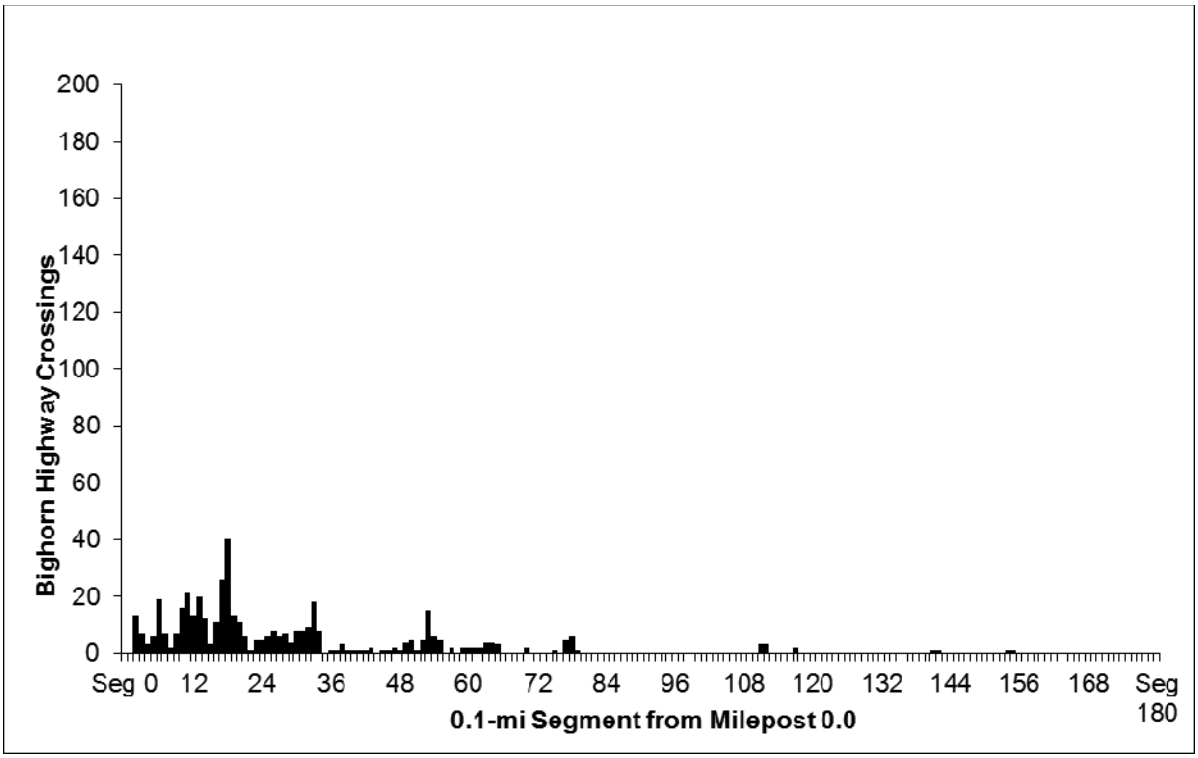


Figure 13. U.S. 93 2009–2010 During-reconstruction Desert Bighorn Sheep Highway Crossings (top) and Weighted Highway Crossings (bottom) by 0.1-mi Segment.



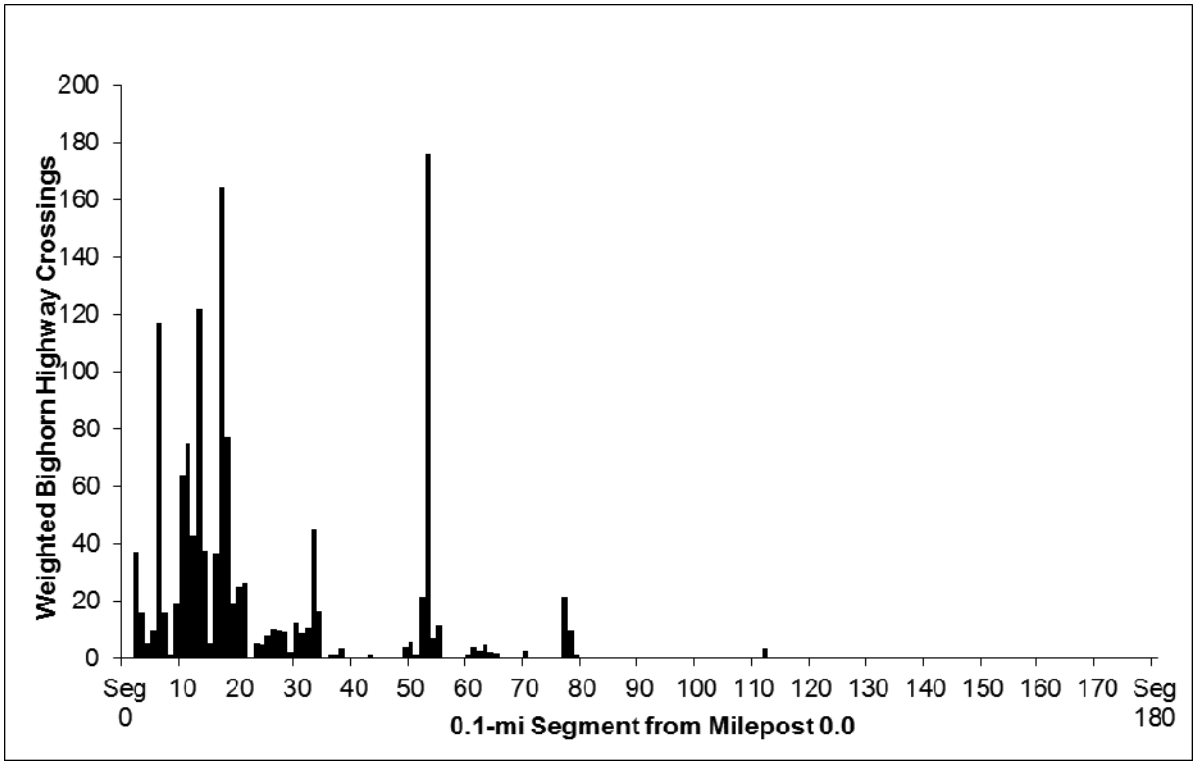


Figure 14. U.S. 93 Combined 2004–2009 Pre-reconstruction Desert Bighorn Sheep Highway Crossings (top) and Weighted Highway Crossings (bottom) by 0.1-mi Segment.

The distribution of sheep crossings among U.S. 93 0.1-mi segments did not occur in a random manner in either the pre-reconstruction phase (K-S test; $d = 0.027$; $P < 0.05$) or the during-reconstruction phase (K-S test; $d = 0.052$; $P < 0.005$) (Figures 12 and 13). Researchers found that a disproportionate frequency of all sheep highway crossings occurred within the stretch of U.S. 93 between MP 0 and 2.2; 51.9 percent before reconstruction and 77.6 percent during reconstruction (Table 3; Figures 12 and 13). The team's pre-reconstruction percentage of sheep crossings in this location was comparable to the percentage of pre-reconstruction crossings (57.6 percent) reported by McKinney and Smith (2007). However, for highway stretches between MP 2.3 and MP 5.0 and between MP 5.1 and MP 9.0, there were dramatic differences in the crossing distribution by reconstruction class (Table 3). The team determined that a considerably higher percentage of sheep crossings occurred between MP 5.1 and 9.0 before reconstruction (40.3 percent) compared to during reconstruction (1.5 percent) (Table 3); there was a large peak in pre-reconstruction highway crossings near the new wildlife underpass at MP 5.1, with 23.4 percent of all crossings between MP 5.0 and 5.4 (Figure 12). The spatial distribution of during-reconstruction crossings differed from both the 2008–2009 pre-reconstruction crossings—especially with the 97 percent drop in crossings between MP 5.1 MP 9.0 during reconstruction ($\chi^2 = 68.7$, df = 3, $P < 0.001$)—and the combined 2004-2009 crossings ($\chi^2 = 25.7$, df = 3, $P < 0.001$; Table 3; Figure 15).

Temporal Crossing Patterns

Researchers found considerable seasonal variation in sheep crossing frequencies by month, day, and time (Figure 16). The monthly crossing frequency exhibited three peaks (Figure 16), and the observed frequency differed from the expected frequency ($\chi^2 = 60.0$, df = 11, $P < 0.001$). The lowest crossing peak occurred in March, which corresponded to the lambing period; an intermediate peak occurred in July, which corresponded to the period of highest water demand; and the highest peak occurred in October, which corresponded to the peak in the sheep breeding season (Figure 16). The relative degree of these peaks, especially those tied to the lambing and breeding periods, was likely influenced by the team's disproportionate sample of GPS-collared male (24) versus female (14) desert bighorn. Since a peak crossing month occurred in each of the three separate seasons when individual months were aggregated, the research team did not find a significant difference among seasonal crossing means by ANOVA; the highest frequency of crossings (34.7 ±6.7) occurred in fall during the breeding season (Table 4).The team found that sheep crossing frequency was lowest on Fridays and Sundays, peak weekend traffic days likely tied to Las Vegas tourist travel; however, the difference in expected versus actual crossings by day was marginally not significant ($\chi^2 = 11.7$, df = 6, $P = 0.068$; Figure 16). Observed crossing frequency by time differed from the expected frequency ($\chi^2 = 36.6$, df = 6, $P < 0.001$). Most of the sheep crossings (60 percent) occurred in the 6-hr block between 0500 hours and 1100 hours; relatively few crossings occurred in the afternoon after 1500 hours, when traffic volume was high. This time of day also coincided with high temperatures during summer (Figure 16).

Table 3. Percentage of Desert Bighorn Sheep Crossings of U.S. 93 within Milepost Stretches by Reconstruction Phase.

	Percentage of All Highway Crossings by Reconstruction Phase			
U.S. 93 MP Stretch (length)	Pre-reconstruction (2004–2006)[a]	Pre-reconstruction (2008–2009)	Combined Pre-reconstruction (2004–2009)	During Reconstruction (2009–2010)[b]
0–2.2 (2.2 mi)	57.6	51.9	56.6	77.6
2.3–5.0 (2.7 mi)	29.4	7.8	25.8	16.0
5.1–9.0 (3.9 mi)	10.1	40.3	15.0	1.5
9.1–18.0 (8.9 mi)	2.9	1.3	2.6	4.9

[a] Data from McKinney and Smith's study (2007).
[b] During-reconstruction crossings differed from the 2008–2009 pre-reconstruction crossings (χ^2 = 68.7, df = 3, P < 0.001) and the combined 2004–2009 pre-reconstruction crossings (χ^2 = 25.7, df = 3, P < 0.001).

Table 4. Comparison of Mean U.S. 93 Desert Bighorn Sheep Highway Crossing Frequency and Passage Rates by Season.

Season	Months	No. of Collared Sheep	Mean No. of Crossings (±SE)	Mean Passage Rate (crossings/approach) (±SE)[a]
Spring	Mar–May	26	21.3 (±3.3)	0.10 (±0.02)
			A	A
Summer	Jun–Aug	10	28.3 (±5.5)	0.25 (±0.08)
			A	B
Fall	Sept–Nov	14	34.7 (±6.7)	0.19 (±0.07)
			A	A, B
Winter	Dec–Feb	25	18.8 (±9.7)	0.08 (±0.03)
			A	A

Note: Letters "A" and "B" denote differences among means by season.
[a] Seasonal passage rates differed by season (ANOVA $F_{3,70}$ = 2.81, P = 0.046).

