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Effectiveness of Night-time Speed Limit Reduction in Reducing Wildlife-Vehicle Collisions

By:

Northern Rockies Conservation Cooperative
Jackson, WY 83001

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Abstract
Wildlife-vehicle collisions are dangerous and costly to the traveling public and pose a threat to wildlife populations. Transportation managers continue to evaluate the effectiveness of measures that have been employed to reduce wildlife-vehicle collisions (WVCs). One potential measure is to reduce the posted speed limit at night and during dawn and dusk hours. The theoretical mechanism for this measure to work is that drivers reduce their operating speeds, increasing their stopping distances when they see an animal in the road, and therefore avoiding collisions with those animals. Although reduced night-time speed limits are being used in many places with the goal of reducing WVCs, there has been almost no research to evaluate whether drivers reduce their operating speeds and whether a reduction in the number of WVCs results. We conducted a thorough experiment in which posted speed limits were reduced from 70 mph to 55 mph during dusk to dawn hours in key deer activity seasons at six sites in southwestern Wyoming. Drivers reduced their speeds in response to the posted speed limit reduction, but the average reduction was only 3-5 mph. At winter sites, where the reduced speed limit was in effect for seven months, there was no evidence of any reduction in WVCs. At migration sites, where the reduced speed limit was in effect for two months at a time, there was some evidence of fewer WVCs, although it was not clear that this could be attributed to the reduced speed limit. We recommend that reduced posted speed limit is not an effective measure to reduce WVCs on high-speed rural two-lane highways.

Key Words: deer-vehicle collision, Wyoming, mule deer, speed, traffic, animal-vehicle crash	Distribution Statement This document is available through the National Transportation Library; and the Wyoming State Library.

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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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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

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LIST OF ABBREVIATIONS AND SYMBOLS

BACI—before after control impact
DVC—deer-vehicle collision
FLIR—forward-looking infrared
FT—foot
GPS—global positioning system
MI—miles
MP—mile post
MPH—miles per hour
ROW—right of way
WGFD—Wyoming Game and Fish Department
WVC—wildlife-vehicle collision
WY—Wyoming
WYDOT—Wyoming Department of Transportation
Y1—year 1
Y2—year 2

CHAPTER 1. EXECUTIVE SUMMARY

Collisions between vehicles and large mammals pose a serious threat both to highway safety and to wildlife populations. Wildlife-vehicle collisions (WVCs) often result in significant damage to vehicles, injury to their occupants, and are usually lethal to the animal. In Wyoming, the direct costs of wildlife-vehicle collisions total nearly $50 million per year. Wyoming is home to abundant large mammals, including long-distance migratory ungulates, such as mule deer, elk, and pronghorn, and the impacts of roads and vehicle collisions on these animals is a concern to transportation managers, wildlife managers, and the general public.

Transportation managers continue to evaluate the effectiveness of measures aimed at reducing WVCs. One possible measure is to reduce posted speed limits in areas known to have high WVC rates, particularly at dusk, night, and dawn, when the majority of collisions occur. The theoretical mechanism is that reduced posted speed limits will cause drivers to reduce their operating speed, which will allow drivers more time to react when they see an animal in the road; this, in turn, will enable drivers to avoid collisions with those animals. This mechanism is intuitive, and the idea of reducing the posted speed limit in key areas with high WVC rates is appealing to many because it is a relatively inexpensive measure that can be implemented on a short timeline. However, transportation engineers caution that drivers may operate at the design speed of the road or at a speed they feel comfortable with, rather than the reduced posted speed limit.

Although reduced night-time speed limits are being used in many places with the goal of reducing WVCs, there has been almost no research to evaluate this measure's effectiveness. We conducted a large-scale experiment in which posted speed limits were reduced from 70 mph to 55 mph during dusk to dawn hours in peak deer activity seasons at six sites in southwestern Wyoming. At three winter sites, we used a before-after-control-impact experimental design with the reduced speed limit in effect for seven months of the second winter of the study. At three migration sites, we used a before-after design with the reduced speed limit in effect for two months at a time in the fall and spring migration seasons. This study focused on mule deer, which make up the overwhelming majority of WVCs in Wyoming.

We collected field data at all sites on (1) vehicle speeds, using remote radar recorders, (2) deer road-crossing behavior using thermal video cameras, and (3) wildlife-vehicle collisions as measured by reported animal-vehicle crashes and roadside carcass removal records. At all six sites, drivers reduced their operating speeds in response to the posted speed limit reduction, but only by 3-5 mph rather than the 15 mph difference in posted speed limit. At winter sites, deer road crossings were equally risky regardless of posted speed limit, and we did not detect any reduction in WVCs. At migration sites, there was some evidence of fewer high-risk deer road crossings, and fewer crashes and collisions when the reduced speed limit was in effect. However, given that driver operating speeds were not different from winter sites it was not clear that these results could be attributed to the reduced speed limit.

Based on these results, we recommend that reducing the posted speed limit is not an effective measure to reduce WVCs on high-speed, rural, two-lane highways, unless other measures can be employed to effectively and consistently influence drivers to reduce their operating speeds.

CHAPTER 2. INTRODUCTION

Background and Rationale

Collisions between vehicles and large mammals pose a serious threat both to highway safety and to wildlife populations. Across the United States, an estimated 1-2 million WVCs occur every year.[1] In Wyoming, an average of nearly 6,000 deer-vehicle collisions—as measured by a composite of crash data and carcass counts—occur every year. Deer-vehicle collisions account for about 88 percent of all wildlife-vehicle collisions, with pronghorn (8 percent), elk (3 percent), and moose (1 percent) also contributing to the total large animal-vehicle collision count. Wildlife-vehicle crashes in Wyoming make up about 15 percent of all vehicle crashes (collisions with substantial vehicle damage and/or human injury) annually.

These collisions pose a safety hazard and are costly; they often result in substantial damage to vehicles, injury to their occupants, and are almost always lethal to the animal. WVCs occur when a vehicle strikes an animal, but animals on roads may also be the secondary cause of additional crashes, such as when a vehicle swerves to avoid an animal and instead drives off the road or into the oncoming lane. In some cases, WVCs are fatal to human occupants of the vehicle. In Wyoming, deer-vehicle collisions alone incur approximately $24-29 million per year, in injury and damage costs, and an additional $20-23 million per year in lost wildlife value.[2] Most likely the total number and value of lost wildlife is much higher since not all carcasses are retrieved, and by some estimates as many as 50 percent of hit animals leave the road or right-of-way before dying so are never recorded.[3]

Highways and vehicle collisions also have a significant negative impact on wildlife populations—reducing their numbers and impeding their movements through their seasonal ranges and along their migratory corridors.[4,5] Where highways create partial or complete barriers to wildlife movements, they threaten populations by impairing their ability to access the resources they need.[5] Wyoming supports one of the largest populations of ungulates in North America, and these animals are important economic and cultural players in the state. However, mule deer populations in Wyoming are in decline, as they are across most of the west, [6] and conserving their populations is an extremely high priority for the Wyoming Game and Fish Department (WGFD).[7] Roads have been identified as posing a significant threat to mule deer populations and their seasonal migrations in Wyoming and across their range.[8]

The Wyoming Department of Transportation (WYDOT) continues to work extensively to reduce the problem of WVCs, both to improve highway safety and to reduce negative impacts on wildlife populations. In the past decade, WYDOT completed highway under-and over-passes (hereafter, crossing structures), coupled with wildlife fencing, at several locations in the state. These have reduced WVCs by 80-90 percent in both the Nugget Canyon and Pinedale areas (from Pinedale to north of Daniel Junction)[9,10] with similar results reported for the Baggs area. Crossing structures have been found to be similarly effective at many other sites around the world.[11-14] Although highly effective, crossing structures are costly[15] and are not always feasible given constraints on road design and the fencing necessary to funnel animals towards safe crossing structures. Consequently, managers are always looking to test and develop alternative means of reducing WVCs that allow for improved driver and wildlife safety.

One possible mitigation measure is to reduce the posted speed limit (the maximum speed permitted by law) in areas known to have high WVC rates, particularly at dusk, night, and dawn, when the majority of collisions occur. A number of broad-scale analyses of the landscape variables associated with high WVC rates have shown that posted speed limit is positively related to collision rates. [16-21] For example, one study found that the odds of hitting a moose increased by 35 percent with each 4.9 mph increase in speed limit, with the highest odds of collisions occurring when speed limits were >44.7 mph.[17] In Wyoming, our own analyses have indicated 61 percent more deer-vehicle collisions in places with speed limits of 65 mph compared to 55 mph.[2] Although these findings suggest that reducing speed limits will reduce WVCs, this may not be the case because drivers tend to drive at the road's speed (the selected speed used to determine the geometric features of a road during road design) or a speed at which they feel comfortable, rather than the posted speed limit.[1,22,23] This problem may—or may not—be addressable through greater enforcement of the speed limit.[1,23] One challenge is that if speed limit is reduced over many and long road sections, greater enforcement levels may not be possible unless the overall law enforcement capacity is increased. Additionally, if people vary in their compliance to a posted speed limit that is well below the design speed of the road, this may cause speed dispersion, or wide variation in vehicle speeds, which can lead to increased incidence of accidents.[24] These lines of evidence have led many traffic engineers to assert that reduced nighttime speed limits in areas with high WVC rates may not be effective in increasing driver safety, and in fact, could reduce overall safety. However, many members of the public strongly believe that reduced speed limits are an effective and low-cost way to reduce the problem of WVCs in Wyoming.

Actual tests of whether reducing the posted speed limit at night are effective in reducing WVCs have been very limited. There are currently no peer-reviewed studies on this topic and only two white-paper studies. The Colorado Department of Transportation (CDOT) conducted the most comprehensive study of the effectiveness of reduced nighttime speed limit in locations with high WVC rates. They measured vehicle speeds before and after the nighttime speed limits were reduced and found no evidence that drivers slowed in response to the reduced speed limits.[25] Changes in WVC rates ranged from substantial decreases to substantial increases. The poor driver compliance and mixed results led CDOT to conclude that reducing nighttime speed limits was not effective. In a less comprehensive study in Jasper National Park in Canada, researchers also concluded that reducing the posted speed limit did not reduce the number of bighorn sheep hit by vehicles.[26]

Given the shortage of empirical data on the effectiveness of variable speed limits in reducing WVCs, we aimed to test their effectiveness using quantitative data obtained through a rigorous study design to inform the decision process on whether nighttime speed limit reduction should be considered to reduce WVCs and other impacts of roads on Wyoming's large mammals.

Study Questions

We used an experimental test of the effects of reduced nighttime speed limit, where the speed limit was reduced from 70 mph to 55 mph on six stretches of two-lane highway in southwestern Wyoming, during the time period from fall 2016 through spring 2018. We measured the effects

of this speed limit reduction on vehicle speeds, deer behavior in the presence of vehicles, and deer crash and carcass numbers. Specifically, we asked the following questions:

Question 1: Did drivers reduce their speed in response to posted night and twilight speed limit reductions?

Question 2: Did road surface and atmospheric conditions affect vehicle speeds and driver responses to reduced speed limits?

Question 3: Did driver responses to reduced speed limits differ among the start, middle, and end of the reduced speed limit zone?

Question 4: Was law enforcement presence higher when reduced speed limits were in effect?

We predicted that the reduced posted speed limit would be more effective in reducing vehicle operating speed (the speed at which vehicles generally operate) under some circumstances than others. Research on the effectiveness of signs warning drivers of the high potential for wildlife in the road indicates that these signs are not effective when present year-round, but can be effective if put in specific locations for a discrete period of time, e.g. peak collision season.[27,28] Drivers are generally thought to habituate to these signs and stop heeding them the longer the signs are up and the less specific they are in location. By the same logic, we expected drivers to better comply with the reduced posted speed limit when that reduction was in place for a limited duration. In our study, limited duration and spatially restricted reduced speed limit occurred at our migration sites, where highways crossed relatively narrow mule deer migration paths and posted reductions were in effect for two months at a time during the fall and spring migration seasons. Longer duration and less spatially restricted speed limit reduction occurred at our winter sites, where highways crossed through more diffuse mule deer winter ranges and posted reductions were in place for seven months at a time.

We also predicted that drivers would comply with posted speed limits more under adverse driving conditions, e.g. wet or slippery roads and/or poor visibility. We predicted that drivers would be more risk-averse under these conditions, resulting in greater compliance with posted speed limits. Further, we predicted that drivers would be more likely to comply with the posted speed limit in the first mile after their first encounter with a 55 mph reduced nighttime speed limit sign compared to several miles into the reduced speed limit stretch.

Question 5: Did reduced speed limit reduce the number of high risk deer-vehicle interactions?

Question 6: Did reduced speed limit increase the ease with which deer crossed the road?

Question 7: Did reduced speed limit decrease the number of deer-vehicle collisions?

We predicted that, if driver operating speed was reduced when the posted speed limit was reduced, that a lower proportion of deer-vehicle interactions would involve high levels of risk of collision. Further, we predicted that this would result in fewer WVCs. We predicted that reduced

driver operating speed would also enable deer to cross roads with greater ease—in other words, that they would require fewer attempts to cross the road.

CHAPTER 3. METHODS

Study Sites

Using our prior analyses of patterns of collisions in the state,[2] and in consultation with WYDOT District 3 Engineer, Keith Compton, we selected six study sites within District 3 (figure 1; table 1). Three of these are "migration" sites—sites where the available evidence indicates that deer primarily get hit as they cross the road while migrating between winter and summer seasonal ranges—and three are "winter" sites—sites where the available evidence indicates that deer get hit as they cross roads while migrating into the area in the fall, while overwintering in the area, and while migrating out of the area in the spring. Our data collection focused on different target months of the year based on our knowledge of peak deer activity at each site (table 1).

All study sites were rural, two-lane highways, in southwestern Wyoming, with posted daytime speed limits of 70 mph.