Passage Rates

The desert bighorn passage rate across the U.S. 93 highway reconstruction corridor between MP 2.3 and MP 17.0 averaged just 0.07 crossings/approach during both pre- reconstruction and during-reconstruction phases (N = 33; Table 2). For sheep that crossed U.S. 93, the mean individual passage rates ranged from 0.01 to 0.47 before reconstruction and 0.06 to 0.52 during reconstruction. Regarding male versus female passage rate comparisons, the overall passage rate for males (0.09 crossings/approach ±0.03) was higher than that for females (0.03 crossings/approach) but was not considered significant (P = 0.082). Only pre-reconstruction male passage rates (0.11 crossings/approach) were significantly higher than female passage rates (0.00 crossings/approach; t_{20} = -2.37, P = 0.028). There was no difference in the overall mean passage rates between male and female desert bighorn (0.07 crossings/approach).

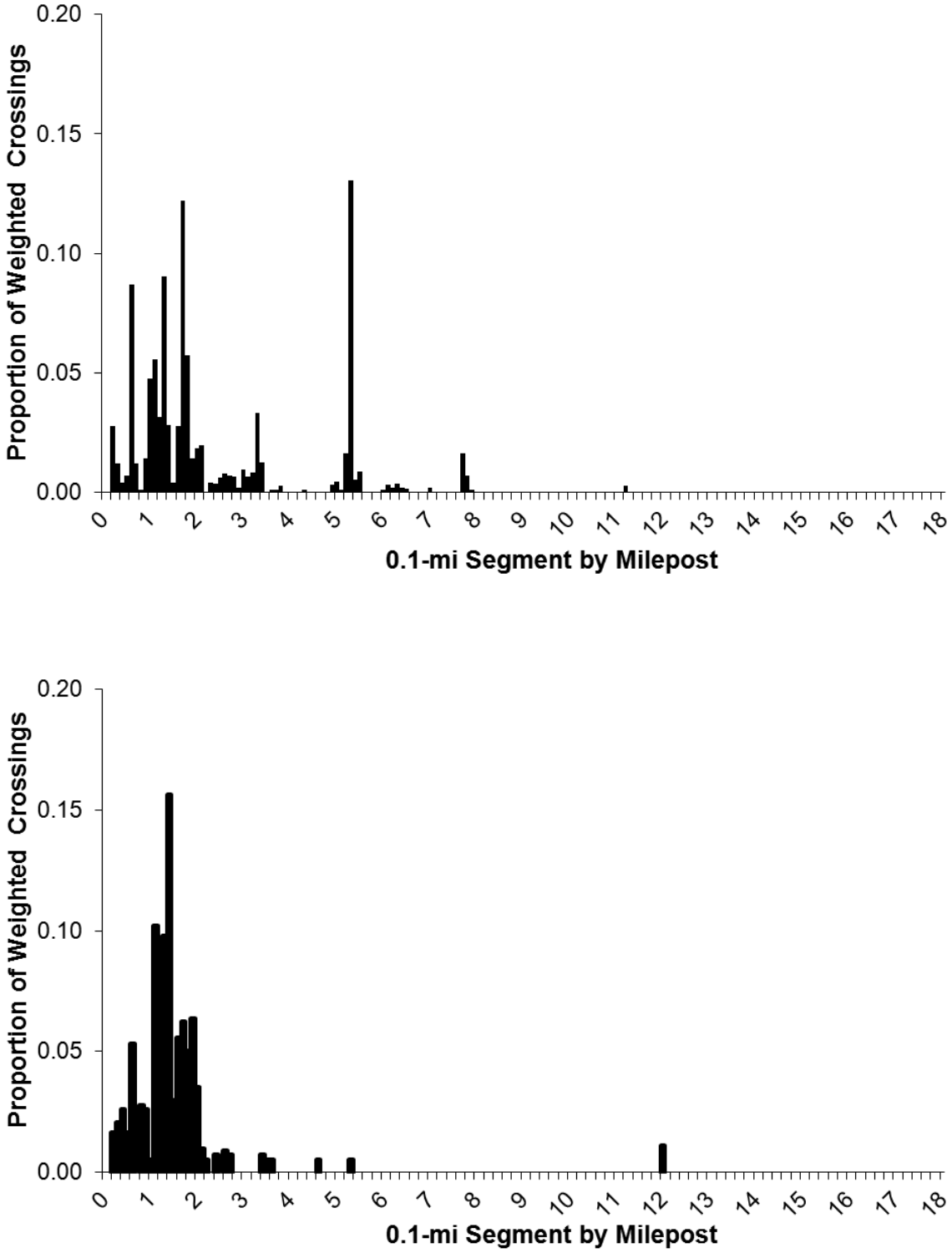


Figure 15. Proportion of U.S. 93 Combined Pre-reconstruction (top) and During-reconstruction (bottom) Weighted Desert Bighorn Sheep Highway Crossings by 0.1-mile Segment.

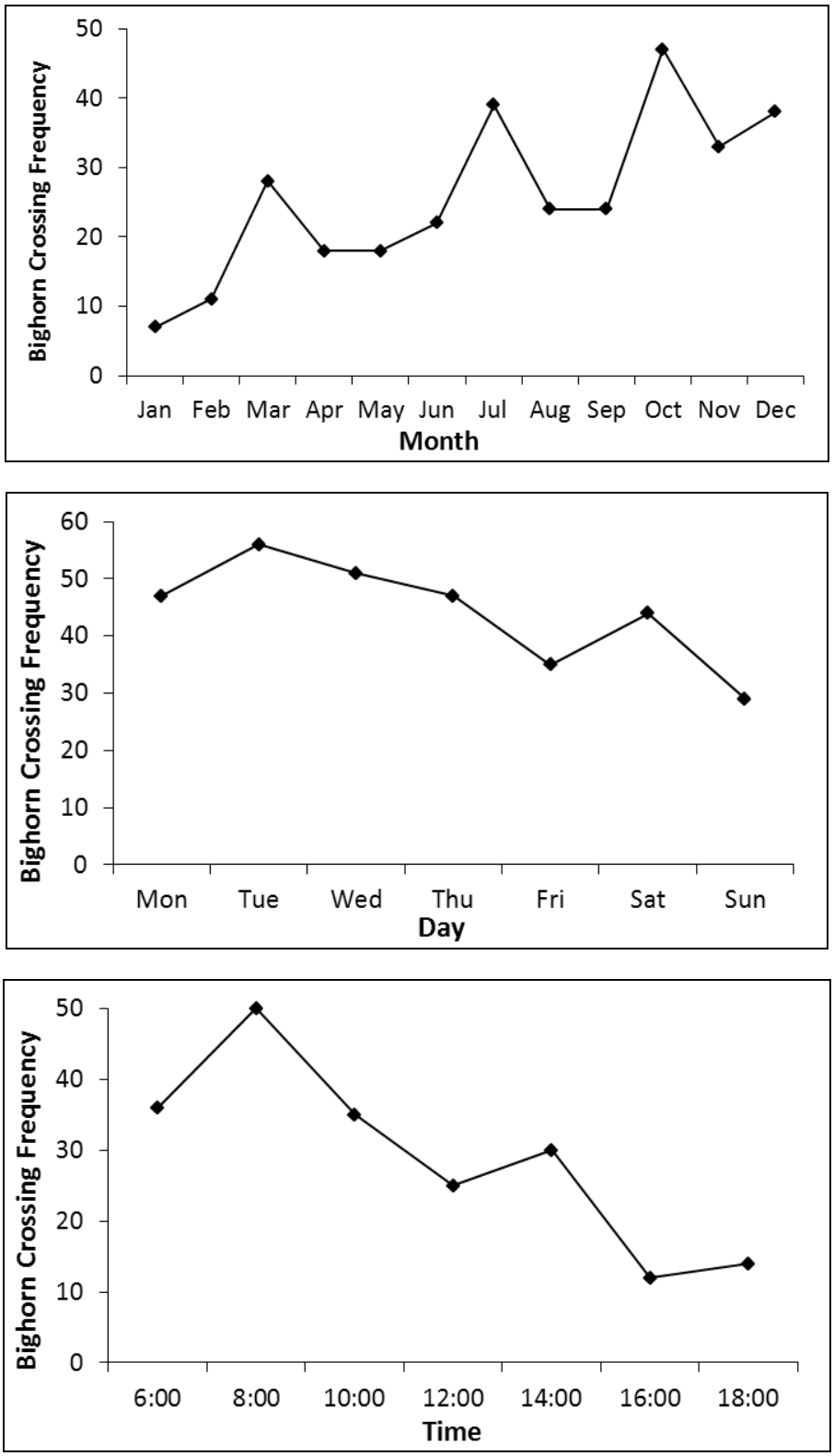


Figure 16. Mean Desert Bighorn Sheep U.S. 93 Crossing Frequencies by Month (top), Day (middle), and Time (2-hr block midpoints; bottom)

Along the stretch of U.S. 93 between Hoover Dam (MP 0) and MP 2.2 where a preponderance of sheep crossings occurred (Table 3), the team found a considerably higher mean passage rate, 0.31 crossing/approach (±0.06), than on the stretch of U.S. 93 under reconstruction between MP 2.3 and MP 17.0. Here, passage rates for sheep that crossed the highway (n = 8) ranged from 0.03 to 0.61 crossings/approach and averaged 0.07 crossings/approach.

Temporal Passage Rate Patterns

Researchers found that mean sheep passage rates varied considerably by month, ranging from 0.02 crossings/approach (January) to 0.38 crossings/approach (July), with large peaks in July and September corresponding to the period of highest temperatures and highest water demand (Figure 17). In fact, temperature accounted for 47 percent of the variation in mean desert bighorn passage rates determined from the team's regression analysis (r = 0.684, r^2 = 0.468, P = 0.014, n = 12; Figure 18). While August exhibited high daily temperatures similar to July and September, the 45 percent drop in the mean passage rate from that recorded in July likely reflects the peak in monthly summer precipitation in August (Figure 18), which increased water availability in washes and tinajas (rocky depressions that hold water), thereby reducing the compelling need for desert bighorn to cross U.S. 93 in pursuit of permanent water.

In aggregating desert bighorn passage rates by season, the research team found significant differences among seasonal means (ANOVA $F_{3,70}$ = 2.81, P = 0.046; Table 4). The mean summer passage rate (0.25 crossings/approach) was higher than those for spring (0.10 crossing/approach, P = 0.029) and winter (0.08 crossing/approach , P = 0.017), and the mean fall passage rate did not differ significantly from other seasons based on the statistical test. The higher summer passage rate reflects that increased water demand is a driving factor in the sheep's crossing U.S. 93 to find permanent water sources.

The research team noted a slight increase in mean sheep passage rates on Tuesdays (Figure 17), when traffic volume was at its lowest level (see Figure 6). Sheep passage rates during the day were relatively consistent, with the exception of between 1500 hours and 1700 hours when there was a sharp drop in the passage rate (Figure 17).

Spatial Passage Rate Patterns

When researchers addressed sheep passage rates between MP 2.3 and MP 18.0 as a function of increasing distance from the Colorado River, they found a strong association—the shorter the distance, the higher the passage rate (r = -0.835, r^2 = 0.697, P = 0.019, n = 7; Table 5). This further underscores the role that proximity to permanent water plays in sheep passage across U.S. 93.

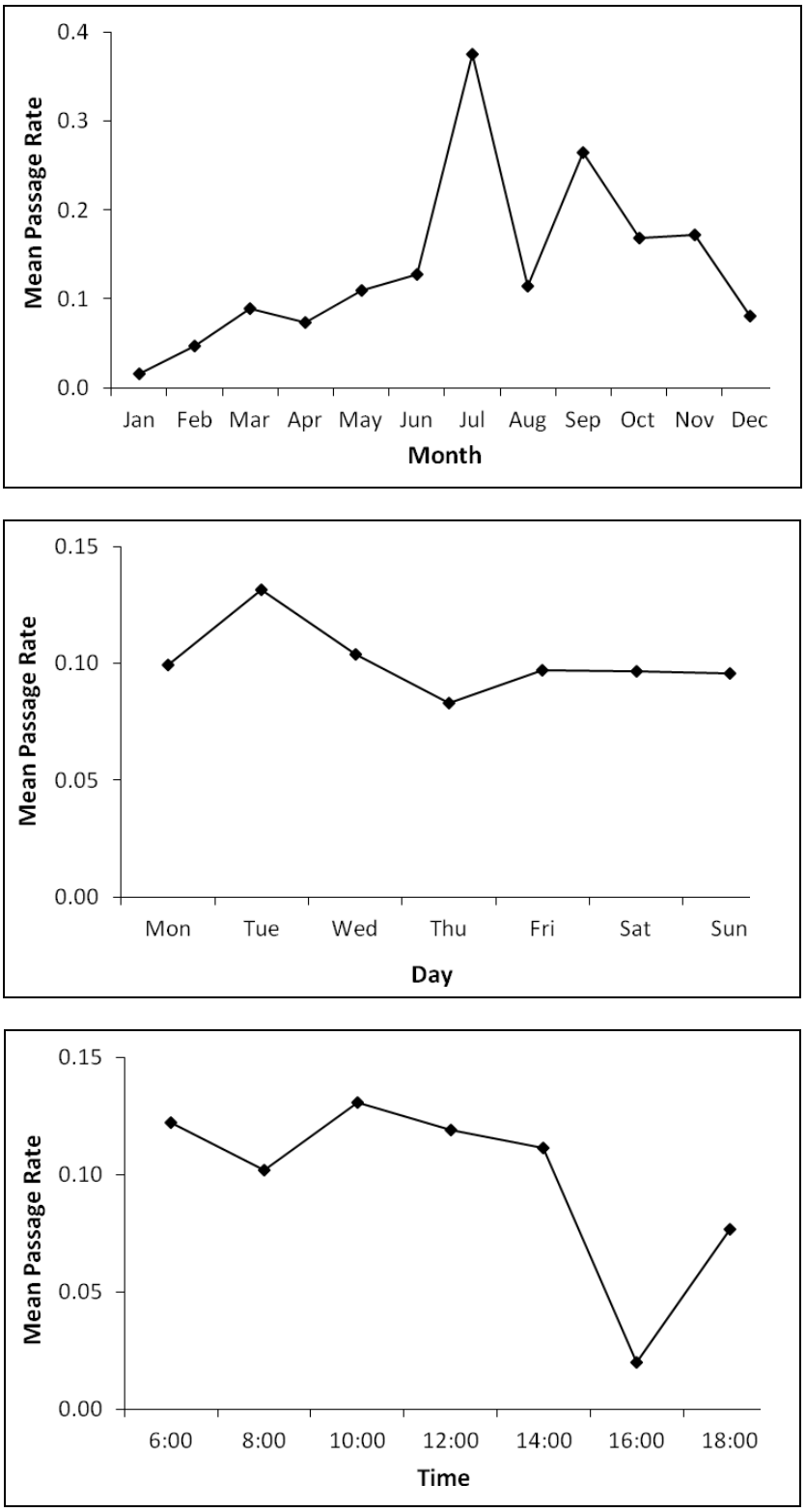
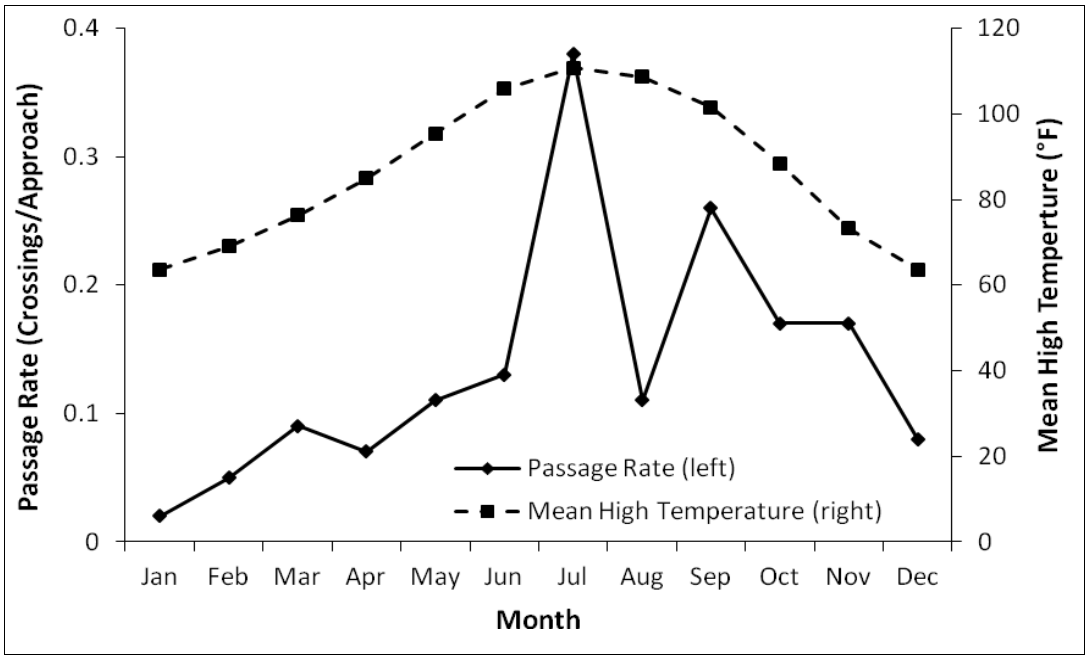


Figure 17. Mean U.S. 93 Desert Bighorn Sheep Passage Rates by Month (top), Day (middle), and Time (2-hr block midpoints; bottom).



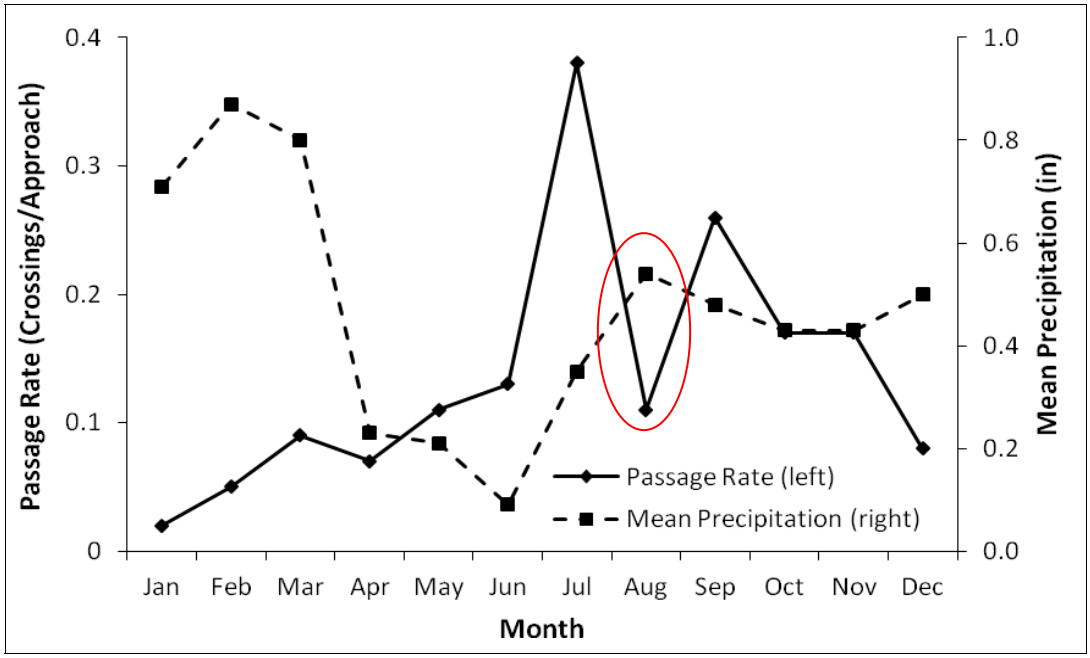


Figure 18. Association between U.S. 93 Desert Bighorn Sheep Monthly Passage Rates and Mean High Temperatures (top) and Mean precipitation (bottom).

(Note: Peak summer precipitation in August [circled in red] corresponds to a 45 percent drop in desert bighorn passage rates from July to August.)

Table 5. Mean Desert Bighorn Sheep Passage Rates by U.S. 93 Distance to Colorado River.

U.S. 93 Distance to Colorado River	Passage Rate[a] (crossings/approach)	±SE	No. of Collared Desert Bighorn
0–0.6 mi (0–1.0 km)	0.29	0.07	9
0.7–1.2 mi (1.1–2.0 km)	0.37	0.08	8
1.3–1.9 mi (2.1–3.0 km)	0.06	0.06	8
1.9–2.5 mi (3.1–4.0 km)	0.11	0.05	9
2.5–3.1 mi (4.1–5.0 km)	0.04	0.02	9
3.2–3.7 mi (5.1–6.0 km)	0.05	0.03	11
>3.7 mi (>6.0 km)	0	—	1

[a] Association between passage rate and distance to river: $r = -0.835$, $r^2 = 0.697$, $P = 0.019$, $n = 7$.

TRAFFIC AND DESERT BIGHORN SHEEP DISTRIBUTION RELATIONSHIPS

The researchers discovered a surprisingly consistent distribution of bighorn relocations among 330-ft distance bands outward from U.S. 93 across all traffic volumes (Figure 19). They found a modestly higher (26 percent) combined mean probability of sheep occurring within 660 ft of the highway below a traffic volume threshold of 400 vehicles/hr (0.29), compared to the mean probability of occurring at the same distance above 400-vehicles/hr threshold (0.23) (Figure 20). However, above 400 vehicles/hr, combined probability of occurring within 660 ft of U.S. 93, varied little even at extremely high volumes over 900 vehicles/hr (Figures 19 and 20). Most consistent was the combined mean probability of sheep occurring within 661−1320 ft of U.S. 93, ranging from 0.34 to 0.39 across all traffic volumes (Figure 20).

The research team found an association between mean monthly traffic and sheep crossings ($r = 0.656$, $r^2 = 0.430$, $P = 0.020$, $n = 12$). Furthermore, in addition to average high temperatures accounting for nearly half the variation in monthly sheep passage rates, mean monthly traffic volume also was associated with mean sheep passage rates, though only marginally so ($r = 0.576$, $r^2 = 0.332$, $P = 0.050$). The team's observed average daily traffic volume at the ATR differed from the expected volume ($\chi^2 = 779.8$, df = 6, $P < 0.001$; see Figure 6) and was strongly associated with mean sheep crossings ($r = 0.937$, $r^2 = 0.879$, $P = 0.002$), which were lowest on Fridays and Sundays when traffic volume was highest. However, daily mean sheep passage rates were not associated with traffic volume, nor were hourly sheep crossings and passage rates.

CONSTRUCTION DISTURBANCE IMPACT ON DESERT BIGHORN SHEEP

Though the research team found no differences between U.S. 93 pre-reconstruction and during-reconstruction mean sheep crossing and passage rates (Table 2), it did find differences in the spatial distribution of crossings—a 50 percent increase in crossings on the old realignment stretch (MP 0−2.2) and a 96 percent decline in crossings between MP 5.0 and MP 9.0 during reconstruction (Table 3; Figure 15).