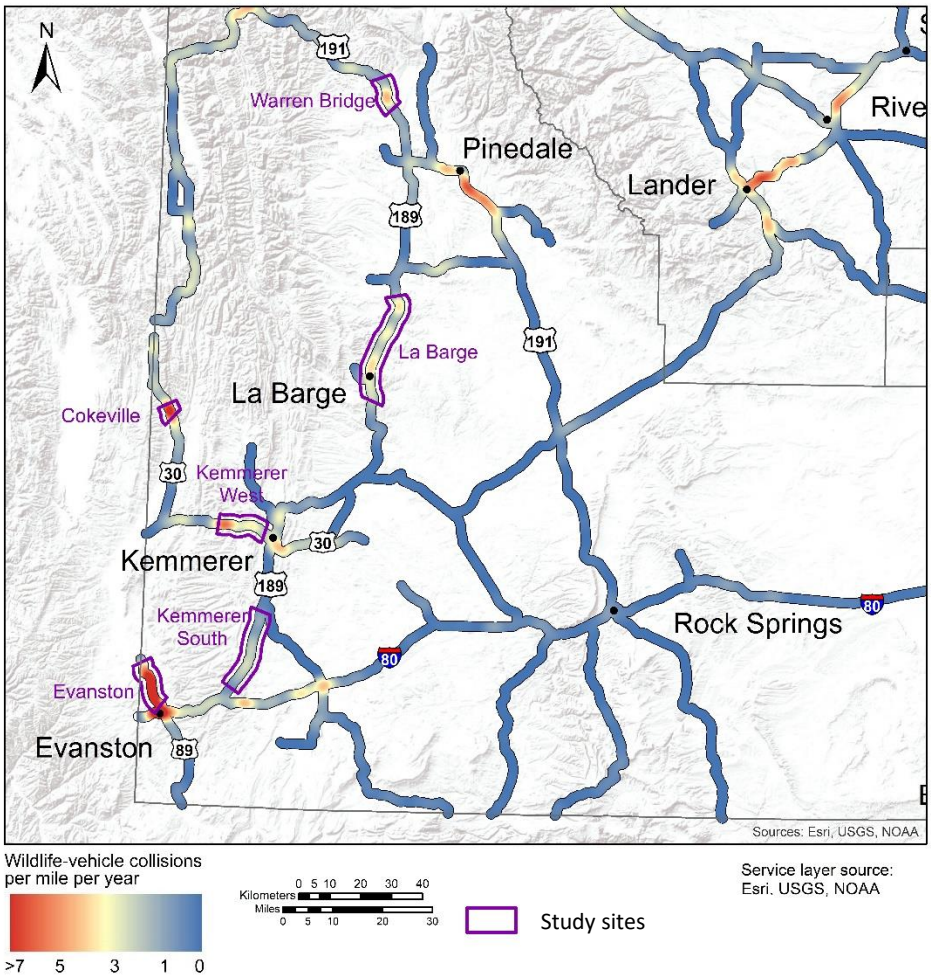

Figure 1. Map. Study site locations.

Table 1. Study site locations and months of data collection.

Road	Site Name	Mile Markers	Site Type	Study Design	Months of Study
US 189 (ML11B)	LaBarge	80.05 – 102.5	Winter	Before-after-control-impact	November - April
US 30 (ML12B)	Kemmerer West	43 – 51.3	Winter	Before-after-control-impact	November - April
US 189 (ML11B)	Kemmerer South	4 – 20	Winter	Before-after-control-impact	November - April
US 30 (ML12B)	Cokeville	4.5 – 8	Migration	Before-after	Oct-Nov and Apr-May
US 191 (ML13B)	Warren Bridge	122 – 128.5	Migration	Before-after	Oct-Nov and May-June (2017) or Apr-May (2018)
WYO 89 (ML50B)	Evanston	1.77 – 11.35	Migration	Before-after	Oct-Nov and March-Apr

Study Design

At all sites, our study included data collection before and after nighttime speed limits were implemented. WYDOT installed signs and flashing beacons to indicate the reduced nighttime speed limits. The signs displayed "Wildlife Crossing Area" at the start and end of the reduced speed limit area in both travel directions. Posted speed limit signs displayed a daytime speed limit (70 mph) and a nighttime speed limit (55 mph) "when flashing" (figure 2). A beacon on top of the sign was programmed to flash during the target months, starting from 30 minutes before sunset until 30 minutes after sunrise. Speed limit signs and flashing beacons were located approximately every 5 mi throughout each reduced speed limit area.

Figure 2. Photo. Split daytime and nighttime speed limit sign with flashing beacon.

Table 2. Before-after-control-impact experimental design used for winter sites.

Time	Stretch type	Posted night speed limit	Treatment combination
Winter 2016-17 (Y1)	Control stretch	70 mph	Y1-control
Winter 2016-17 (Y1)	Reduced stretch	70 mph	Y1-not reduced
Winter 2017-18 (Y2)	Control stretch	70 mph	Y2-control
Winter 2017-18 (Y2)	Reduced stretch	55 mph	Y2-reduced

Table 3. Before-after and before-after-case-control experimental design used for migration sites.

Time	Stretch type	Posted night speed limit	Treatment combination
Fall 2016	Reduced	70 mph	Fall 2016, not reduced
Spring 2017	Control*	70 mph	Spring 2017, control
Spring 2017	Reduced	55 mph	Spring 2017, reduced
Fall 2017	Control*	70 mph	Fall 2017, control
Fall 2017	Reduced	55 mph	Fall 2017, reduced
Spring 2018	Control*	70 mph	Spring 2017, control
Spring 2018	Reduced	70 mph	Spring 2018, not reduced

*Only for speed data, not behavior or collision data

At the three winter sites, we used a before-after-control-impact (BACI) study design (table 2). We collected data in fall-winter 2016-17 before nighttime speed limit signs were installed (year 1, or Y1). In fall 2017 and winter 2018, reduced nighttime speed limits were applied to half of each study site, leaving the other half unchanged (year 2, or Y2). This allowed us to compare differences in vehicle speeds, deer behavior, and collisions before and after nighttime speed limits were implemented while controlling for both spatial and temporal variability in road conditions and deer numbers. This is the most robust experimental approach possible for this study.

For the winter study sites, there were four combinations of time and treatment: (1) “Y1-control” = data from Y1 of the study from the half of the site that remained an untreated control in Y2; (2) “Y1-reduced” = data from Y1 of the study in the half of the site that was untreated in Y1 but had reduced speed limit in Y2; (3) “Y2-control” = data from Y2 of the study from the half of the site that remained an untreated control in both years; and (4) “Y2-reduced” = data from Y2 of the study from the half of the site that was untreated in Y1 but had reduced speed limit in Y2.

At the three migration sites, we used a before-after study design (table 3). We collected data in fall 2016, before nighttime speed limit signs were installed, and in spring 2017 and fall 2017 with nighttime speed limits in effect, and again in spring 2018 after the reduced speed limit signs were removed. Both fall 2016 and spring 2018 were intended to be “before” to compare against the two “after” time periods of experimental nighttime speed limit reduction. (Although spring 2018 was temporally after the reduced speed limit, the design was still a before-after design

because the two treatments, 70 mph and 55 mph speed limit, were applied at different times.) Unfortunately, several of the flashing beacons were malfunctioning in March and April 2017 at the Cokeville, Wyoming and Evanston, Wyoming sites, making data from that time period unreliable; we did not use those data in any of our analyses.

At migration sites, we also collected speed data in control stretches that were next to but outside the study stretches, making the speed data have a before-after-case-control study design (table 3). We could not do the same for deer behavior and collision data because there was not nearly as much deer activity in those adjacent stretches. Deer activity in migration sites was concentrated in specific, shorter segments of road, and therefore, any deer-related data collected outside those stretches were not comparable to data collected inside the migration stretches.

Vehicle Speeds

Data Collection

We measured vehicle speeds and gaps between vehicles using five radar recorders (JAMAR Technologies Inc., Hatfield, PA) for approximately 4-5 days per month of the study at each site. WYDOT installed dedicated posts for the radar recorders at predetermined locations. At migration-only sites, two radars were located 0.5 mi inside the reduced speed limit zone (one on each end), with a third radar in the middle of the reduced speed limit zone, and an additional two radars located > 1 mi outside the study site where speed limit was not reduced starting in Spring 2017 (figure 3a). (Note that at Evanston no suitable locations could be found outside the study site with the same speed limit as the daytime speed limit within the study site.) At winter-long sites, three radars were located inside the reduced speed limit zone (0.5 mi from each end and one in the middle) and two were located in the control zone (figure 3b). We positioned the radar locations within the reduced speed limit stretches at the beginning, middle, and end of the stretch to be able to investigate whether vehicle speeds differed among these locations for both directions of travel.

We also obtained road condition data from WYDOT and enforcement records from the Wyoming Highway Patrol. Road condition data were recorded by WYDOT maintenance staff and included descriptions of road surface conditions, such as ice or blowing or drifted snow, and atmospheric conditions such as precipitation and fog, and the time window and mile posts for the stretch corresponding to the description. Enforcement data consisted of warnings and citations and were referenced by time, date, and the nearest mile post.

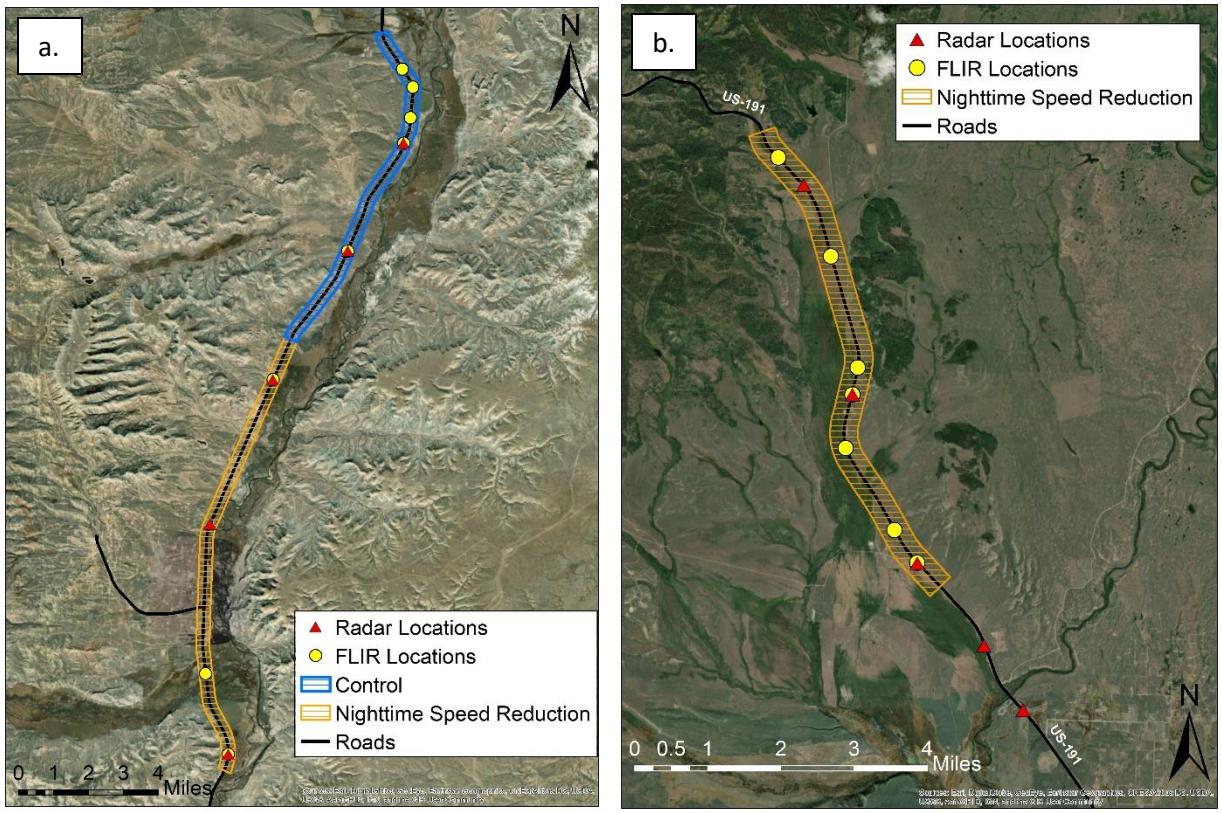

Figure 3. Maps. Radar recorder and thermal camera (FLIR) locations for (a) a winter site, and (b) a migration site.

Data Processing

Prior to analyzing the speed data, we performed several steps of data manipulation:

1. We removed observations from March and April 2017 at Cokeville and Evanston when flashers were malfunctioning. This left 1 month of spring 2017 data from Cokeville (May) and no spring 2017 data from Evanston.
2. We removed vehicles with recorded speed >200 mph, which we assumed to be faulty recordings.
3. We removed vehicles with recorded speed <35 mph, which we assumed were vehicles that were not at full traveling speed (e.g. had just entered the highway or were slowing to turn or pull off the highway).
4. We classified vehicles into two length categories: vehicles 6.5-22 ft in length we classified as "passenger vehicles" and vehicles > 22 ft in length we classified as "cargo vehicles." (We excluded the <5% of vehicles that had recorded lengths <6.5 ft, which were likely the result of radar recorder errors in most cases).
5. We assigned each vehicle to a direction of travel based on which lane it was in.
6. We assigned each site to the nearest major town (Pinedale, Wyoming, Kemmerer, Wyoming, and Evanston, Wyoming) for which U.S Naval Observatory sunrise and sunset data were available.[29] We used sunrise and sunset data to define three time periods for each day of speed data: "dusk" = 25 minutes pre-sunset until 30 minutes

post-sunset; “night” = 30 minutes post-sunset until 30 minutes pre-sunrise; and “dawn” = 30 minutes pre-sunrise until 25 minutes post-sunrise. We used 25 minutes instead of 30 minutes pre-sunset and post-sunrise to allow some buffer in case the U.S. Naval Observatory sunrise and sunset data did not perfectly match the sunrise and sunset times used by WYDOT to program the flashing beacons. For ease of analysis, we grouped “dusk” and “dawn” observations into a single “twilight” category, which we compared against “night” observations. All observations collected between 30 minutes post-sunrise and 30 minutes pre-sunset were grouped into a “daytime” category.

7. We obtained WYDOT road condition data matched to each road segment and time period where vehicle speeds were measured. One radar recorder was located outside of any road segment where road condition data were available; vehicles from this recorder were assigned conditions from the nearest road segment (< 2 mi away). Road condition data were also collapsed into three categories for analysis: “good”, “moderate”, or “poor”. Atmospheric and surface condition data were collapsed independently as follows:
    a. Atmospheric conditions recorded by WYDOT varied widely but reflected either “favorable” conditions or various combinations of severe or moderate wind, snow, fog, and rain. Vehicles that passed our radar detectors in “favorable” conditions were assigned to the “good” category. Vehicles measured in conditions with snowfall, blowing snow, fog, or otherwise limited visibility were assigned “poor”, and all other conditions were assigned to the “moderate” category. (see appendix A for details).
    b. Road surface data included conditions such as “dry”, “wet”, “slick in spots”, “slick”, and “drifted snow”. Vehicles recorded with “dry” roads were assigned to “good”, vehicles with “slick” conditions were assigned a value of “poor”, and all others were assigned a surface conditions value of “moderate”. (see appendix A for details).
8. We created a data subset from which we removed all vehicles that had <10 seconds following distance from the preceding vehicle. We did this to remove platooned vehicles—that is, vehicles whose speed was likely being influenced by the vehicle(s) in front of them. We did this to assess the speed of independently-acting drivers so that we could best answer the question of “does reduced posted speed limit lead to changes in driver behavior.” However, we recognize that a second relevant question is “how does reduced posted speed limit affect the speed of all traveling vehicles”; to answer this we used the full data set of all vehicles, regardless of following distance.

Data Analysis

Question 1: Did drivers reduce their speed in response to posted night and twilight speed limit reductions?

For winter site data, we used the standard approach to analyzing BACI experiments: we used a two-way analysis of variance (ANOVA) with main and interacting effects of “year” (where Y1 = before speed limit reduction and Y2 = after speed limit reduction) and “treatment” (where control = the control stretch where the speed limit was never reduced, and reduced = the reduced

stretch where limit was reduced in Y2). We used the speed of the non-platooned (independent) vehicles as the response variable to be able to ask whether independently-acting drivers reduced their speed. A significant interaction between year and treatment would indicate an effect of reduced night-time posted speed limit because the combination of Y2-reduced led to different vehicle speeds than any other combination of year and control versus reduced stretch (see Chapter 4: Results for a more detailed explanation). We applied this analysis separately for cargo and passenger vehicles at night, twilight and daytime. Daytime drivers did not experience reduced speed limits, so daytime speed data serves as another form of control against which to compare speed data from reduced speed limit conditions. We also analyzed data separately for each of the three winter sites since the patterns were somewhat different from site to site.

For migration site data, the study design did not allow a BACI analysis. We analyzed all combinations of time (e.g. fall 2016, spring 2017), and whether the radar recorder was in the migration site (where speed limit was reduced in spring and fall 2017) or outside the migration area (where speed limit was never reduced) as one-way ANOVAs. We then used Tukey's tests to compare targeted pairs of these combinations, such as spring 2017, inside the migration site versus outside. We ran separate models for each site, and for cargo and passenger vehicles at night, twilight and daytime.

In addition to understanding how independently-acting drivers respond to speed limit changes, we were also interested in understanding how the speed limit change affected the speeds of all drivers, whether traveling in platoons or not. To examine this, we calculated the 85th percentile of vehicle speeds for the full data set (including platooned vehicles) for each combination of vehicle type, time (night, twilight, daytime), and study site under each set of year and treatment conditions.

Question 2: Did road surface and atmospheric conditions affect vehicle speeds and driver responses to reduced speed limits?

This study encompassed two very different winters in western Wyoming. The winter of 2016-17 (Y1) experienced precipitation, in the form of snow, well above average (January and February were 215 and 214 percent above average, respectively) and below-average temperatures in December and January.[30] The winter of 2017-18 (Y2) was a much more benign winter, with precipitation below average and temperatures above average for all months of the winter. [31

In order to understand how these different winter conditions might have affected our results, we calculated the percent of vehicle speed observations that occurred under "good", "moderate" and "poor" road surface and atmospheric conditions in all combinations of year and treatment. We used these to help interpret differences in average speeds between years and across sites.

We also wanted to know whether drivers responded to reduced speed limits differently in good versus poor weather conditions. Adverse weather conditions might cause all drivers to go slower, regardless of posted speed limit. Alternatively, drivers might heed a reduced speed limit more in adverse conditions than benign conditions. To examine possible differences in driver response to speed limit depending on conditions, we analyzed winter site data separately for surface conditions = "good" compared to surface conditions = "poor" and atmospheric conditions =

"good" compared to atmospheric conditions = "poor". Because "moderate" surface and atmospheric conditions encompassed a wide variety of conditions, we did not include them in this analysis. We performed this analysis only for night data and passenger vehicles, since drivers overall tended to slow more at night and since passenger and cargo vehicles had otherwise similar responses to reduced speed limit. We used the same ANOVA models as described above for winter sites. Because there were very few observations under "poor" conditions at Kemmerer South, we only did this analysis for LaBarge and Kemmerer West.

Question 3: Did driver responses to reduced speed limits differ among the start, middle, and end of the reduced speed limit zone?

We hypothesized that drivers would slow down after encountering the first reduced speed limit sign and flashing beacon but that their speeds would increase several miles into the reduced speed limit zone. To test whether this was the case or not, we separated data from each winter site by direction of vehicle travel (e.g., northbound vs. southbound lanes) and compared speeds at each radar location. The placement of radar locations allowed us to compare driver speeds 0.5 mi into the reduced speed limit stretch, halfway through it, and 0.5 mi from the end of the stretch. Reduced speed stretches ranged from 4.5 to 11 mi. We compared speeds at these three locations using one-way ANOVAs with radar location as the predictor. We again focused on passenger vehicles at night as a relevant subset of all vehicles. We focused on winter sites because the reduced speed limit stretches are longer than at migration sites, and we had hypothesized that drivers might not sustain reduced speeds over these longer stretches.

Question 4: Was law enforcement presence higher when reduced speed limits were in effect?

We tallied the number of citations and warnings that occurred within each study area during each time period of the study and divided this by the number of days in that time period to get a standardized number of citations and warnings per night. We used this standardized number as our indicator of law enforcement presence. The ideal measure would have been the number of hours of enforcement presence in each study stretch—regardless of whether they issued citations or not; however, it was not possible to obtain this information. Unfortunately, no enforcement data were available for the Kemmerer South site.

Deer Behavior

Data Collection

We collected data on deer-road and deer-vehicle interactions using three Forward Looking Infrared (FLIR) Scout and one Scion model outdoor thermal monoculars (FLIR Systems, Inc., Stillwater, OK) deployed for approximately 4-5 days per month of the study at each site. Each FLIR monocular was mounted in a metal housing on top of a post so that it had a clear view of the road and the right of ways to the extent possible. Each FLIR was connected to a deep cycle battery for power and a laptop to which it recorded footage continuously over the course of the whole night. The battery and laptop were housed in a metal box at the base of the pole, and all

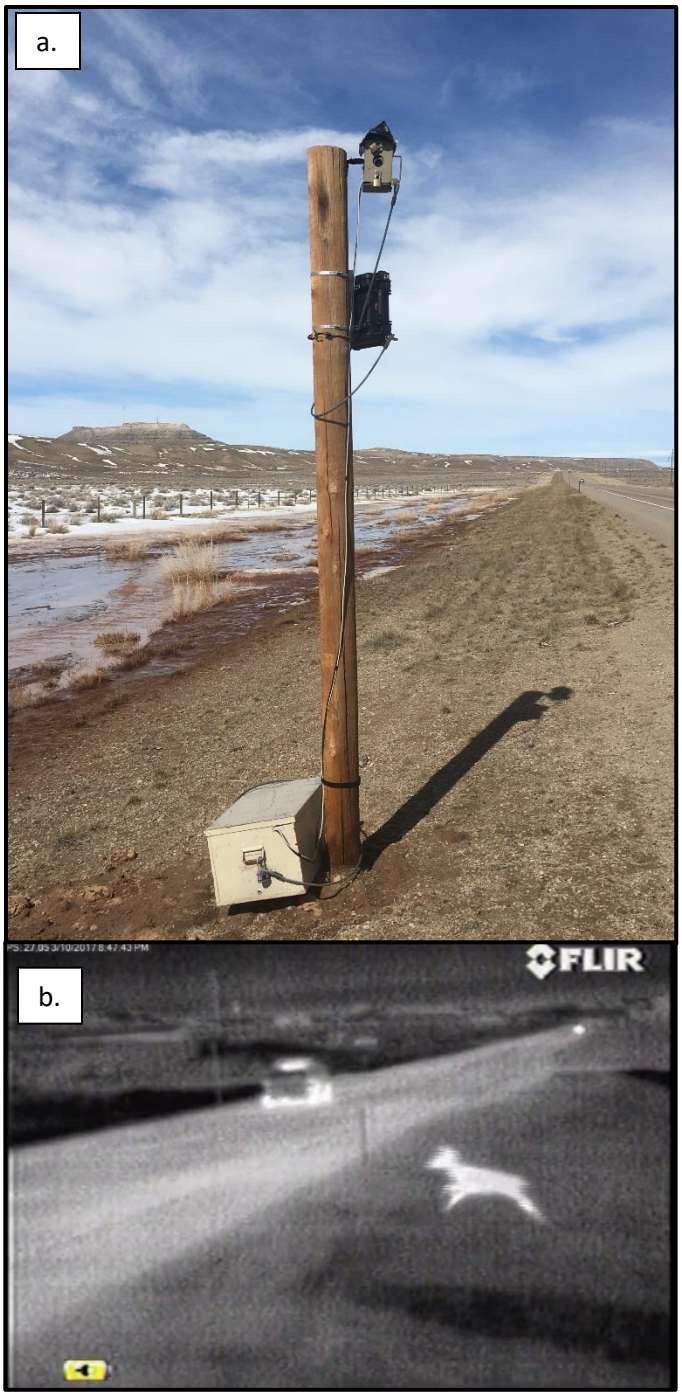

Figure 4. Photos. (a) FLIR set up in the field and (b) FLIR image of a deer-vehicle interaction.

equipment was locked to the pole (figure 4). In winter sites, two FLIRs were deployed in the reduced speed limit stretch and two in the control stretch. At migration sites, all four FLIRs were located within the study area. Within study sites, we positioned the FLIRs in locations with high deer road-crossing activity in order to maximize the number of deer crossings captured on video.

We reviewed thermal video footage to find deer-road interactions during the dusk-dawn periods defined above for the vehicle speed data. We only scored deer behavior for deer-road interactions that were relatively close to the camera and clearly visible. We defined a deer-road interaction as starting when a deer in the right-of-way (ROW) moved directionally towards the road with intent to cross (moving consistently towards road and/or waiting to enter the road) and ending with (a) a successful crossing and exit from road on other side, or (b) failure to cross, with the deer exiting view and not immediately re-entering the ROW or staying in view but no longer showing intent to cross (e.g. if it started grazing). In between the start and end of a deer-road interaction, a deer could make several attempts to cross. We defined an attempt to cross as the deer approaching the edge of the road and either continuing onto the road or turning away from the road.

In many cases, deer were part of a group of two or more animals. We defined group members as having fewer than 120 seconds between consecutive animals attempting to cross at the same place and in the same direction. If a deer was part of a group, we identified the deer's order in the group (first, second, third, etc.) and the group size. We also recorded the start and end time of the group-road interaction, which began with the first deer showing intent to cross and ended when the last deer completed crossing or failed to cross.

For each deer-road interaction, we recorded the number of attempts to cross, whether the deer successfully crossed the road or not, and whether or not there was a deer-vehicle interaction. We defined a deer-vehicle interaction as the situation where a deer and a vehicle were close enough to each other that there was potential for the deer to get hit. For each deer-vehicle interaction, we scored the overall risk level of the interaction as follows:

- Collision: vehicle hit deer
- Narrowly-avoided collision: deer was within a few feet of the vehicle and the deer and vehicle would have collided without a major behavior change on the part of the driver (swerving, braking suddenly) and/or deer (moving out of the way)
- High risk: deer and vehicle were within close proximity of each other and typically the deer or the driver modified behavior as a result of the interaction
- Medium risk: deer crossed in front of the vehicle but was not immediately threatened by the vehicle
- Low risk: vehicle was on the road at a time when a deer was showing intent to cross, but the deer did not attempt to cross right in front of the vehicle

For all collisions and narrowly-avoided collisions, we recorded the type of vehicle involved (passenger car, pickup truck, cargo vehicle) and the driver's behavioral modifications, such as swerving or slowing.

For each group-road interaction, we also counted the number of vehicles that passed during the entire duration of the interaction.

Data Analysis

We recorded 1,087 deer-road interactions, of which 350 were deer-vehicle interactions. Most deer-road interactions occurred when there was no vehicle present. Although we put out FLIRs at all sites in a fairly equal distribution, the distribution of deer-road interactions and deer-vehicle interactions was highly unequal across sites, times (years for winter sites and fall/spring seasons for migration sites), and reduced versus control sections of road at winter sites. This impacted data analysis and interpretation. Replication was too low to analyze sites separately, but pooled data sets were highly unequal in where the observations came from for both winter sites (figure 5) and migration sites (figure 6). For example, when behavior data from all winter sites was pooled together, Y1-control and Y2-control data were mostly represented by LaBarge, whereas Y1-reduced data was mostly from Kemmerer West and Y2-reduced data was mostly from Kemmerer South. There were almost no deer-road interactions in Y2 at Kemmerer West. These disparities were consequential because deer behavior differed among sites, as explained

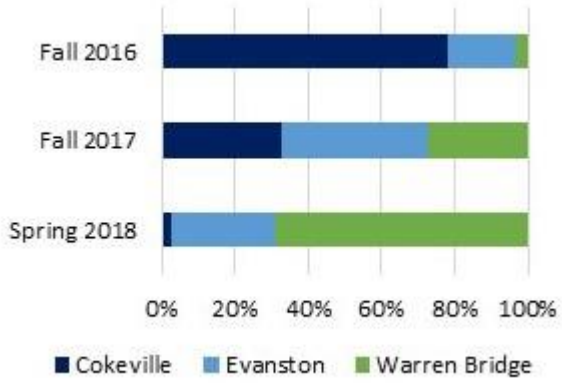

Figure 5. Graph. Percent of deer-road interactions from each site that contributed to pooled datasets for winter sites.

further in Chapter 4: Results. One possible solution to this problem would have been to randomly subsample deer from each site to create more equal representation of sites in the pooled datasets, but there were not enough deer-road interactions to do this.

For migration site data, even when all sites were pooled, there were only three deer-vehicle interactions observed in spring 2017 after excluding Evanston data and March Cokeville, Wyoming, data (due to faulty flashers at that time). This was insufficient data to be able to analyze any patterns for spring 2017, leaving fall 2017 as the only migration data from reduced night speed limit conditions at these sites.

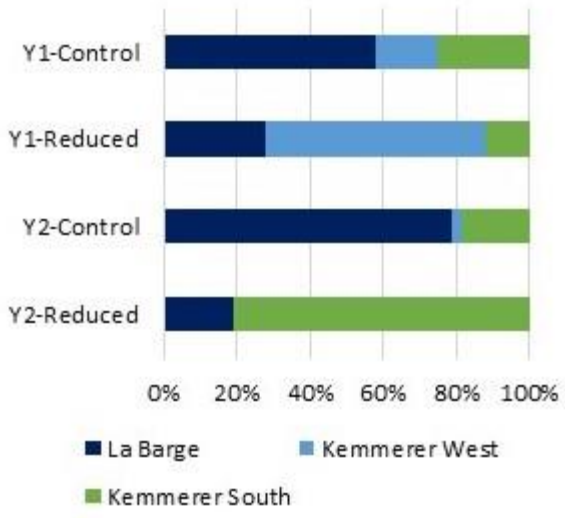

Figure 6. Graph. Percent of deer-road interactions from each site that contributed to pooled datasets for migration sites.

Question 5: Did reduced speed limit reduce the number of high risk deer-vehicle interactions?

Question 6: Did reduced speed limit increase the ease with which deer crossed the road?

To address these two questions, we analyzed three key outcomes of deer-road interactions:

1. The risk level of the interaction, as an indicator of human safety and risk of deer mortality.
2. The number of attempts to cross that the deer made, as an indicator of how much of a barrier the road was for the deer.
3. Whether or not the deer was ultimately successful in crossing the road or not, also as an indicator of how much of a barrier the road was for the deer.

To facilitate statistical analyses of risk, we collapsed the five risk levels into two: “higher risk” = collisions, narrowly-avoided collisions, and high-risk interactions, and “lower risk” = medium and low risk interactions. We examined the effects of experimental treatments, site and traffic levels (vehicle counts) on these behavior responses. All but traffic levels were categorical variables, and we tested their effects on the categorical deer behavior variables using chi-squared tests.