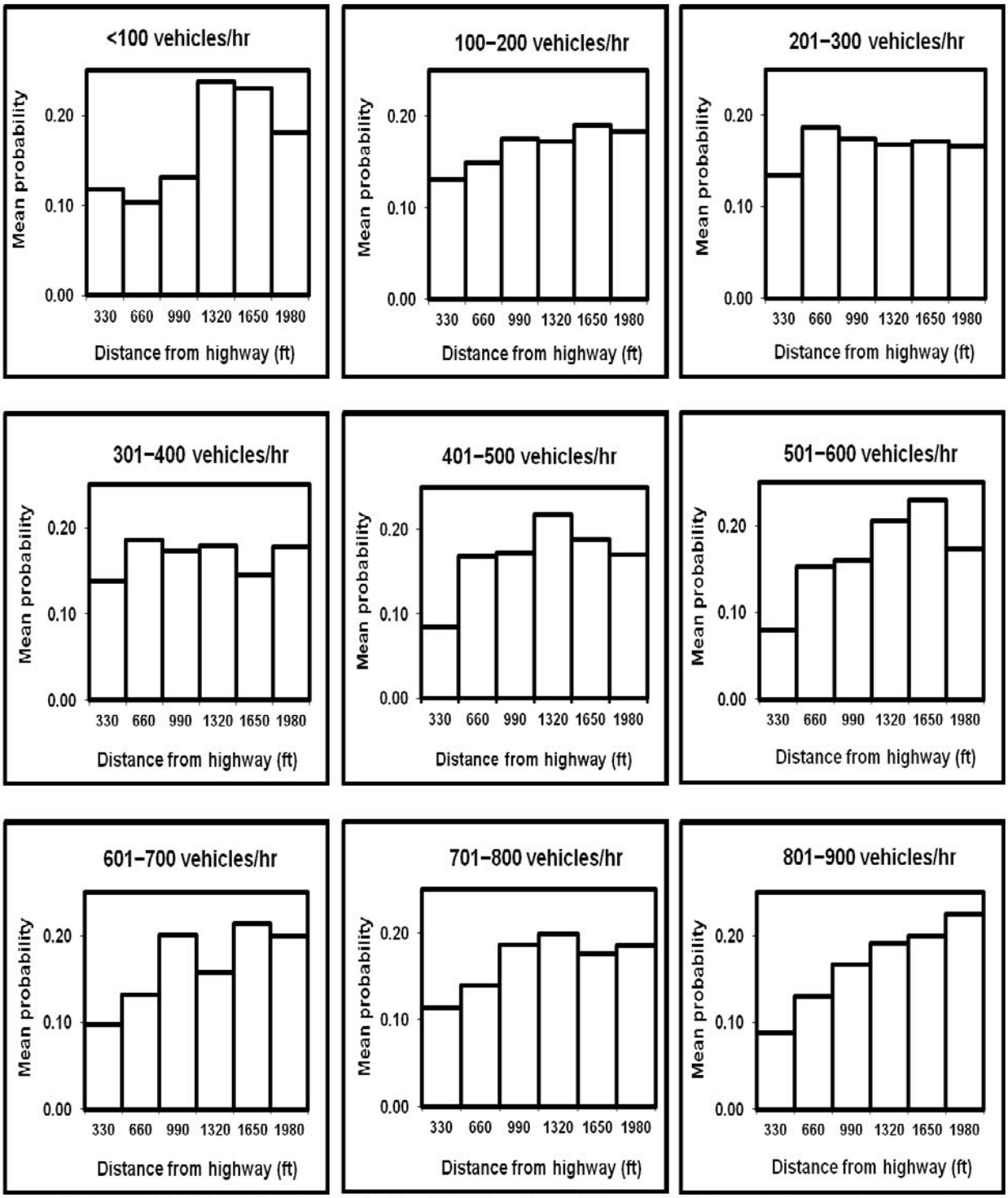


Figure 19. Mean Probability of GPS-collared Desert Bighorn Sheep Occurrence within 330-ft Distance Bands Away from U.S. 93 at Varying Traffic Volumes between 0 and 900 Vehicles/hr.

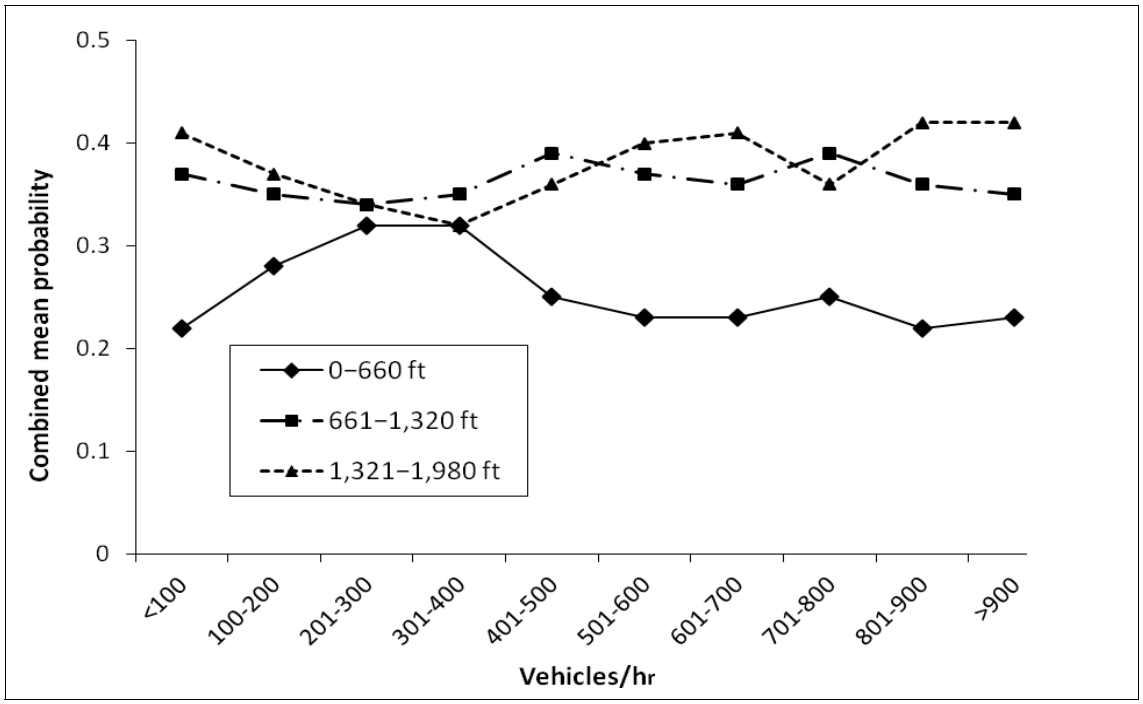


Figure 20. Combined Mean Probabilities of Desert Bighorn Sheep Occurrence within Three Distance Bands Away from U.S. 93 at Varying Traffic Volumes.

Desert Bighorn Sheep Distribution by Construction Disturbance Levels

When the team aggregated mean probabilities of desert bighorn occurring within various distance bands from U.S. 93, there was minimal difference among the no, low-moderate, and high disturbance level classes (Table 6). Neither the low-moderate (P = 0.238) or high (P = 0.763) disturbance probabilities across distance bands differed from the expected no-disturbance probabilities. However, researchers found that the very high disturbance probabilities across distance bands differed from the no-disturbance probabilities (χ^2 = 27.1, df = 3, P < 0.001; Table 6). With very high disturbance blasting, there was a large displacement in the probability of desert bighorn occurrence within 990 ft of the highway outward to 1980 ft compared to other disturbance levels.

Female Desert Bighorn Sheep Distribution during Peak Lambing Period

The research team found no difference between the pre- and during-reconstruction means for female sheep relocation distance from U.S. 93 during the lambing period (Table 7). However, the team did find a significant difference in the distribution of female relocations among distance bands from U.S. 93 (χ^2 = 63.4, df = 2, P < 0.001). Adjusted for the number of relocations, there were 68 percent fewer during-reconstruction relocations within 0.31 mi and 50 percent fewer relocations within 0.62 mi of the highway compared to before reconstruction (Table 7).

Table 6. Combined Mean Probabilities of Desert Bighorn Sheep Occurring within Three Distance Bands from U.S. 93 by Highway Reconstruction Disturbance Level.

Highway Construction Disturbance Level	Combined Probability of Desert Bighorn Occurring in Distance Bands from U.S. 93			
	0–330 ft	331–990 ft	991–1320 ft	1320–1980 ft
No disturbance	0.11	0.31	0.40	0.19
Low-moderate	0.05	0.35	0.43	0.17
High	0.09	0.35	0.37	0.20
Very high[a]	0.11	0.14	0.64	0.11

[a] Distribution of very high disturbance probabilities across distance bands differed from the no-disturbance probabilities (χ^2 = 27.1, df = 3, P < 0.001).

Table 7. Pre- and During-reconstruction Desert Bighorn Sheep Female GPS Relocations by Distance Bands within 1.2 mi of U.S. 93 during the Lambing Period (March–May) and the Mean Distance from the Highway.

Reconstruction Phase (no. of sheep)	No. of Relocations (% of total) within Distance Bands from U.S. 93[a]			Mean Distance from U.S. 93 (±SE)
	<0.31 mi	0.31–0.62 mi	0.62–1.2 mi	
Pre-reconstruction 2004–2006[b] (n =10)	491 (35.5%)	380 (19.6%)	1245 (44.9%)	1904.5 ft (±191.8) A
During reconstruction 2009–2010 (n = 6)	348 (11.3%)	538 (16.0%)	2891 (72.7%)	1875.5 ft (±79.2) A

[a]Difference between reconstruction-phase distributions among distance bands (χ^2 = 63.4, df = 2, P < 0.001).
[b]Unpublished data from McKinney and Smith's (2007) study.

Blasting Analysis

The research team conducted extensive exploratory analysis of potential blast-related disturbance impacts on U.S. 93 desert bighorn. The team found considerable variation in disturbance response among collared sheep, with some sheep movements appearing to generally reflect a response to blasting (Figure 21). However, the team's overall assessment found that blasting activities at either of the two sites had limited impact on sheep movements and distribution. Researchers found that there was no difference in the proportions of sheep GPS relocations within the 0.6-mi distance bands outward from the blast sites on the days before and days after blasting (Figure 22); the proportions also did not differ from the controls.

While the team did determine that there were significant differences in the mean distance from blasting sites between the day before and the day after blasting for desert bighorn found within the 0–2 mi

distance band (1511.1 ft; t = -3.06, P < 0.001) and 2–3 mi distance band (590.9 ft; t = -1.64, P < 0.050) (Figure 23), sheep actually were located closer to the blasting sites on the day after blasting; sheep GPS locations the day after blasting were not significantly different from the controls. However, when examined over a week, the mean relocation distance from the blast site initially decreased the first day after blasting, consistent with Figure 23, but then increased steadily each successive day thereafter, suggesting a delayed response to blasting (Figure 24); the team found a strong association between days after blasting and mean distance from blast sites (r = 0.920, r^2 = 0.846, n = 7, P = 0.001). The team was unable to discern a similar pattern in mean distance from blasting sites and the potential cumulative effect of repeated blasting events on sheep, reflected in the number of days that a blast occurred after the prior blast event (Figure 24). Likewise, the research team did not find any association between the amounts of explosives used in the blasting and subsequent sheep movement patterns.

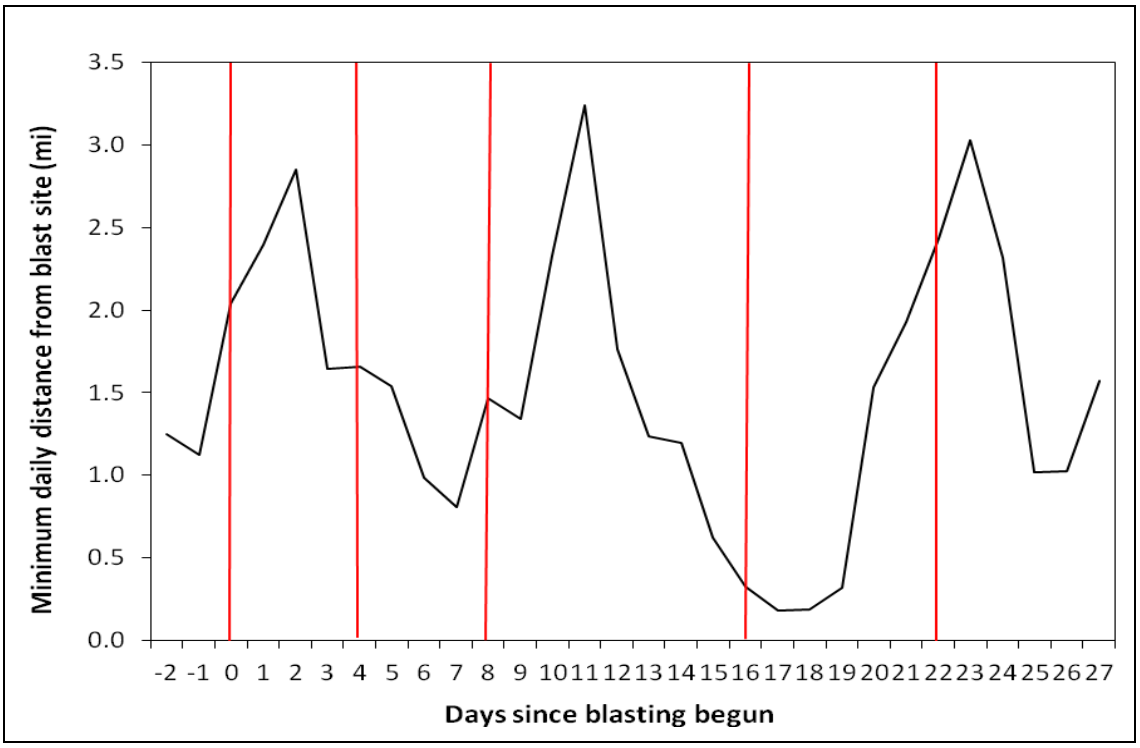


Figure 21. Minimum Daily Distance from the U.S. 93 Milepost 8.0 Blasting Site by Sheep No. 28 over the Blasting Period.
(Note: Blasts are indicated by the vertical lines.)

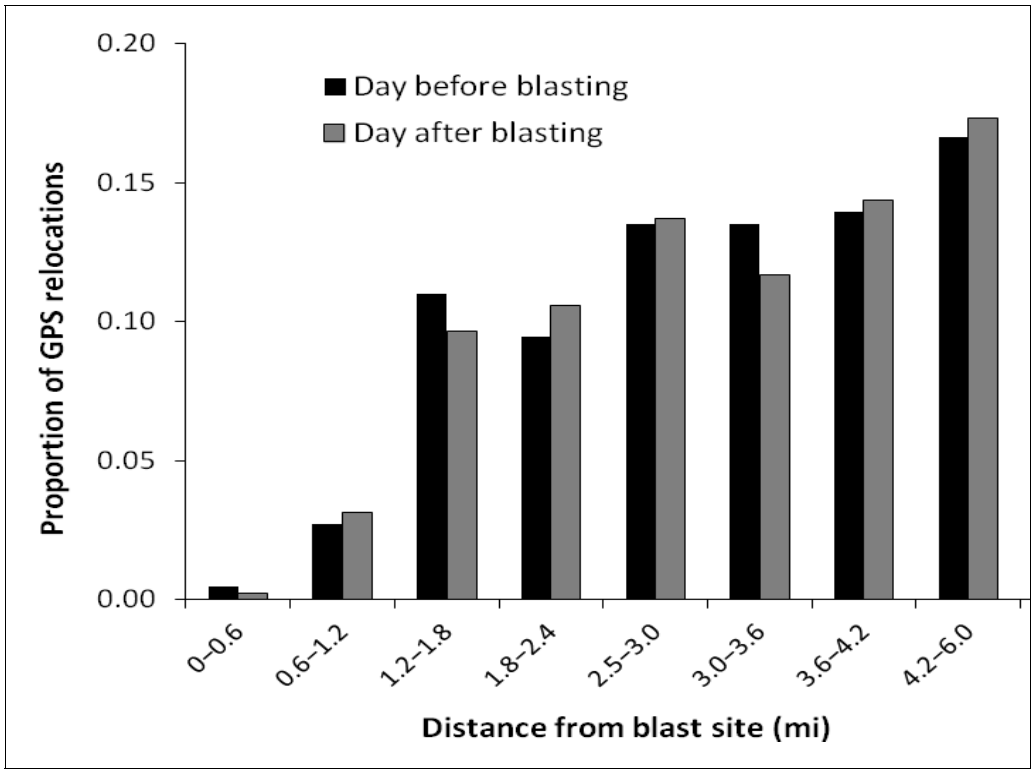


Figure 22. Mean Proportions of Desert Bighorn Sheep Occurring within Distance Bands on the Days Before and After Blasting along U.S. 93.

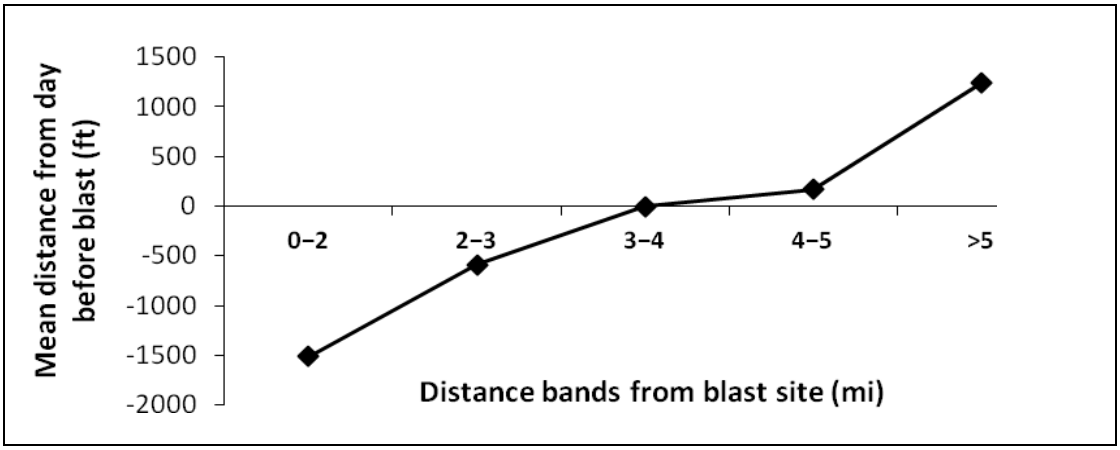


Figure 23. Mean Distance between Desert Bighorn Sheep GPS Relocations on the Day Before Versus the Day After Blasting along U.S. 93 by Distance Bands where Desert Bighorn Sheep Were Relocated.

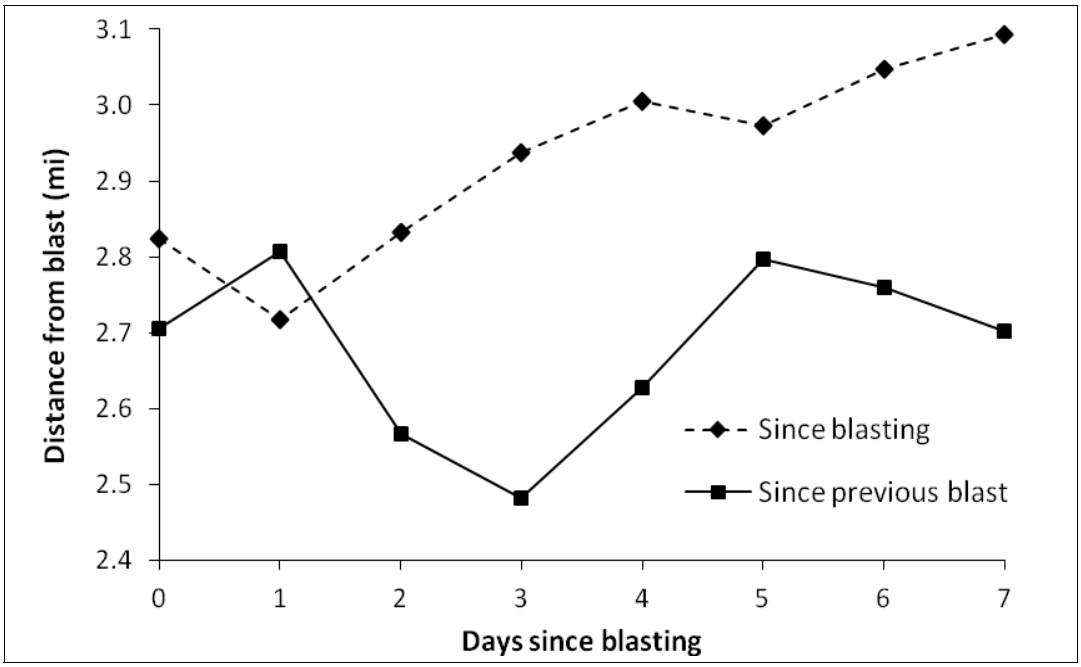


Figure 24. Mean GPS Relocation Distance from U.S. 93 Blasting Sites on Subsequent Days after Blasting and the Number of Days that a Blast Occurred after the Prior Blast Event.

DESERT BIGHORN SHEEP–VEHICLE COLLISION RELATIONSHIPS

During the research team's study, six WVCs involving sheep were documented along U.S. 93 (Table 8); four involved females, of which one was a juvenile. One sheep-vehicle collision occurred in late 2008 after the study commenced, two in 2009, and three in 2010; two-thirds of the collisions occurred on the old highway bypass alignment between MP 1.3 and MP 2.2 (Table 8). The increase in collisions on the old bypass alignment—from one in 2008 and two in 2009 to three in 2010—coincides with the large increase in sheep crossings here by collared sheep (Table 3). For 2009−2010, sheep-vehicle collisions averaged 2.5 collisions/yr and 0.15 collisions/mi/yr (MP 0−17.0).

Table 8. Desert Bighorn Sheep-Vehicle Collisions Documented along U.S. 93 between 2008 and 2010.

Year	Month	U.S. 93 MP	Sex/Age
2008	November	1.9	Female/Adult
2009	May	12.2	Female/Adult
2009	August	2.5	Female/Adult
2010	January	2.2	Male/Adult
2010	September	1.6	Male/Adult
2010	November	1.3	Female/Juvenile

CHAPTER 5. DISCUSSION

This telemetry-based research study represents the fifth major Arizona highway and fifth species for which the research team has investigated highway barrier effects to wildlife permeability in relation to traffic volume, highway size, and habitat conditions. After 10 years of near-continuous GPS telemetry in which nearly a million GPS relocations have been accrued, the collective results of these studies provide an ever-clearer understanding of the complex relationships between wildlife and highways and validate heretofore largely theoretical models to describe such relationships. GPS telemetry is an invaluable tool that has facilitated an increased understanding of wildlife-highway relationships that ultimately will promote safer and ecologically sensitive transportation systems in Arizona and elsewhere. This study also establishes an important U.S. 93 pre-reconstruction baseline against which post-reconstruction assessment of desert bighorn permeability and passage structure efficacy, using sound BACI experimental design, may be made.