For traffic levels, we considered the total vehicle count during the entire group-road interaction as well as this number divided by the duration of the group-road interaction to get a standardized rate of vehicles per minute. These captured two different ways that traffic might affect deer and allowed us to examine whether (a) deer responded to the traffic dynamics experienced by the whole group during the entire group-road interaction, which captured how deer respond to one or two vehicles versus a platoon of vehicles, or (b) deer responded simply to the volume of traffic,

or standardized rate of vehicles per minute, at the time when they were attempting to cross the road.

We used one-way analysis of variance to examine the relationships between traffic count data and deer behaviors. To facilitate visualization of deer behaviors in response to traffic variables, we divided traffic count data into quartiles (25th percentile and below, 25th-50th percentile, etc.) and showed deer behavior for each traffic quartile. This allowed us to display the effects of traffic in the same way that we displayed the effects of the other predictors of deer behavior.

Wildlife-Vehicle Collisions

Data Collection

We used two sources of data to examine the effects of reduced speed limit on the number of WVCs. First, we used WYDOT's animal-vehicle crash data; these are crashes that resulted in some significant level of damage or injury and were reported to highway patrol. We used only deer-vehicle crash data in our analyses. Second, we used roadside carcass counts of deer; these are the number of dead deer collected and removed by WYDOT highway maintenance crews. (Although other species of interest were recorded in both the crash and carcass data, such as moose, elk, and pronghorn, these were few in number and we excluded them from analyses.) Carcass count data have a number of challenges: maintenance crews differ in the frequency with which they remove carcasses, and sometimes carcasses are too decomposed to be counted or removed by the time a maintenance crew comes through. Carcasses can also get buried in snow so they are only counted after the winter is over. This was particularly true in Y1 of the study, which experienced very high snowfall and a deep snowpack that trapped many carcasses until spring. By the time the snow melted, many carcasses were in such decomposed condition that they were never removed or reported, resulting in an under-estimation of deer-vehicle collisions that winter. For our study, these biases are more of a problem for the migration sites; the before-after-control-impact design at our winter sites accounts for year to year variation effectively. Crash data have fewer biases than carcass data. However, crash numbers were far lower than carcasses numbers, so that analyses of crash data have less power than analyses of carcass counts.

Crash data come with GPS coordinates and a time associated with the incident. We queried WYDOT's crash database to identify the deer-vehicle crashes that occurred in our study areas during the months of the study and during dusk, dawn, or night hours, as defined above. Carcass data are typically recorded by highway maintenance crews to the nearest whole mile or, less often, tenth of a mile. We worked with maintenance supervisors to have crews record GPS locations of carcasses near our study sites so that we could accurately assign each carcass to the treatment (control or reduced speed limit) in effect at that location at that time. However, the time of day an animal was hit was unknown for the carcass data so carcass counts may include animals that were hit during daytime hours.

Data Analysis

Question 7: Did reduced speed limit decrease the number of deer-vehicle collisions?

We wanted to ensure a thorough analysis of the potential effects of speed limit reduction on deer-vehicle collisions, considering multiple possible ways of looking at the data. To accomplish this, we analyzed crash and carcass data in three ways.

First, we used chi-squared tests for the winter study sites to ask whether the proportional distribution of crashes and carcasses was equal or unequal among the four combinations of year and treatment. We did this for each site separately (less statistical power, but enabled us to assess whether results were consistent or divergent among sites) and for all three sites combined (more statistical power, but obscures consistencies or differences among sites). This approach could only be used for the winter site data.

Second, we used analysis of variance for crash and carcass data from all three winter sites, with site as a random effect and year, treatment, and the year x treatment interaction as fixed effects. In this BACI design, an interaction between year and treatment (year x treatment effect) would indicate an effect of the reduced speed limit. We standardized crashes and carcasses to a per mile rate over the six month winter period for these analyses.

Third, we used paired *t*-tests to analyze crash and carcass data from the three migration sites, including fall data from all three migration sites and spring data from Warren Bridge. Data were again standardized to per mile rates of crashes and collisions per two-month migration period. We paired data by sites and compared them under the conditions of 70 mph and 55 mph (reduced night speed limit) conditions. Warren Bridge was the only migration site for which we had paired data for both the fall and spring, and we kept these separate in the analyses by treating fall and spring as separate "sites." In this before-after analysis, a significant effect would indicate an effect of reduced speed limit.

CHAPTER 4. RESULTS

For all of our winter sites, where we used a BACI design, there were several different possible results scenarios, only one of which would provide evidence for an effect of reduced speed limit. Some of the possible scenarios are given here using hypothetical examples of crash data, but the same concept applies for interpretation of speed data, deer behavior data, and collision data. These hypothetical examples give a general framework for understanding the BACI results.

Across our four combinations of Y1-control, Y1-reduced, Y2-control, and Y2-reduced, the number of crashes could have differed for several reasons. First, the paired control and reduced speed limit sections of road might have had different risk of crashes, despite our efforts to pick two similar stretches of road. Second, the risk of crashes could have varied from year to year because of differences in deer population size, deer presence near the roads, or weather conditions that affected, visibility, driver speed, and deer food accessibility. Third, crashes might have changed in response to the reduced speed limit. As a consequence of these different factors all operating at once, there were several possible scenarios of results (figure 7):

- Scenario 1: Similar numbers in all year-treatment combinations—indicating that control and reduced sections were well matched in terms of risk of crashes, there was no year-to-year variation in the number of crashes, and there was no effect of reduced speed limit.
- Scenario 2: Consistently different number of crashes in control versus reduced sections in both years—indicating that the two sections were not well matched in terms of risk of crashes, but there was no effect of reduced speed limit. This could manifest with, or without, differences in risk of crashes between years.
- Scenario 3: Different number of crashes between years but proportional in both control and reduced sections—indicating that the two years differed in terms of overall risk of crashes, but there was no effect of reduced speed limit.
- Scenario 4: Scenarios 2 and 3 operating simultaneously, but no effect of speed limit.
- Scenario 5: Proportionally fewer crashes in Y2 in the reduced speed limit section compared to other combinations of year and treatment—indicating an effect of reduced speed limit.
- Scenario 6: Scenario 5 with year-to-year variation in risk and differences in risk between control and reduced stretches.

For migration sites, we used a before-after (behavior and collisions) and before-after-case-control (speed data) experimental design. Interpretation of results from the before-after design involves only two things to compare: unaltered speed limit (before) and reduced speed limit (after). However, interpretation is difficult because a change between these two situations could have been caused by one or more factors—such as changes in deer population size, changes in deer activity, and effect of speed limit reduction—and we cannot know which or how many were operating. This does not invalidate data from a before-after design, but it makes it harder to draw strong conclusions than from a BACI design. The before-after-case-control design used for speed data is more straight-forward to interpret, since it also allows comparison of reduced speed limit conditions against unaltered speed limit conditions at the same time.

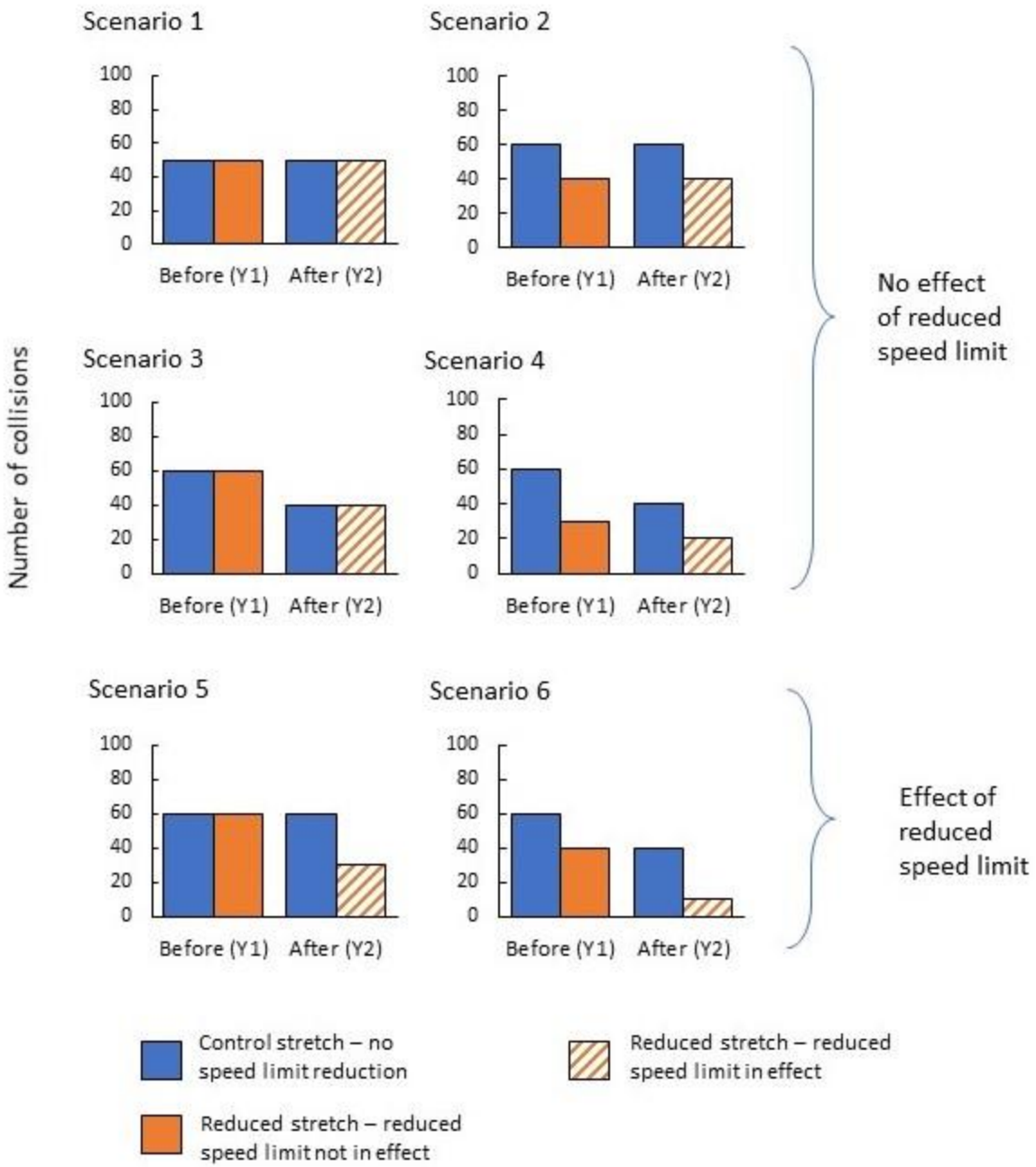

Figure 7. Graphs. Hypothetical scenarios of crash data results to illustrate interpretation of results from a BACI experimental design.

Vehicle Speed

Due to the very high number of vehicles for which we obtained speed data, our statistical power to detect differences was very high. This means that there could be statistically significant differences among different sites or different conditions, even when the magnitude of those differences is small. For example, a difference in average speed of only 1 mph was statistically

significant in our analyses. It is therefore important to also look at the magnitude of differences in addition to the probability values (*p*-values, or significance) of the results.

Question 1: Did drivers reduce their speed in response to posted night and twilight speed limit reductions?

Drivers at all sites—three winter and three migration—drove more slowly when the speed limit of 55 mph was in effect compared to when the flashing beacons were off and the speed limit was 70 mph. Passenger and cargo vehicle drivers consistently showed the same patterns, with cargo vehicles traveling slightly slower than passenger vehicles. For the sake of simplicity, and because drivers of passenger vehicles are more vulnerable to injury from wildlife-vehicle collisions, we have presented results for passenger vehicles only. Results for cargo vehicles are available on request from the authors of this report.

At all three winter sites, there were significant interactions between year and treatment, both during night and twilight hours (table 4), indicating that drivers slowed under the conditions of Y2-reduced speed limit when the posted speed limit was 55 mph. These interactions were not present during daytime hours, providing additional evidence that drivers were responding to the reduced posted speed limit.

Table 4. Results of analysis of variance models testing the effects of year, treatment, and year x treatment interactions on passenger vehicle speeds for three times of day at three winter study sites.

	Night		**Twilight**		**Daytime**	
	F value	*p* value	*F* value	*p* value	*F* value	*p* value
LaBarge (n=18,435)						
Year	593.0	<0.0001	179.6	<0.0001	395.1	<0.0001
Treatment	608.8	<0.0001	171.6	<0.0001	16.6	<0.0001
Year*Treatment	415.4	<0.0001	114.4	<0.0001	21.7	<0.0001
Kemmerer West (n=25,410)						
Year	304.4	<0.0001	222.9	<0.0001	2136.4	<0.0001
Treatment	397.1	<0.0001	108.2	<0.0001	6.5	0.01
Year*Treatment	207.6	<0.0001	84.9	<0.0001	0.4	0.53
Kemmerer South (n=21,391)						
Year	247.5	<0.0001	148.1	<0.0001	4453.5	<0.0001
Treatment	804.4	<0.0001	209.0	<0.0001	13.7	<0.001
Year*Treatment	420.4	<0.0001	118.0	<0.0001	0.6	0.45

At LaBarge, passenger vehicles at night traveled an average of 65.7-66.2 mph when the posted speed limit was 70 mph, both in Y1 and Y2, compared to an average of 60.9 mph when the posted speed limit was 55 mph (figure 8a). The pattern was the same at twilight, with overall speeds slightly higher (figure 8b). During daytime hours, there was a significant interaction

between year and treatment (table 2) but this was driven by slightly lower speeds in the reduced stretch in Y1, rather than Y2; in Y2, average speeds were identical in the control and reduced stretches (70.1 mph; figure 8c).