DESERT BIGHORN SHEEP HIGHWAY PERMEABILITY

The research team found that U.S. 93 between MP 2.2 and MP 17.0 constitutes a significant barrier to the passage of desert bighorn. The mean passage rate of 0.07 crossings/approach determined for sheep both before and during reconstruction was comparable to the low rates measured for species typically considered sensitive to highway barrier effects, including white-tailed deer along SR 260 control sections (0.03 crossings/approach; Dodd and Gagnon 2011), pronghorn along U.S. Route 89 and SR 64 (<0.01 crossings/approach; Dodd et al. 2011; Dodd, Gagnon, Sprague, et al. 2012), and wolves along the high-traffic-volume Trans-Canada Highway (0.06 crossings/approach; Paquet and Callaghan 1996). These low passage rates contrast with those for elk along SR 260 control sections (0.88 crossings/approach; Dodd et al. 2007a) and for mule deer along SR 64 (0.54 crossings/approach; Dodd, Gagnon, Sprague, et al. 2012).

The overall low mean U.S. 93 sheep passage rate was ameliorated considerably under three circumstances, which provided for some level of connectivity and genetic interchange before the highway was fully reconstructed to a higher design standard.

1. During summer months, the mean sheep passage rate (0.25 crossings/approach) was 3.5 times higher than the overall study mean, reflecting that an increased water demand during the year's hottest months drives the need for sheep to cross U.S. 93 in search of permanent water sources. This seasonal water need of desert bighorn is similar that of elk; higher spring elk passage rates along SR 260 (Dodd et al. 2007a) and Interstate 17 (I-17) were associated with increased elk tolerance to traffic volume (Gagnon, Theimer, Dodd, and Schweinsburg 2007) when elk were pursuing high-quality forage in riparian-meadow habitats adjacent to the highways to support gestation and rapid antler growth (Manzo 2006).

2. During the fall months corresponding to the sheep breeding season, the mean sheep passage rate (0.19 crossings/approach) was nearly three times the overall study mean; the fall season correlated with the highest incidence of sheep highway crossings. Cunningham and Hanna (1992) documented their highest incidences of both highway crossings, by 15 of their 18 collared male sheep, and sheep-vehicle collisions during the fall months. Bristow and Crabb (2008) also recorded the majority of passage structure crossings along SR 68, all by male sheep, during the fall months. Male sheep are universally regarded as being more likely than females to make long-distance movements (Epps et al. 2007), especially during the breeding period, and the research team indeed found that U.S. 93 male home ranges were three times larger than those for female sheep.
3. Along the old U.S. 93 alignment between MP 0 and MP 2.2, the mean sheep passage rate (0.31 crossings/approach) was more than four times the mean for the remainder of the highway study area. Cunningham and Hanna (1992) likewise noted a higher incidence of highway crossings along this stretch and noted that the sheep band in this area exhibited a higher level of habituation to the highway than sheep crossing elsewhere along the highway. This stretch of highway also accounts for those 0.1-mi segments located within 1.2 mi of the Colorado River, where the mean passage rate was 0.33 crossings/approach, suggesting that the proximity to permanent water contributed to a higher passage rate.

DESERT BIGHORN SHEEP PERMEABILITY AND TRAFFIC RELATIONSHIPS

Unlike elk distribution along SR 260 (Gagnon, Theimer, Dodd, and Schweinsburg 2007) and SR 64 (Dodd, Gagnon, Sprague, et al. 2012), where animals shifted away from the highways as traffic levels increased and then returned closer to the highways when traffic abated, desert bighorn along U.S. 93 showed negligible shifts in distribution across traffic volume levels. This response, or lack thereof, to traffic was similar to distributions exhibited by elk along I-17, pronghorn along U.S. 89 (Dodd et al. 2011) and SR 64 (Dodd, Gagnon, Sprague, et al. 2012), and white-tailed deer along SR 260 (Dodd and Gagnon 2011) where animals were exposed to constant high traffic volume during periods when they were active. At such high volumes, vehicular traffic serves as a “moving fence” that physically renders highways impermeable to wildlife (Bellis and Graves 1978). It also results in a “noise effect zone” adjacent to highways that varies with volume and affects wildlife passage and habitat use (Reijnen et al. 1995); this zone can extend 0.25 mi or more with volumes equivalent to 8000−15,000 vehicles/day.

Theoretical models developed by Seiler (2003) and Iuell et al. (2003) suggest that highways with an AADT of 4000–10,000 vehicles/day present strong barriers to wildlife passage; above 10,000 vehicles/day, highways present impermeable barriers to wildlife. The AADT associated with five northern Arizona highways along which the research team has assessed wildlife movements has ranged from 4275 to 16,015 vehicles/day (Table 9); the linear regression association between passage rates for five species and AADT was weak and accounted for only 9 percent of the variation in passage rates (r =−0.303, r^2 = 0.092, P = 0.465, n = 8). However, as Gagnon, Dodd, et al. (2007) pointed out, traffic

volume levels that occur when different species are active have a greater influence on their distribution and passage rates; thus, diurnal species (e.g., pronghorn, desert bighorn) are generally subjected to higher traffic volumes than strictly nocturnal species (e.g., elk) when traffic volume is substantially lower. When the team calculated active-period AADT-equivalent volumes corresponding to the times at least 90 percent of highway crossings (or highway approaches, in the case of pronghorn which seldom crossed) occurred (Table 9), it found that the linear regression association accounted for three-quarters of the variation in passage rates ($r = -0.863$, $r^2 = 0.746$, $P = 0.005$, $n = 8$). Thus, active-period AADT-equivalent volumes far better describe what appears to be a universal impact of traffic volume across numerous highways and wildlife species.

When the team considered active-period traffic volume for U.S. 93 desert bighorn, it found that desert bighorn are subjected to the highest volume of all Arizona highways assessed to date, with an AADT-equivalent volume approaching 12,000 vehicles/day during the desert bighorn's active period of 0600 hours−1800 hours (Table 9); this partly explains the overall low mean passage rate for desert bighorn. Furthermore, some diurnal species such as pronghorn inhabit open habitats (e.g., grasslands) and rely heavily on visual stimuli in predator avoidance and survival (Dodd et al. 2011; Dodd, Gagnon, Sprague, et al. 2012). The same is true of desert bighorn that inhabit open desert habitats (Geist 1971; McKinney and Smith 2007). As such, these diurnal species appear especially susceptible to the visual "moving fence" associated with high traffic volume that renders highways impermeable to wildlife (Bellis and Graves 1978).

Table 9. Mean Passage Rates for Five Wildlife Species on Arizona Highways and AADT-equivalent Traffic Volume during the Active Periods Accounting for 90 Percent of Crossings.

Species	Highway	AADT (vehicles/day)	Active-period AADT-equivalent (vehicles/day)	Mean Passage Rate (crossings/approach)
Desert bighorn sheep	U.S. 93	8,720	11,918[a]	0.07
Pronghorn[1]	U.S. 89	6,310	9,611[a]	<0.01
Pronghorn[2]	SR 64	4,275	7,464[a]	<0.01
White-tailed deer[3]	SR 260	8,700	7,551[b]	0.03
Mule deer[2]	SR 64	4,275	2,568[c]	0.54
Elk[4]	I-17	16,015	10,186[d]	0.09
Elk[2]	SR 64	4,275	2,016[d]	0.44
Elk[5]	SR 260	8,700	3,914[d]	0.50

[1] Dodd, Gagnon, Boe, et al. 2012; [2] Dodd, Gagnon, Sprague, et al. 2012; [3] Dodd and Gagnon 2011; [4] I-17 elk movements data; [5] Dodd, Gagnon, Boe, et al. 2012.

Active Periods:

[a] Desert Bighorn and Pronghorn: 0600 hours−1800 hours; [b] White-tailed Deer: 2300 hours−1100 hours and 1600 hours−2200 hours; [c] Mule Deer: 2200 hours−1000 hours; [d] Elk: 1800 hours−0800 hours.

Across all highways and species for which the team has conducted research, the passage rate threshold at which highways become impermeable appears to be well under 10,000 vehicles/day (Figure 25). Passage rates for species with active-period AADT-equivalent volumes below 4000 vehicles/day averaged 0.49 crossings/approach, but above that volume, passage rates averaged just 0.04 crossings/approach (Table 9; Figure 25). The I-17 elk study compared elk permeability data associated with three Arizona highways (SR 260, SR 64, and I-17) and found that passage rates declined 81 percent from an average of 0.86 crossings/approach below an AADT-equivalent 5000 vehicles/day to an average of 0.16 crossings/approach between 5000 and 10,000 vehicles/day; a similar trend is apparent for all species and highways (Figure 25). However, as expected, near or above an AADT-equivalent of 10,000 vehicles/day, average elk permeability was very low (0.06 crossings/approach on I-17), and this phenomenon also was noted for U.S. 93 desert bighorn and U.S. 89 pronghorn (Dodd et al. 2011); these high-volume highways are impermeable to these species.

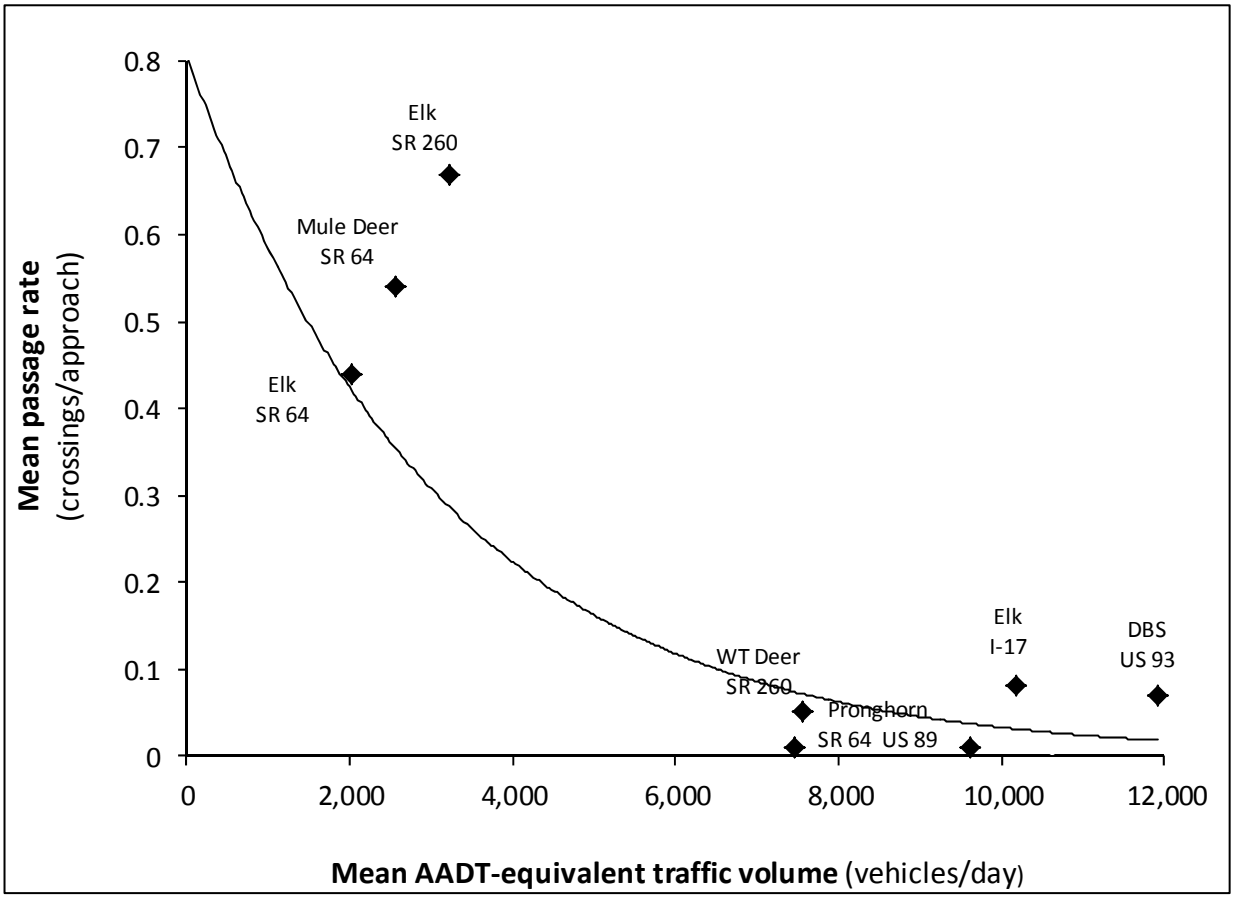


Figure 25. Mean Highway Passage Rates for Five Arizona Wildlife Species and Highways and Mean Active-Period AADT-equivalent Traffic Volume.