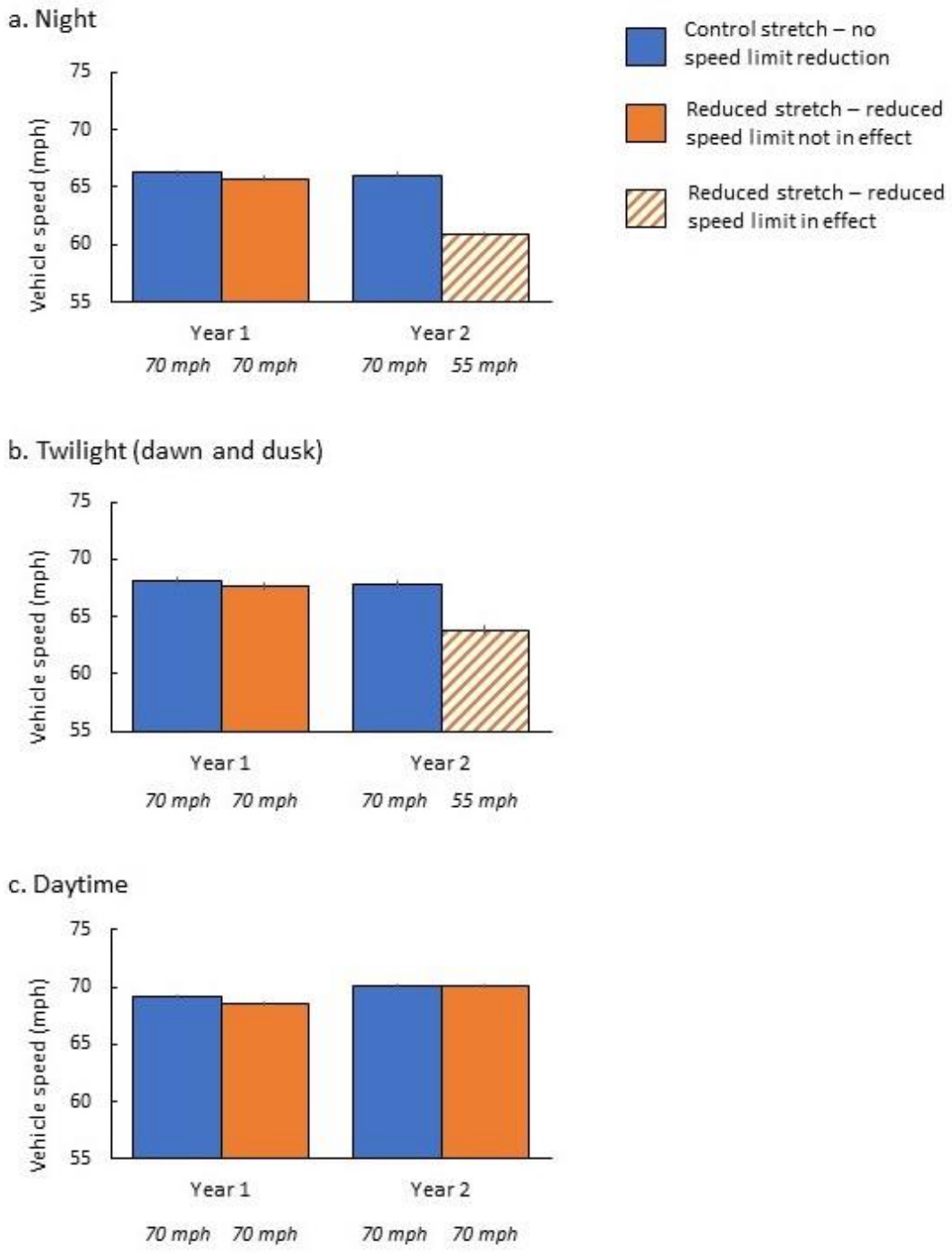

Figure 8. Graphs. Mean (± standard error) vehicle speeds at LaBarge.

At Kemmerer West, drivers generally traveled at higher speeds in Y2 than Y1. At night, vehicles in Y1 averaged 64.9 and 64.6 mph in control and reduced stretches, respectively, whereas vehicles in Y2 averaged 68.6 mph in the control stretch and 65.1 mph in the reduced stretch, where the posted speed limit in effect was 55 mph (figure 9a). As at LaBarge, the pattern was the same at twilight, with overall speeds slightly higher (figure 9b). During daylight hours, there was

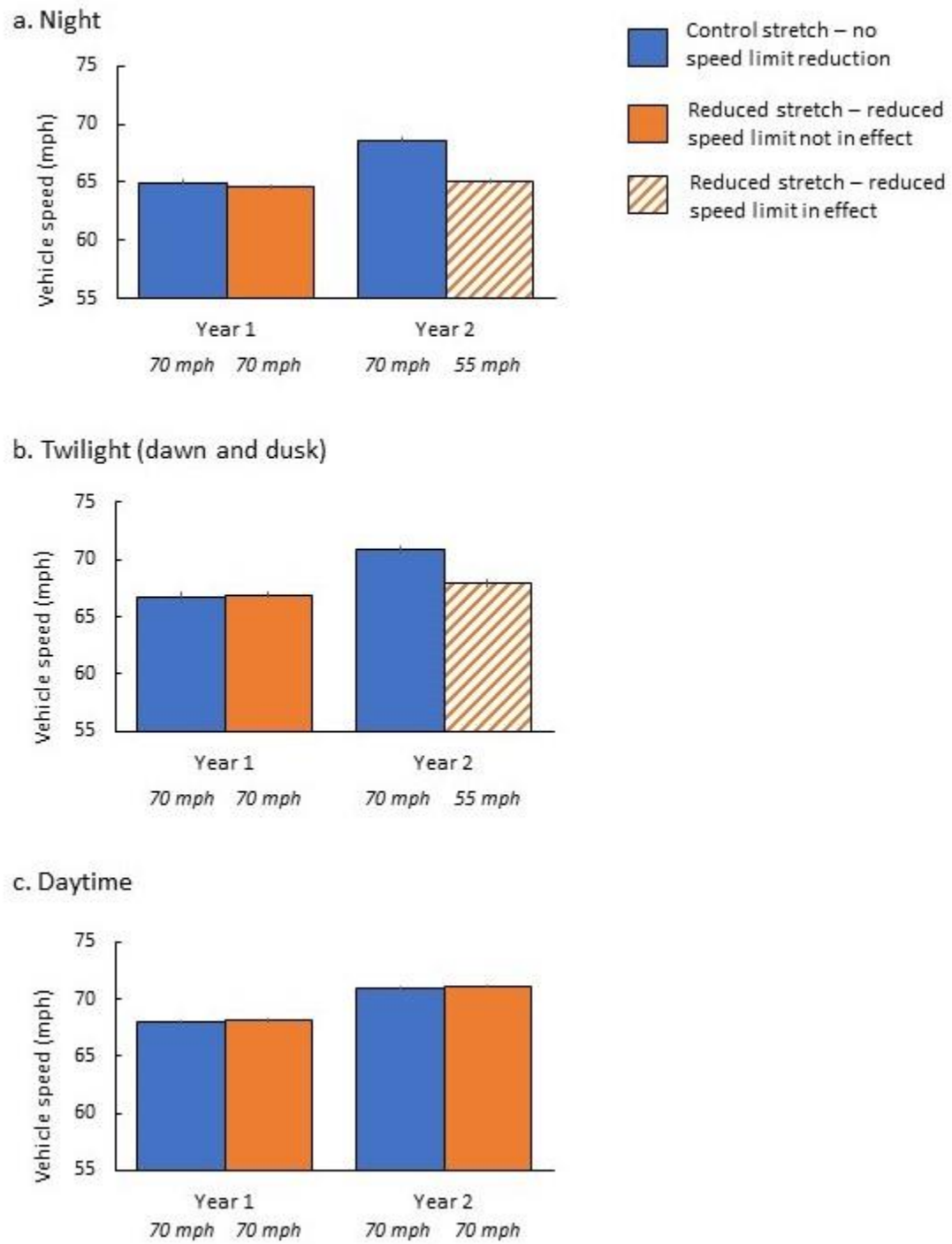

Figure 9. Graphs. Mean (± standard error) vehicle speeds at Kemmerer West.

a strong effect of year but no year by treatment interaction (table 4). Vehicles averaged 67.9 and 68.1 mph in the control and reduced stretches, respectively, in Y1, versus 71.0 and 71.1 mph in these stretches in Y2 (figure 9c).

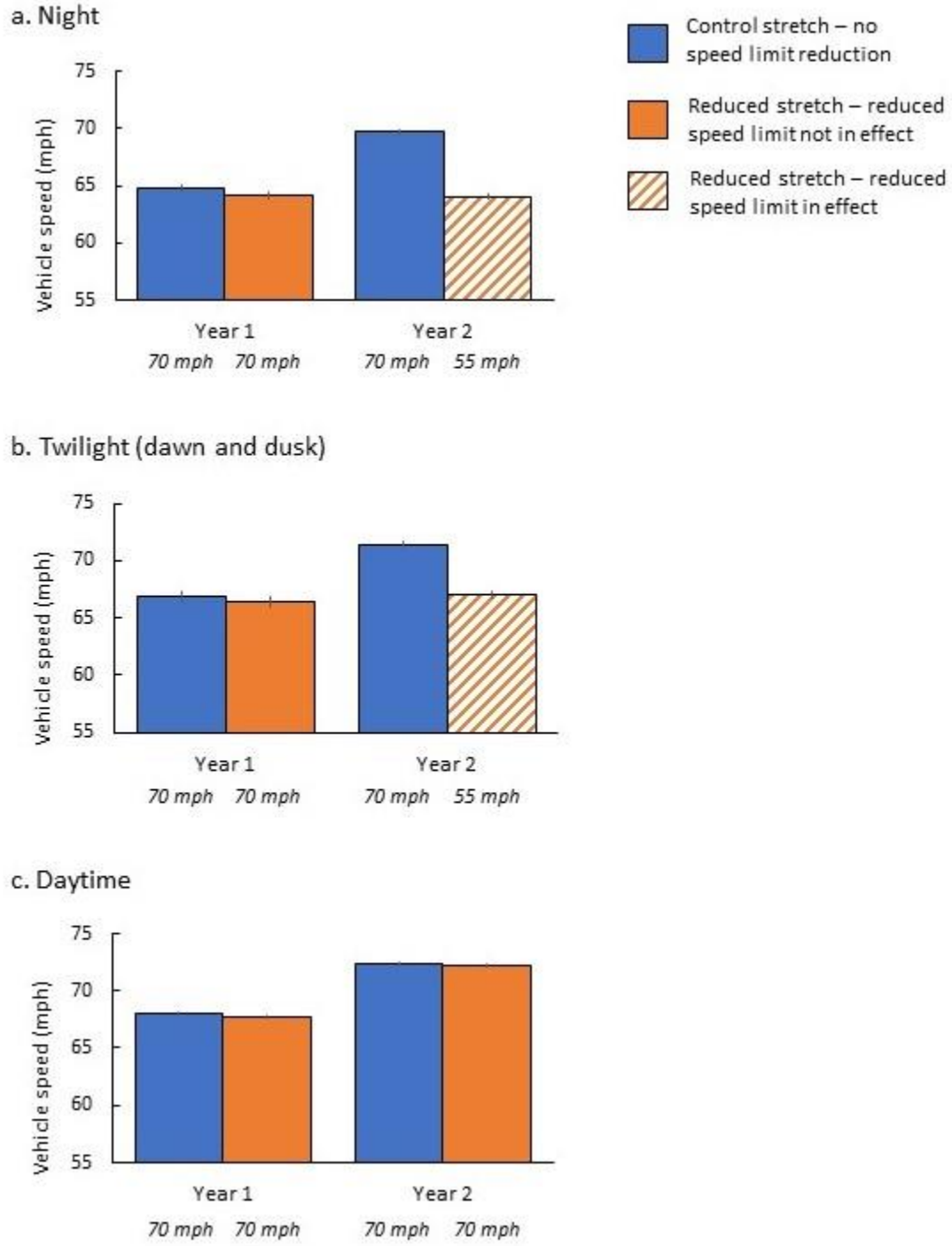

Figure 10. Graphs. Mean (± standard error) vehicle speeds at Kemmerer South.

At Kemmerer South, speed patterns were very similar to Kemmerer West. At night, vehicles in Y1 averaged 64.7 and 64.1 mph in control and reduced stretches, respectively, whereas vehicles in Y2 averaged 69.7 mph in the control stretch and 64.1 mph in the reduced stretch, where the posted speed limit in effect was 55 mph (figure 10a). Again, the pattern was the same at twilight, with overall speeds slightly higher (figure 10b). During daylight hours, there was again a strong effect of year but no year by treatment interaction (table 4). Vehicles averaged 68.0 and 67.7 mph in the control and reduced stretches, respectively, in Y1, versus 72.4 and 72.2 mph in these stretches in Y2 (figure 10c).

Vehicle speed patterns at migration sites were generally similar to patterns at winter sites (figure 11). At Cokeville, night speeds in spring 2018, when there was no speed limit reduction, were not significantly different from each other inside the study site compared to the adjacent outside study site area (t=0.46, p=0.99), whereas vehicle speeds in spring and fall 2017, when the speed limit was reduced in the study site, were significantly lower inside the study site compared to outside (spring 2017: t=12.63, p<0.0001; fall 2017: t=13.91, p<0.0001). Speeds at night under reduced speed limit conditions averaged 65.4 and 65.3 mph in spring and fall 2017, respectively, compared to 68.4 and 68.3 mph outside the study site at those times (figure 11a). At twilight, vehicle speeds in spring and fall 2017, when the speed limit was reduced in the study site, were also significantly lower inside the study site compared to outside, but the magnitude of this difference was only about 2 mph (figure 11b). During the day, average speeds were slightly and significantly higher in the study site compared to outside (figure 11c), supporting the evidence that drivers did slow down by 2-3 mph when the night speed limit was in effect.

At Warren Bridge, night speeds in spring 2017, fall 2017, and spring 2018 (the latter being when there was no speed limit reduction) were all significantly lower inside the study site compared to the adjacent outside study site stretches (figure 11d; spring 2017: t=20.02, p<0.0001; fall 2017: t=30.09, p<0.0001; spring 2018: t=16.43, p<0.0001). Speeds at night under reduced speed limit conditions were 3.5-5.3 mph lower than in the adjacent road stretch. Twilight speeds were also all significantly lower inside the study site compared to outside, with speeds at twilight under reduced speed limit about 2.5 mph lower than in the outside road stretches (figure 11e). During the day, average speeds were also significantly lower in the study site compared to outside, although with a smaller difference than at night (figure 11f). The consistently lower speed in the study site may have occurred because the road is more curved compared to the straighter area where the “outside study area” radar recorders were placed.

Data at Evanston were limited because there was no “outside study area” location available that had a posted speed limit of 70 mph because there was no usable data from spring 2017. However, the general pattern at this site was consistent with other migration sites: vehicle speeds at night were 4 and 4.6 mph lower, and at twilight 3-4 mph lower, when the speed limit was reduced in fall 2017 compared to fall 2016 and spring 2018 (when speed limit was not reduced), respectively. Daytime speeds were similar across all three time periods.

We focused our analyses on the speeds of non-platooned vehicles, but patterns were similar, though muted, for 85th percentiles of vehicles speeds for all vehicles (tables 5 and 6). Eighty-fifth percentiles were generally 1-2 mph lower when nighttime posted speed limit was 55 mph to 70 mph over all the winter and migration sites.