ROLE OF WILDLIFE PASSAGE STRUCTURES AND FENCING

Without the integration of comprehensive connectivity mitigation measures, the recently completed widening of U.S. 93 to a four-lane divided highway, along with projected increases in the AADT, could exacerbate the existing barrier effect and hasten potential genetic isolation within subunits of the Black Mountains desert bighorn population (Jaeger et al. 2005; Epps et al. 2005). While modeling of the impact of traffic volume and highway size on highway barrier effects found that traffic volume exerts the greater influence of the two factors (Jaeger et al. 2005), increasing highway size also amplifies the degree of the barrier effect (e.g., a large highway with high AADT has a greater impact on permeability than a small highway with the same AADT). Dodd, Gagnon, Manzo, et al. (2007) found that the mean SR 260 elk passage rate declined 35 percent after reconstruction to a four-lane divided highway standard but before ungulate-proof fencing was erected to funnel elk to underpasses (Dodd et al. 2007b). The recently completed reconstruction and widening of U.S. 93 would likely similarly impact the already low overall sheep permeability without the incorporation of measures to promote sheep passage. The three completed wildlife overpasses and three bridged underpass structures between MP 0 and 12.2 (see Table 1; Figure 26), along with 7-ft ungulate funnel fencing, are anticipated to promote permeability and reduce WVC incidences.

Figure 26. Completed U.S. 93 Wildlife Overpass at Milepost 5.1 (looking east). Inset Photograph Shows One of the First Desert Bighorn Sheep Highway Crossings via the Overpass.

Along SR 260, Dodd et al. (2007b) found that the mean elk passage rate along one segment with seven passage structures increased 58 percent after reconstruction and strategic erection of funnel fencing (half the section was selectively fenced), and these measures achieved an 85 percent reduction in elk-vehicle collisions. This research pointed to the importance of funnel fencing in achieving desired wildlife use of passage structures that otherwise proved to be minimally used since animals continued to make at-grade highway crossings (Dodd et al. 2007b). Fencing also plays a crucial role in helping animals overcome the impact of high traffic volume and thus promotes permeability. In assessing traffic influences on elk permeability, Gagnon, Theimer, Dodd, and Schweinsburg (2007) found that increasing traffic volume decreased the probability of at-grade crossings and temporarily shifted elk away from the highway. Conversely, Gagnon, Theimer, Dodd, Manzo, et al. (2007) found that traffic levels did not influence elk passage rates during below-grade underpass crossings. This finding helps account for the benefit of structures and fencing in promoting permeability, where fences funnel elk to underpasses where traffic has minimal impact compared to crossing at-grade. Similar results were obtained for white-tailed deer along SR 260, where Dodd and Gagnon (2011) documented a fivefold increase in permeability after reconstruction with passage structures compared to two-lane highway controls; deer passage rates were minimally affected by traffic on sections where passage structures facilitated below-grade passage. The research team expects U.S. 93 sheep crossing patterns to exhibit a dramatic shift and concentration toward overpasses and bridges, similar to elk crossing patterns after ungulate funnel fencing was erected along SR 260 (Gagnon et al. 2010).

The U.S. 93 EIS recommended only limited funnel fencing with passage structures. The original reconstruction plans for MP 2.3–17.0 detailed only 1.6 mi (11percent) of the highway corridor being fenced with 7-ft fencing, with only 100-ft wing fences on either side of the overpasses at MP 5.1 and MP 12.2 and none at the Devils Wash Bridge at MP 8.0 (FHWA 2001). Such a limited fencing approach demonstrated to be ineffective in achieving the desired wildlife use of passage structures along SR 260 and failed to promote elk permeability and highway safety from reduced incidence of WVCs (Dodd et al. 2007b). As such, AGFD advocated for additional U.S. 93 fencing during reconstruction, illustrating how the planned approach was anticipated to intercept and funnel only 28 percent of crossing sheep toward the passage structures. Based on AGFD recommendations, 31 percent (4.5 mi) of the highway corridor was ultimately fenced with7-ft-high fencing, including the entire stretch between MP 2.4 and MP 5.7, and 0.3 mi on either side of the Devils Wash Bridge and MP 12.2 overpass; this extent of fencing was anticipated to intercept 82 percent of crossing sheep and funnel animals toward passage structures. The remainder of the highway corridor was fenced with 5-ft fencing.

Along with structural characteristics, proper location and placement of wildlife crossing structures are vital considerations to maximizing wildlife use (Reed et al. 1975; Foster and Humphrey 1995; Clevenger and Waltho 2000, 2003; Gagnon et al. 2011; Clevenger and Huijser 2011). Prior commitments to previous U.S. 93 research (Cunningham and Hanna 1992; McKinney and Smith 2007) facilitated data-driven placement of passage structures that is anticipated to enhance their prospect for success. Spacing between passage structures also is an important consideration, and Bissonette and Adair (2008) have recommended that passage structure spacing for several species be tied to isometric scaling of home ranges. Their spacing recommendations, when used with other criteria, were intended to help

maintain landscape connectivity. For bighorn sheep, they have recommended spacing passage structures 2.4 mi apart. Between MP 0 and 17.0, the average spacing of U.S. 93 structures (six excluding the Kingman Wash Traffic Interchange) conducive to sheep passage is 2.8 mi; between MP 0 and MP 12.2, where the vast majority of crossings have been documented by this and previous studies, the average passage structure spacing is 2.0 mi. Thus, the ultimate spacing of passage structures should further contribute to their long-term success in promoting permeability for desert bighorn.

CONSTRUCTION DISTURBANCE IMPACT ON DESERT BIGHORN SHEEP

Relatively few studies have conducted scientifically rigorous assessments of pre- and post-reconstruction impacts on wildlife under BACI experimental design, and even fewer studies have assessed during-reconstruction impacts on wildlife since a study of construction impacts on mountain goats in Montana (Singer and Doherty 1985). Though during-construction impacts are typically viewed as short term, for some species even short-term disturbance may have significant and potentially long-term impacts if construction impedes access to critical habitats such as watering or lambing sites. Elucidating such impacts is vital to developing mitigation strategies to minimize or avoid adverse impacts during future reconstruction projects.

The research team took a comprehensive, multiscale approach to its assessment of potential U.S. 93 reconstruction impacts on desert bighorn. Reconstruction appeared to have no impact on mean sheep crossing and passage rates, though the rates were consistently low across both treatments. The during-reconstruction impact on elk permeability along SR 260 similarly was minimal, with traffic limited to the narrow two-lane roadway for both classes (Dodd et al. 2007a), which was consistent with modeling by Jaeger et al. (2005). Even though reconstruction activities extended across the entire four-lane highway corridor while SR 260 was under reconstruction, traffic was confined to two lanes and the highway remained a functional relatively small road.

Though the U.S. 93 sheep crossing rate did not differ between pre- and during-reconstruction classes, the spatial distribution of crossings between classes did differ, shifting dramatically to the old U.S. 93 alignment (MP 0–2.2), and provides some of the best evidence of an impact on desert bighorn. The fact that the spatial distribution of during-reconstruction crossings differed from both the distribution of the research team's 2008–2009 pre-reconstruction crossings and the 2004–2006 pre-reconstruction distribution (McKinney and Smith 2007) reduces the likelihood that the shift was an anomaly.

At its most refined scale, the research team's assessment did not detect any significant difference in desert bighorn probabilities of occurrence out to 1980 ft from U.S. 93 among no, low-moderate, and even high disturbance reconstruction activities that included heavy equipment operation and bridge/overpass construction. Only with very high disturbance blasting was there a significant change in the probability of occurrence within distance bands, with a displacement beyond 990 ft of the highway compared to other activities. Sheep tolerance to high-disturbance construction activities was similar to the adaptability exhibited by mountain goats during underpass and bridge construction in Montana, though special efforts were made there to limit construction during daily peak goat crossing and activity

periods (Singer and Doherty 1985). The team suspects that the high traffic volumes that U.S. 93 desert bighorn encountered on a continual basis during active periods contributed to their high tolerance and consistent pattern of occurrence adjacent to the highway across all construction activities except blasting.

At a larger scale, the research team's assessment found a significant difference in the proportion of female GPS relocations that occurred within 1.2 mi of U.S. 93 during the lambing season between pre- and during-reconstruction periods. Though the 68 and 50 percent fewer relocations made within 0.31 and 0.62 mi of the highway, respectively, during reconstruction suggests an impact on female sheep distribution during the lambing period, the team did not assess nor can it speculate on whether such a difference in distribution had an impact on females accessing traditional lambing areas or lambing success in the vicinity of the highway.

At its largest scale, the team's assessment of blasting-activity impacts on sheep distribution outward to 6.0 mi from U.S. 93 found no difference in the proportion of GPS relocations within 0.6-mi bands one day before and after blasting. However, the assessment did find a strong association between the distance from U.S. 93 and the days after blasting, pointing to blasting's delayed impact on sheep distribution. Because all blasting activities occurred in an eight-month period (mid-September to early May) that excluded the summer months, any potential adverse impacts on sheep's reaching water sources were avoided during the critical hot and dry months. Further, like the monitoring of the impact of the Hoover Dam Bypass project (Douglas and McMahon 2009), the researchers did not document any instance where construction activities impacted sheep access to water sources.

Lastly, the researchers noted no instances of desert bighorn exhibiting any outward symptoms of respiratory distress associated with potential airborne dust contamination from highway reconstruction activities. Dust abatement and fill compaction spraying were apparently effective in minimizing or preventing sheep dust exposure, as also noted by Douglas and McMahon (2009).

DESERT BIGHORN SHEEP-VEHICLE COLLISION RELATIONSHIPS

Between September 2001 and October 2010, the stretch of U.S. 93 associated with the research team's study was closed to commercial truck traffic as a precautionary measure to prevent a terrorist attack at the Hoover Dam. And between 2003 and November 2010, active highway reconstruction further altered pre-reconstruction traffic and driving patterns (e.g., reduced traffic speeds in the construction zone). Thus, both factors preclude the use of the research team's data and data from McKinney and Smith (2007) in establishing comparable pre-reconstruction baselines against which to compare post-reconstruction sheep-vehicle collision incidences; the documentation of five sheep-vehicle collisions during 2009–2010, an average of 2.5/yr, or just 0.16/mi/yr, likely underestimates the actual long-term pre-reconstruction and pre-9/11 incidences of collisions involving desert bighorn.