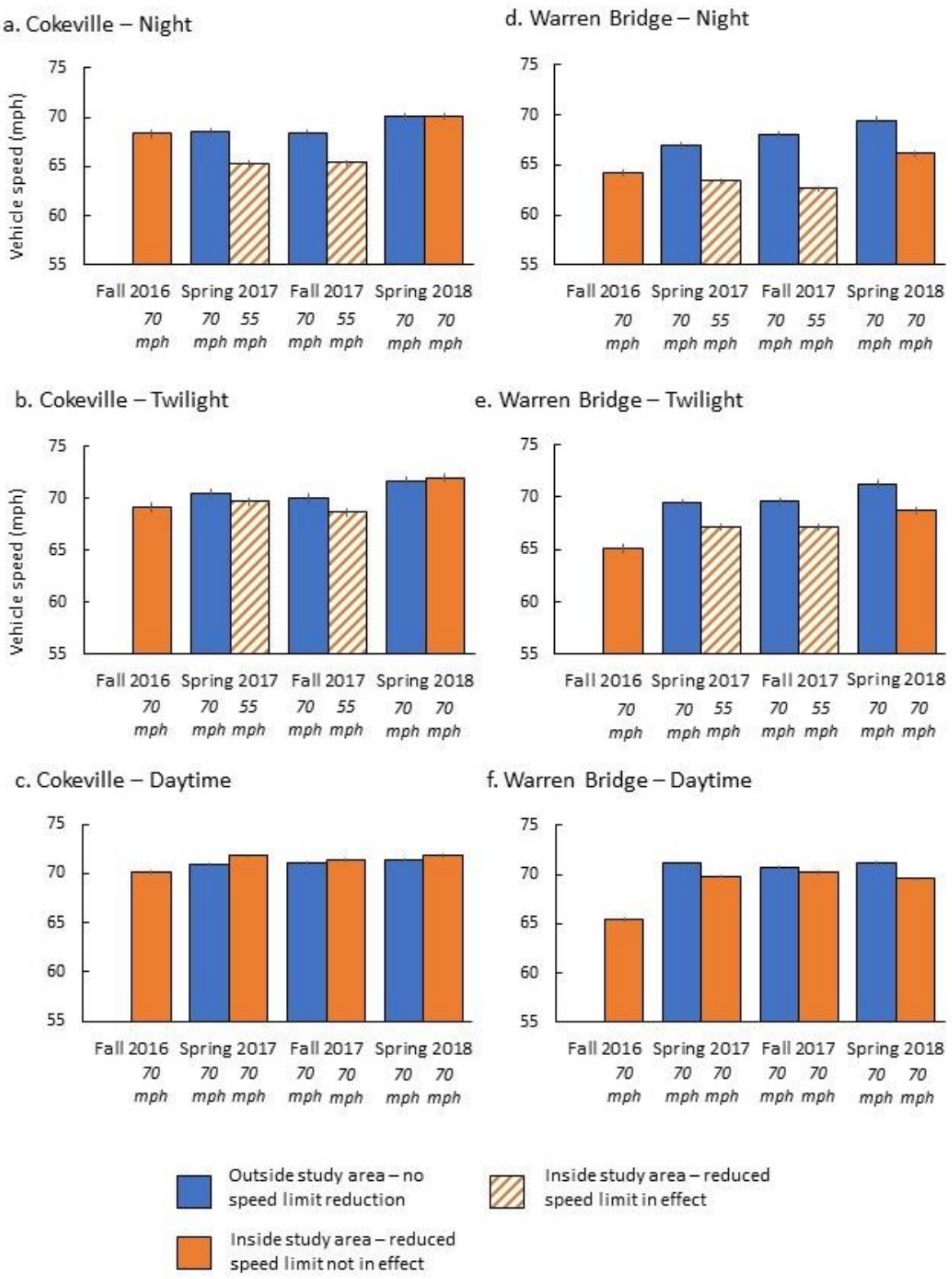

Figure 11. Graphs. Mean (± standard error) vehicle speeds at three migration sites.

Table 5. Eighty-fifth percentile speeds for passenger vehicles at winter sites.

Time	Hotspot	Year 1, control stretch	Year 1, reduced stretch (reduction not in effect)	Year 2, control stretch	Year 2, reduced stretch (reduction in effect)
Night	LaBarge	73	73	73	69
Night	Kemmerer West	72	72	74	73
Night	Kemmerer South	74	74	76	73
Twilight	LaBarge	74	73	74	72
Twilight	Kemmerer West	73	73	76	75
Twilight	Kemmerer South	75	75	76	74
Daytime	LaBarge	74	74	75	75
Daytime	Kemmerer West	74	73	76	75
Daytime	Kemmerer South	75	75	76	76

Table 6. Eighty-fifth percentile speeds for passenger vehicles at migration sites.

Time	Hotspot	Fall 2016 (reduction not in effect)	Spring 2017 control stretch	Spring 2017 (reduction in effect)	Fall 2017 control stretch	Fall 2017 (reduction in effect)	Spring 2018 control stretch	Spring 2018 (reduction not in effect)
Night	Cokeville	74	74	73	74	73	75	75
Night	Evanston	71	-	-	-	65	-	70
Night	Warren Bridge	71	74	71	75	71	75	73
Twilight	Cokeville	74	75	76	75	76	76	76
Twilight	Evanston	72	-	-	-	69	-	71
Twilight	Warren Bridge	71	75	74	76	75	76	74
Daytime	Cokeville	75	75	76	76	76	75	76
Daytime	Evanston	73	-	-	-	71	-	71
Daytime	Warren Bridge	71	75	76	76	76	75	75

Question 2: Did road surface and atmospheric conditions affect vehicle speeds and driver responses to reduced speed limits?

At both Kemmerer West and Kemmerer South, vehicle speeds were higher in Y2 compared to Y1, but this was not the case at LaBarge. Road surface and atmospheric conditions appear to explain these differences. At Kemmerer West, surface conditions in Y1 were "good" for 22 and 28 percent of the vehicles in the control and reduced sections respectively, whereas in Y2 they were "good" for 82 and 83 percent of the vehicles in those same sections. Atmospheric conditions were similar at this site in both years ("good" for 92-94 percent and "poor" for 5-8 percent in both Y1 and Y2). At Kemmerer South surface conditions in Y1 were "good" for 36 percent of vehicles and "poor" for 33 percent of vehicles in both sections, whereas in Y2 they were "good" for 92 and 89 percent of vehicles and "poor" for 0 percent of vehicles in those same sections. Atmospheric conditions were "good" for 57 percent of vehicles and "poor" for 40 percent of vehicles in Y1, compared with "good" for 99 percent of vehicles and "poor" for 1 percent of vehicles in Y2. At LaBarge, however, conditions were similarly good or poor across both years. In Y1, surface conditions were "good" for 30-52 percent of vehicles and "poor" for 0-17 percent of vehicles, and in Y2 they were "good" for 45-49 percent of vehicles and "poor" for 15-18 percent. Atmospheric conditions were "good" for 79-90 percent of vehicles and "poor" for 8-15 percent in both years.

At both LaBarge and Kemmerer West, average vehicle speed was lower under "poor" atmospheric and road surface conditions compared to "good" conditions. However, the sites differed in terms of how these conditions affected driver response to the reduced speed limit. At LaBarge, drivers responded to reduced speed limits to a similar degree in both "good" and "poor" atmospheric and road surface conditions. In "good" atmospheric conditions, average speeds in the Y2-reduced treatment combination was 5.2 mph lower than in Y2-control, and in "poor" atmospheric conditions average speeds in the Y2-reduced treatment combination was 4.2 mph lower than in Y2-control. In "good" surface conditions, average speeds in the Y2-reduced treatment combination was 5.7 mph lower than in Y2-control, and in "poor" atmospheric conditions average speeds in the Y2-reduced treatment combination was 4.8 mph lower than in Y2-control.

At Kemmerer West, on the other hand, drivers responded to reduced speed limits only in "good" atmospheric and road surface conditions. In "good" atmospheric conditions, average speed in the Y2-reduced treatment combination was 3.7 mph lower than in Y2-control, and in "poor" atmospheric conditions average speed in the Y2-reduced treatment combination was no different from Y2-control. In "good" surface conditions, average speed in the Y2-reduced treatment combination was 3.7 mph lower than in Y2-control, and in "poor" atmospheric conditions average speed in the Y2-reduced treatment combination was 0.3 mph lower than in Y2-control. Vehicle speeds averaged around 59 mph under "poor" atmospheric conditions and around 56 mph in "poor" surface conditions. These were overall lower speeds than occurred at LaBarge under the same condition classifications.

Question 3: Did driver responses to reduced speed limits differ among the start, middle, and end of the reduced speed limit zone?

Within reduced speed limit stretches, vehicle speeds differed significantly among the three radar locations for both directions of travel at all three sites ($p<0.0001$ in all cases). However, there was no clear pattern of speeds being lower or higher 0.5 mi into the reduced stretch relative to the other two radar locations (figure 12). For LaBarge northbound traffic and Kemmerer South northbound and southbound traffic, vehicle speed was lowest at the midpoint of the reduced speed limit stretch. At Kemmerer West eastbound, speed was lowest at the last radar location. Only at LaBarge southbound and Kemmerer West westbound were vehicle speeds lowest 0.5 mi and halfway into the reduced speed limit stretch relative to the last radar locations near the end of the speed limit zone.

Question 4: Was law enforcement presence higher when reduced speed limits were in effect?

The rate of warnings and citations per night varied among sites, with overall higher rates at migration sites than winter sites (figure 13). At Kemmerer West, this rate was much higher in the Y2-reduced treatment combination—when the 55 mph speed limit was in effect—than in any other stretch-time combination. At LaBarge, enforcement rates were higher in Y2 than in Y1 in both the control and reduced stretch, which may have had an overall effect on driver behavior in both stretches. At Cokeville, enforcement rates were higher in spring 2017, when the reduced speed limit was in effect, than at other times. However, at the other two migration sites, there was no pattern of higher enforcement when the reduced speed limit was in effect relative to when it was not in effect.

Deer Behavior

Question 5: Did reduced speed limit reduce the number of high risk deer-vehicle interactions?

For all winter site data pooled together, there was a significant difference among year-treatment combinations in the proportion of higher-risk versus lower-risk deer-vehicle interactions ($\chi^2=9.0$, n=112, $p=0.03$), with relatively fewer higher-risk deer-vehicle interactions in the reduced speed limit stretches in both Y1 and Y2 (figure 14a). This did not indicate an effect of reduced speed limit, since the speed limit reduction was only in effect in Y2. For migration site data pooled together, there was a slightly lower proportion of higher-risk interactions in fall 2017, when the speed limit reduction was in effect, compared to fall 2016 and spring 2018 when it was not in effect (figure 14b); however this was not statistically significant ($\chi^2=2.7$, n=204, $p=0.26$).

Question 6: Did reduced speed limit increase the ease with which deer crossed the road?

We analyzed both number of attempts to cross and final crossing success versus failure as indicators of how easy or difficult it was for deer to cross roads. These two variables showed similar results, and across all deer-vehicle interactions they were significantly related to each other ($\chi^2=10.3$, n=316, $p=0.03$). Crossing success rate was >80 percent when the deer made only one or two attempts to cross, 73 percent when the deer made three attempts to cross, and 50 percent when the deer hade to make four or more attempts to cross. Because of the relationship between these two variables, we focused presentation of results on the number of attempts to cross as the main indicator of ease versus difficulty of crossing.

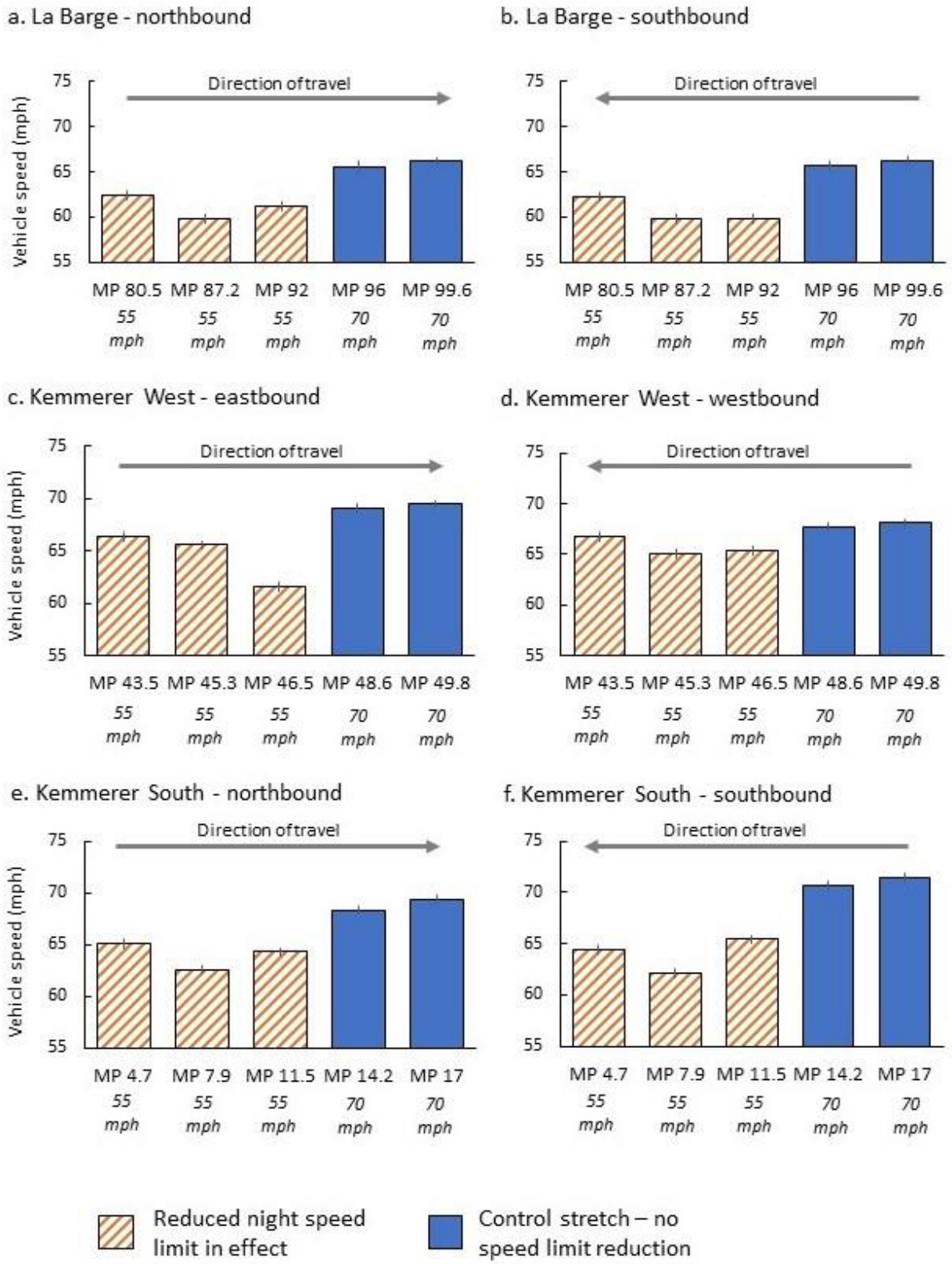

Figure 12. Graphs. Mean (± standard error) vehicle speeds by location within the reduced speed limit zone.

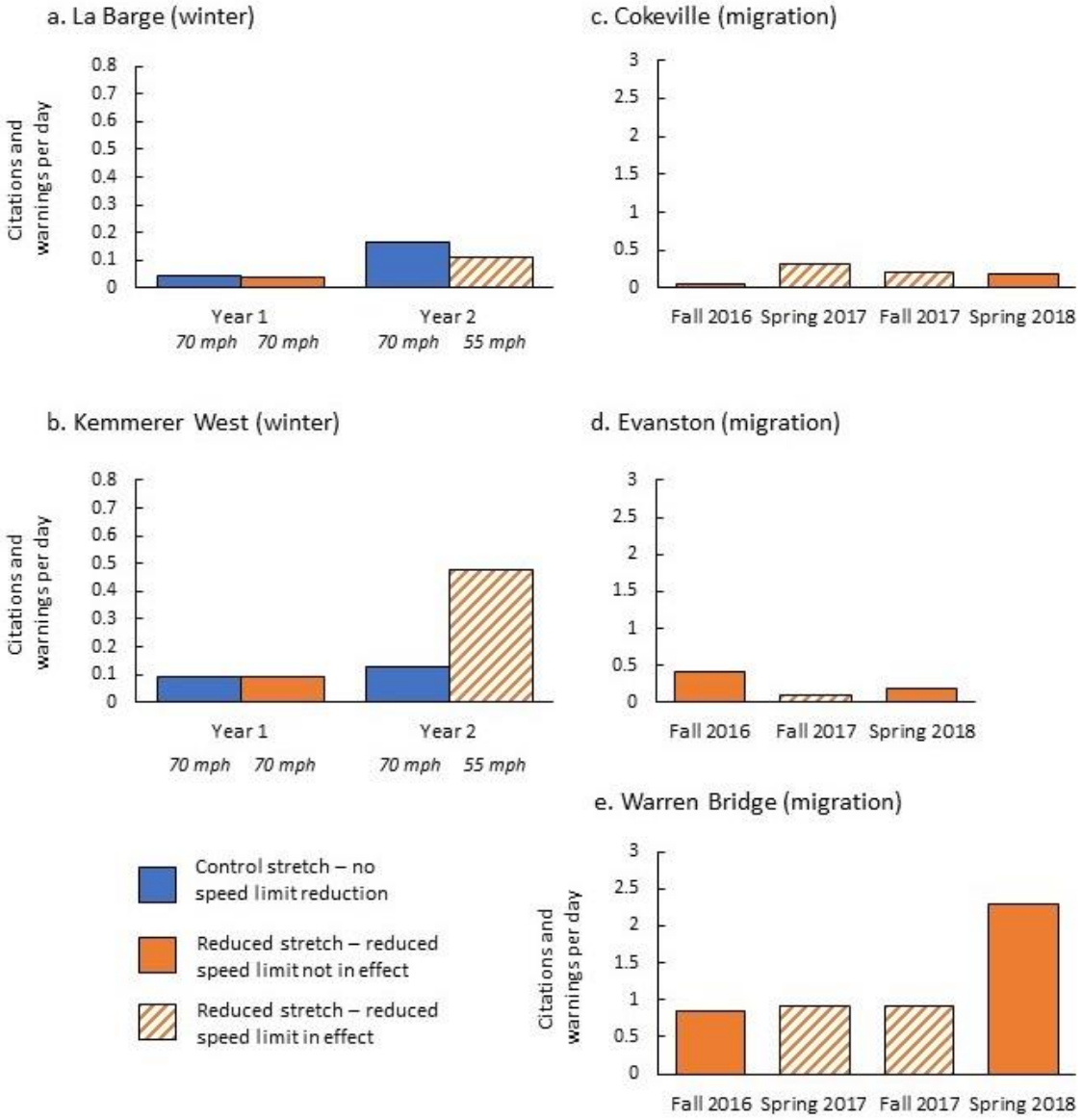

Figure 13. Graphs. Enforcement rate per night at each study location.

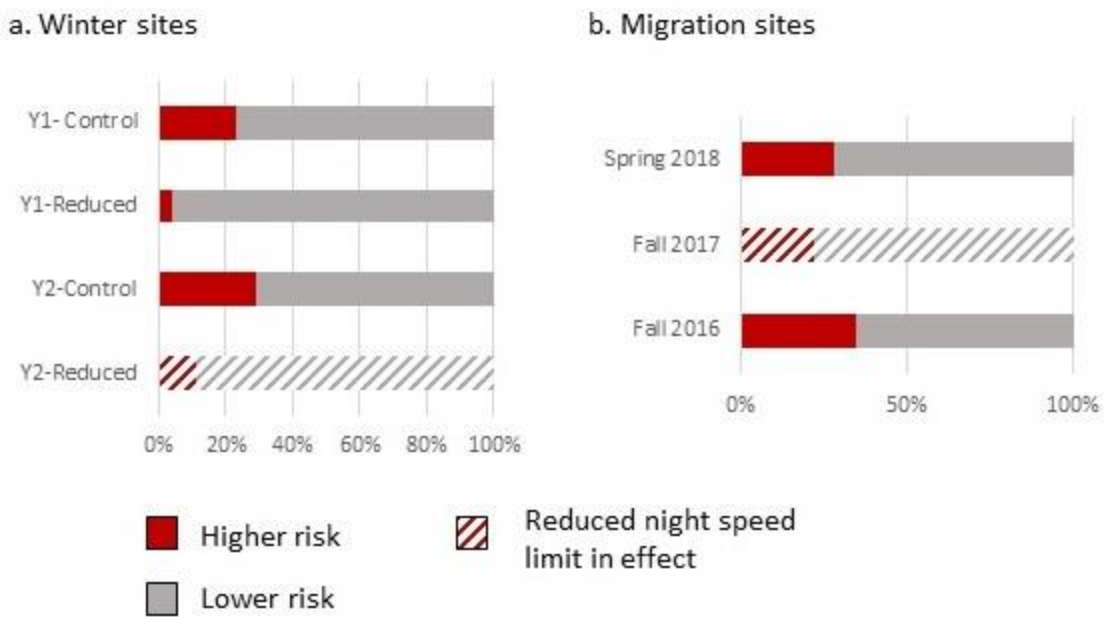

Figure 14. Graphs. Proportion of deer that exhibited different risk levels during deer-vehicle interactions at (a) winter sites, and (b) migration sites.

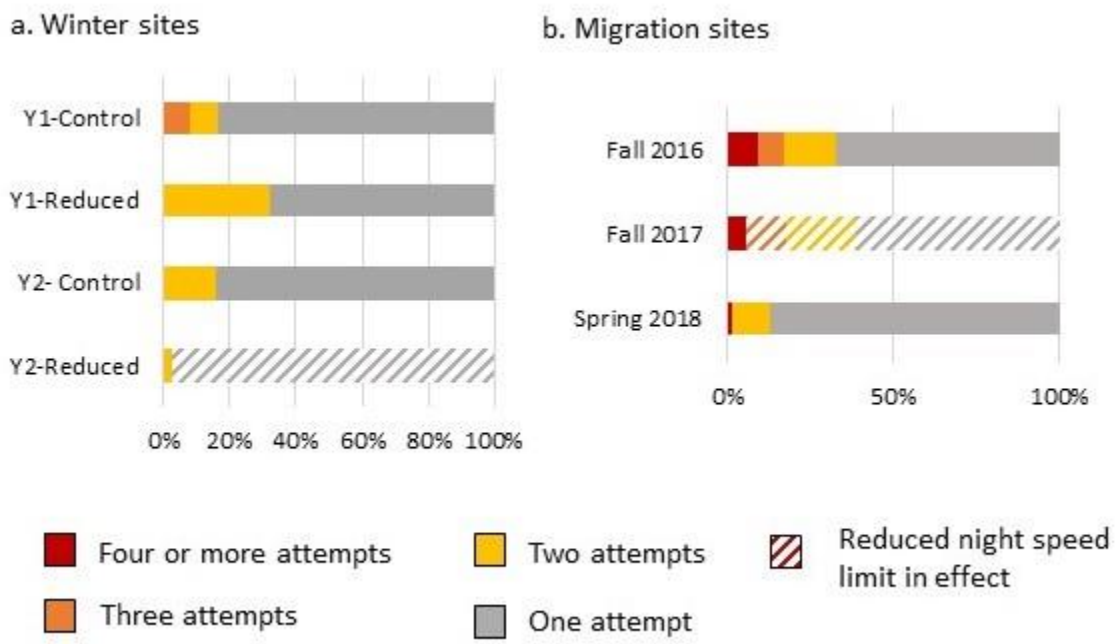

Figure 15. Graphs. Proportion of deer that required multiple attempts to cross at (a) winter sites, and (b) migration sites.

For all winter site data pooled together, there was a significant difference among year-treatment combinations in the number of attempts to cross (χ^2=15.7, n=112, p=0.01), with fewer attempts

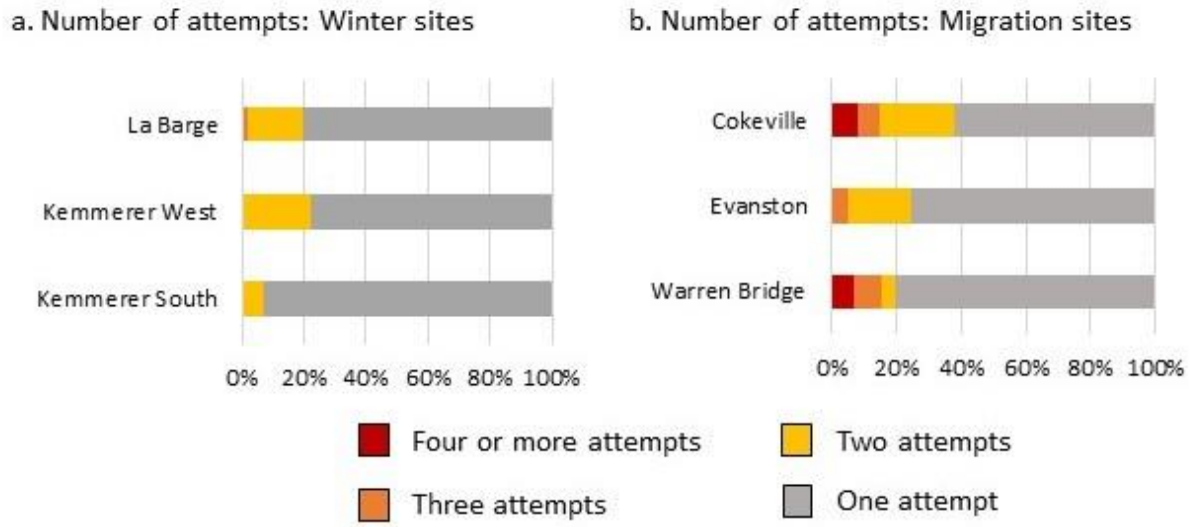

Figure 16. Graphs. Proportion of deer that required multiple attempts to cross at (a) winter sites, and (b) migration sites, by site.

to cross (more easy crossing conditions) in the reduced speed limit stretch in Y2 when the speed limit reduction was in effect (figure 15a). For migration site data, there was a marginally significant difference among times (χ^2=22.4, n=208, p=0.06), but number of crossing attempts was greatest in fall 2017, when the speed limit reduction was in effect, and lowest in spring 2018 when it was not in effect (figure 15b).

Further examination of the data helped to make sense of these inconsistent and apparently contradictory results. Winter data in the Y2-reduced year-treatment combination was mostly made up of deer from Kemmerer South (figure 5), which almost all required only one attempt to cross (figure 16a), whereas other treatment combinations were mostly made up of deer from LaBarge and Kemmerer West, which had higher fractions of deer that made multiple attempts. For the migration data, the fraction of deer making three or four attempts to cross was higher in Cokeville and Warren Bridge than Evanston (figure 16b), but the majority of the spring 2018 observations were from Evanston (figure 6), explaining why the number of crossing attempts was low for spring 2018 relative to spring 2017 and fall 2016.

Role of traffic

Deer behavior results did not provide clear evidence that reduced night speed limit impacted the level of risk that deer experience or the ease with which they were able to cross roads. However, traffic during the group-road interaction was strongly related to the number of crossing attempts deer made. The number of crossing attempts that deer made was progressively higher as the number of vehicles in the group-road interaction increased (figure 17a), and a one-way analysis of variance showed that traffic counts were significantly higher as number of crossing attempts increased (F=14.7, n=321, p<0.0001). The proportion of deer involved in higher risk deer-road

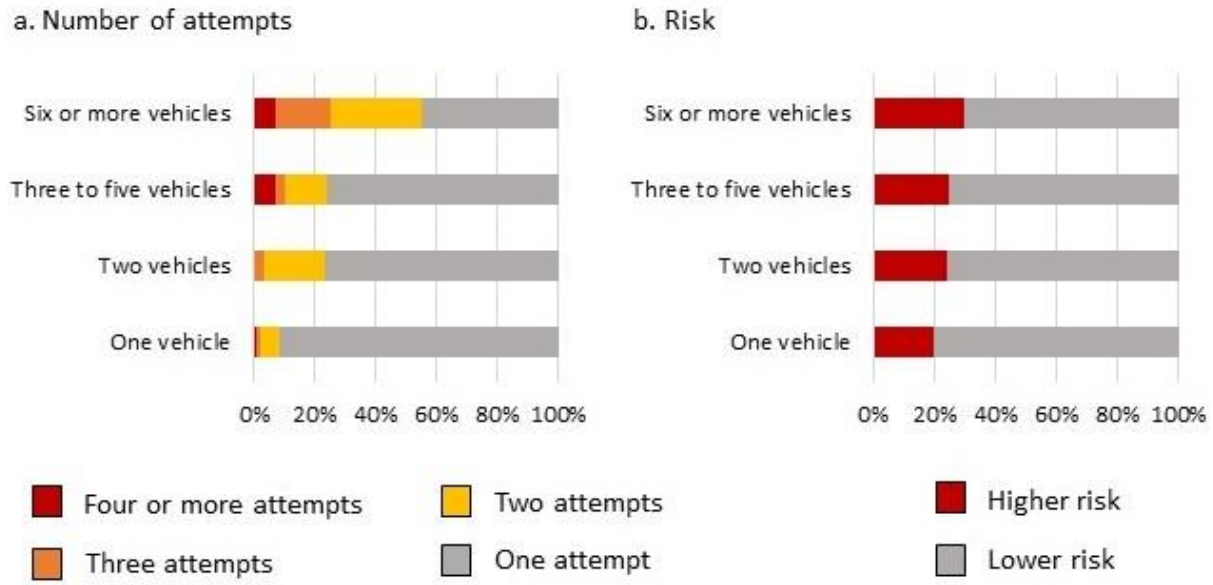

Figure 17. Graphs. Effects of traffic on the proportion of deer that (a) required multiple attempts to cross the road and (b) exhibited different risk levels.

interactions was also progressively higher as the number of vehicles in the group-road interaction increased (figure 17b), although there was no significant difference in number of vehicles by risk level (t=0.7, n=321, p=0.5). Interestingly, the standardized rate of vehicles per minute was not related to number of crossing attempts (F=0.9, n=321, p=0.4) or risk level (t=0.6, n=321, p=0.5). These results suggest that deer crossing behavior was influenced by whether or not deer encountered vehicle platoons, and likely the associated spacing between vehicles within platoons, rather than the average traffic volume.

Wildlife-Vehicle Collisions

Question 7: Did reduced speed limit decrease the number of deer-vehicle collisions?

The chi-squared analysis of winter site data did not show evidence of reduced WVC in response to reduced speed limit for crash or carcasses data. When data from all winter sites were pooled together, crash numbers were highest, rather than lowest, in the reduced speed limit conditions (Y2-reduced, which was 25-100 percent higher than other treatment combinations; figure 18a) and the chi-squared test was not significant (χ^2=1.2, n=30, p=0.27). All three sites contributed similarly to the pooled crash results. LaBarge was the only site to show slightly lower crash numbers under reduced speed limit (figure 18b), but separate chi-squared tests for each winter site were not significant.