Given documentation of 24 sheep-vehicle collisions before the 9/11-related closure to commercial truck traffic (Cunningham and Hanna 1992), their study provides the best estimate of pre-reconstruction

sheep-vehicle collision incidences, though their study too has associated limitations. They recorded over half their sheep roadkills in the last four months of 1989, eight collisions in 1990, and only two in 1991 through early November, making the establishment of meaningful annual averages problematic. However, given that 9 of the 11 sheep-vehicle collisions in 1990 and 1991 (82 percent) occurred in August or later in the year, it is reasonable to use 1989 collisions in the calculation of annual averages. Conversely, as 64 percent of the collisions in 1989 and 1990 occurred later than the November date that monitoring ceased in 1991, the team did not use the 1991 figures in deriving averages as they would likely underestimate the year's totals. For 1989–1990 Cunningham and Hanna (1992) recorded an average of 11.0 sheep-vehicle collisions/yr, and 0.69 collisions/mi/yr, or more than four times the rate documented by the research team for 2009–2010. Cunningham and Hanna (1992) recorded a relatively equal distribution of collisions by sex: 10 male and 9 female.

The research team anticipates that the combination of the implemented passage structures and ungulate funnel fencing will dramatically reduce the WVC incidences along U.S. 93. Several studies and a growing body of evidence point to the integral role that 6.5- to 8-ft ungulate-proof fencing plays in achieving highway reconstruction objectives for minimizing WVCs and promoting highway safety, as well as promoting wildlife permeability (Dodd et al. 2007b; Dodd, Gagnon, Boe, et al. 2012). This important role of fencing, in conjunction with passage structures, has been stressed by Romin and Bissonette (1996a, 1996b), Forman et al. (2003), and others, and the empirical basis for fencing's role in reducing WVCs has continued to grow, with reductions in WVCs of anywhere from 80 percent (Clevenger et al. 2001) to over 90 percent (Ward 1982; Woods 1990; Gagnon et al. 2010). The portions of U.S. 93 fenced with ungulate funnel fencing between MP 0 and MP 17.0 correspond with the location of (1) 92.5 percent of all pre-reconstruction (2004–2009) sheep highway crossings, (2) 81.8 percent of the pre-reconstruction (1989–1990) sheep-vehicle collisions, and (3) 100 percent of the six collisions documented by the research team. For this reason, passage structures and fencing are predicted to result in a more than 90 percent post-reconstruction decline in sheep-vehicle collisions.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

This study facilitated a data-driven approach to quantifying U.S. 93 sheep pre- and during-reconstruction permeability. It also established a baseline against which to assess the post-reconstruction benefit of passage structures and ungulate funnel fencing in enhancing permeability and reducing WVC incidences. Combined with studies already completed on other Arizona highways (employing consistent and comparable methodologies), this study has contributed significantly to the understanding of wildlife-highway interactions in relation to traffic volume, highway size, and habitat conditions. The following are key conclusions and recommendations from this research project.

DESERT BIGHORN SHEEP HIGHWAY PERMEABILITY

- The research team's U.S. 93 desert bighorn GPS assessment and comparison to other Arizona highways was facilitated by using passage rate as a comparable metric for permeability (Dodd et al. 2007a).
- The GPS telemetry analysis found that, overall, U.S. 93 constituted a significant barrier to sheep passage, with a mean passage rate of just 0.07 crossings/approach between MP 2.3 and 17.0. This is one of the lowest mean passage rates documented among five species and five highways studied in Arizona to date.
- The sheep highway passage rate varied by season, with the summer rate (0.25 crossings/approach) significantly higher than the winter and spring rates, though not significantly different from the fall rate (0.19). The demand for water during the extreme summer months likely accounts for the higher passage rates, given that sheep showed increased traffic tolerance when crossing U.S. 93 to reach permanent water sources. The relatively high fall passage rate coincides with the sheep breeding season when male sheep exhibit extensive movements.
- There was no difference between pre- and during-reconstruction sheep crossing and passage rates, partly because of the consistent impact of high traffic volume and because the reconstructed highway still functioned as a "small" two-lane roadway until traffic was allowed on all four lanes (Jaeger et al. 2005), as also noted for elk highway permeability on SR 260.
- Based on the research team's prior work along SR 260, where a 35 percent drop in elk highway permeability occurred between pre- and post-reconstruction phases, the team anticipates that the already low U.S. 93 passage rate would be further reduced with the completion of U.S. 93, especially for situations where the pre-reconstruction passage rate was higher than the overall mean (e.g., spring and fall, along the old highway alignment between MP 0 and MP 2.2).
- The significant measures promoting sheep highway permeability—including the three new wildlife overpasses, other bridges to accommodate wildlife passage, and ungulate funnel fencing—are expected to have a beneficial impact given prior SR 260 research on elk and white-tailed deer that has recorded dramatically improved permeability related to added passage structures and fencing.

Recommendation:
Considering ADOT and FHWA's commitment to integrating a comprehensive set of wildlife measures to promote permeability into the highway reconstruction, it is imperative that post-reconstruction monitoring, with a rigorous BACI experimental design, assess the efficacy of the measures. ADOT has already funded this post-reconstruction research, which began at the completion of reconstruction in October 2010 and will last through 2014.

DESERT BIGHORN SHEEP PERMEABILITY AND TRAFFIC RELATIONSHIPS

- The research team used an ATR installed at MP 18.0 to measure U.S. 93 traffic volume and found that the AADT was 8720 vehicles/day. However, during the diurnal period when desert bighorn were most active (0600 hours−1800 hours), the AADT-equivalent volume approached 12,000 vehicles/day; this was the highest active-period volume recorded by the studies of five highways and species in Arizona.
- The researchers found a static distribution of desert bighorn sheep relocations among 330-ft distance bands outward from U.S. 93 across all traffic volumes. This limited response reflected the constant exposure to high traffic volume that sheep met when active. At such high volumes, traffic acts as a moving fence, physically rendering highways impermeable to wildlife (Bellis and Graves 1978), and creates noise effect zones extending from highways (Reijnen et al. 1995).
- Mean monthly sheep crossing and passage rates were both associated with monthly traffic volume, all of which were highest during summer; these associations, however, likely reflected sheep's seasonal tolerance to high traffic volume while seeking water sources during the hot, dry summer months. Sheep highway crossings were negatively associated with daily traffic volume.
- The researchers found a very strong negative association between mean passage rates for five wildlife species along five highways, including for U.S. 93 desert bighorn, and active-period AADT-equivalent traffic volumes. This association accounted for three-fourths of the variation in passage rates, and it better describes a seemingly universal impact of traffic volume across highways and species, nocturnal and diurnal, than the association with highway AADT. Across these highways and species, passage rates for species with active-period AADT-equivalent volumes below 4000 vehicles/day averaged 0.49 crossings/approach, but passage rates above that traffic volume averaged just 0.04 crossings/approach.

Recommendation:
As part of a post-reconstruction evaluation of the efficacy of wildlife overpasses and bridges in promoting desert bighorn highway permeability, researchers should assess and validate the influence of traffic volume. This is especially important since never-before-implemented wildlife overpasses may cause animals making above-grade crossings of the highway to react differently to traffic volume/noise and other factors, as opposed to behavior with underpasses.

CONSTRUCTION DISTURBANCE IMPACT ON DESERT BIGHORN SHEEP

- Though the research team found no differences between pre- and during-reconstruction mean sheep crossing and passage rates, it did find a significant difference in the spatial distribution of crossings, with a 50 percent increase in crossings on the old realignment stretch (MP 0–2.2) and a 96 percent decline in crossings between MP 5.0 and MP 9.0 during reconstruction.
- There was minimal difference in mean probabilities of desert bighorn sheep occurring within various distance bands from U.S. 93 among the no, low-moderate, and high disturbance level classes associated with reconstruction; sheep apparently tolerated heavy equipment and bridge construction activities. However, researchers did find that very high disturbance (blasting) probabilities across distance bands differed from the no-disturbance probabilities with a delayed shift away from the highway.
- The research team found a significant difference in the distribution of female GPS relocations among distance bands from U.S. 93 between pre- and during-reconstruction phases during the lambing period, with 68 percent fewer during-reconstruction relocations within 0.31 mi and 50 percent fewer relocations within 0.62 mi of the highway compared to before reconstruction.
- The research team's overall assessment found limited blasting-activity impacts on desert bighorn sheep movements and distribution. There was no difference in the proportions of sheep GPS relocations within the 0.6-mi distance bands outward from the blast sites on the days before and days after blasting. At a larger scale, the team found no difference in the mean distance from blasting sites between the day before and the day after blasting for desert bighorn found within 6 mi of the highway. However, when examining data over a week's time, the team found a strong association between days after blasting and mean distance from blast sites, which suggests a delayed desert bighorn response to blasting.

  Recommendation:
  By design or not, all U.S. 93 blasting activities occurred outside the summer months when desert bighorn sheep most need to cross the highway to reach permanent water sources critical to their survival. Such timing of blasting likely helped minimize the adverse disturbance and should be considered as an important mitigation measure in future projects. Likewise, highway reconstruction dust abatement activities helped prevent any potential respiratory illness among desert bighorn and should also be a required mitigation measure to prevent respiratory impacts.

DESERT BIGHORN SHEEP–VEHICLE COLLISION RELATIONSHIPS

- The researchers documented six sheep-vehicle collisions during the study, recording five between 2009 and 2010, for an average of 2.5/yr or just 0.16/mi/yr. However, this underestimates the actual long-term pre-reconstruction number of collisions, because commercial truck traffic had been detoured since the 9/11 terrorist attacks and constant construction had been ongoing since 2003.

- A more representative pre-reconstruction baseline for sheep-vehicle collisions was derived from Cunningham and Hanna (1992); their study for 1989–1990 recorded an average of 11.0 sheep-vehicle collisions/ yr (0.69 collisions/mi/yr).
- Stretches of U.S. 93 along which 7-ft ungulate funnel fencing was erected in association with wildlife overpasses and bridges correspond to where over 90 percent of all sheep highway crossings have occurred and are anticipated to dramatically reduce the incidence of vehicle collisions involving desert bighorn.

  Recommendation:
  With the completion of reconstruction and the return of commercial truck traffic to U.S. 93 as of October 2010, post-reconstruction monitoring is vital for evaluating the efficacy of wildlife overpasses, bridges, and fencing in reducing the number of sheep-vehicle collisions compared to the pre-reconstruction baseline.

WILDLIFE PASSAGE STRUCTURES AND FENCING

- Through funding of prior research (Cunningham and Hanna 1992; McKinney and Smith 2007), ADOT, FHWA, and Reclamation have committed to assessing the impacts of U.S. 93 reconstruction on desert bighorn and to developing comprehensive strategies to address these impacts, promote highway permeability, and reduce sheep mortality from vehicle collisions.
- As a result of these studies and extensive agency and public interaction, a comprehensive set of measures to promote wildlife, including sheep highway permeability, was integrated into U.S. 93 highway reconstruction. These measures include three overpasses specifically for wildlife passage ranging in width from 50 to 100 ft. They represent the first wildlife overpasses built in Arizona and the first designed specifically for desert bighorn sheep in North America.

  Recommendation:
  Post-reconstruction monitoring of wildlife use of the three overpasses is vital to yielding insights regarding their efficacy in promoting bighorn permeability, as well as passage rate relationships to design characteristics (e.g., width) and placement for application in future projects.

- The amount of 7-ft ungulate funnel fencing implemented during reconstruction was increased substantially from that in the original construction plans and will promote desert bighorn permeability and use of passage structures, as well as reduce the incidence of sheep-vehicle collisions. However, only limited 7-ft fencing (0.3 mi in each direction) was used at the Devils Wash Bridge at MP 8.0 and the MP 12.2 overpass.

  Recommendation:
  This limited-fencing approach at these structures should be evaluated during post-reconstruction monitoring to assess the efficacy of this approach and to ensure that potential end-runs by sheep do not occur. The efficacy of 5-ft fencing used where 7-ft fencing was not erected should be evaluated as well.

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