Pooled carcass numbers were higher in Y2 in both control and reduced sections relative to Y1, and the reduced sections had higher carcass counts than the control sections in both years (figure 19a), but there was no proportional difference in the reduced section in Y2 and the chi-squared test was not significant (χ^2=0.03, n=238, p=0.86). The pooled carcass results patterns were strongly influenced by the LaBarge site, which had much higher carcass numbers than either of

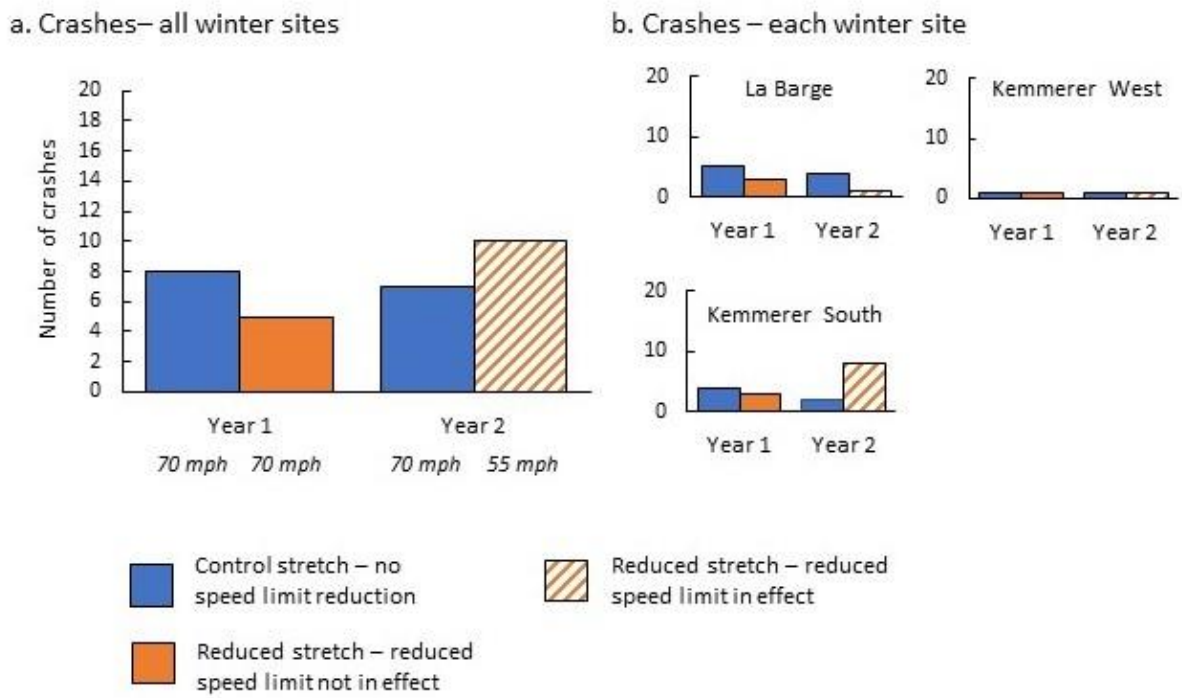

Figure 18. Graphs. Crash numbers by year and treatment for winter sites.

the other two sites (figure 19b). However, none of the sites showed any pattern of lower carcass numbers under reduced speed limit conditions and chi-squared tests for each winter site were not significant.

Analysis of variance on winter sites using the BACI design also showed no evidence of an effect of reduced speed limit. For both crashes and carcasses, there was no significant year x treatment interaction (crashes: F=0.91, df=1, p=0.37; carcasses: F=0.008, df=1, p=0.93). Crash rates were actually 20-70 percent higher under reduced speed limit (Y2-reduced) compared to the other three year-treatment combinations, while carcass rates were almost identical across year and treatment combinations (figure 20).

In contrast to the results at winter sites, migration sites showed some indication that the reduced speed limit translated to fewer crashes and carcasses. The average number of crashes per mile across all four pairs of data was 37 percent lower in reduced speed limit conditions relative to 70 mph speed limit conditions (figure 21a), and this difference was statistically significant (t=2.28, df=6, p=0.03). The pattern was consistent for three of the four pairs of data, with all but Cokeville showing a lower rate of crashes per mile under reduced speed limit conditions (figure 21b). Similarly, the average number of carcasses per mile across all four pairs of data was 31 percent lower in reduced speed limit conditions relative to 70 mph speed limit conditions (figure 21c). Although this difference was not statistically significant at the p<0.05 level (t=1.42, df=6, p=0.10), it might be considered marginally significant given the low replication and power associated with these data. The pattern was again consistent for three of the four pairs of data, with all but Warren Bridge, in spring, showing a lower rate of carcasses per mile under reduced speed limit conditions (figure 21d).

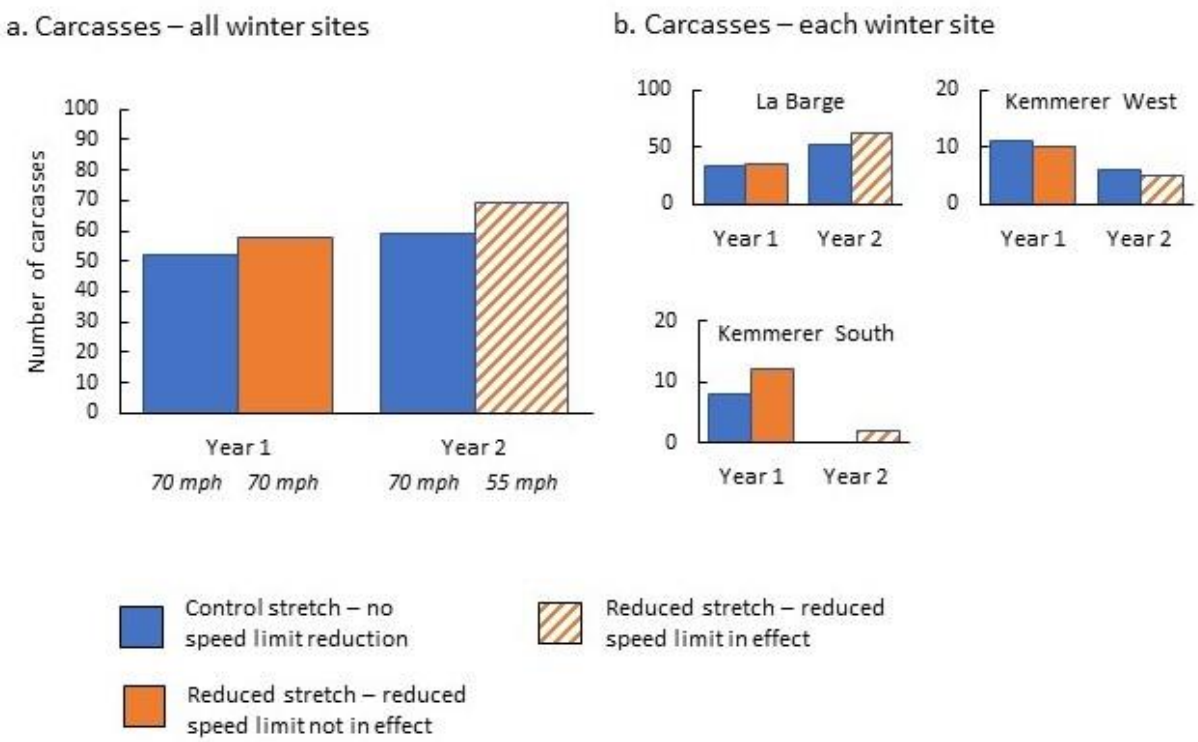

Figure 19. Graphs. Carcass numbers by year and treatment for winter sites.

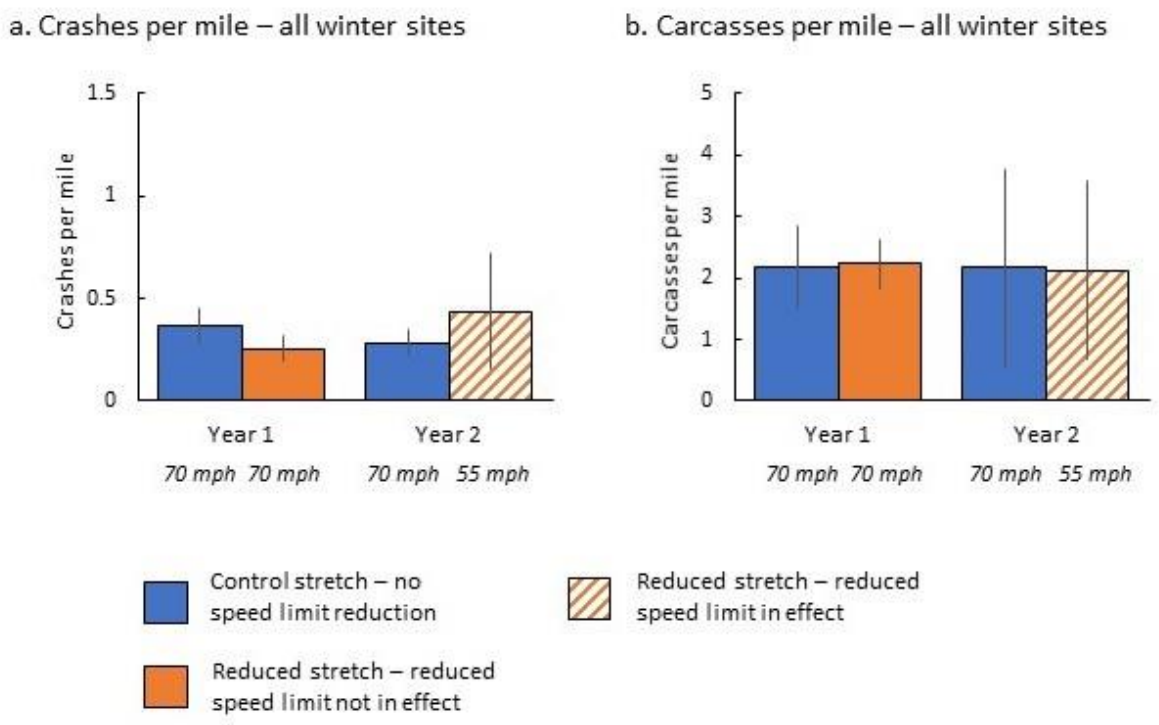

Figure 20. Graphs. Mean (± standard error) number of crashes and carcasses per mile by year and treatment for winter sites.

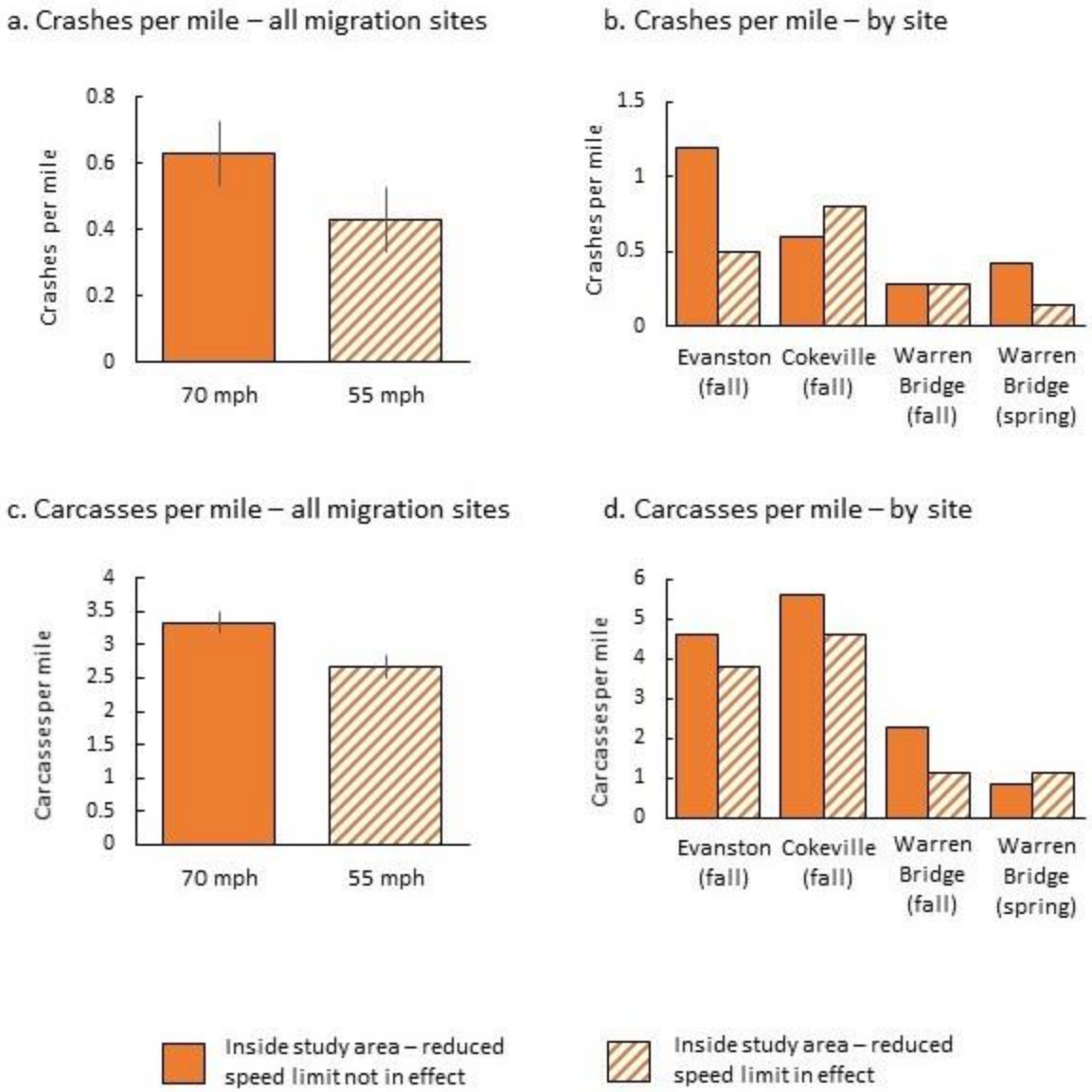

Figure 21. Graphs. Crashes and carcasses per mile by year and treatment for migration sites.

CHAPTER 5. DISCUSSION AND RECOMMENDATIONS

There are only a handful of studies that have investigated the effect of reduced posted speed limit on collisions with large wild mammals. In this study, we did three things that had not been done before in prior studies. First, we used a BACI experimental design, which is the most robust study design for this type of study. Second, we conducted the experiment at multiple locations, three of which were shorter stretches of road with short-duration (two-month) periods of reduced speed limit, and three of which were long stretches of road with longer-duration (seven-month) periods of reduced speed limit. Third, we tested the whole causal chain from vehicle speed to deer-vehicle interaction dynamics to the number of deer-vehicle collisions.

The effect of reduced posted night time speed limit on vehicle speed was remarkably consistent and clear. At all sites, independently-acting (non-platooned) drivers drove more slowly when the posted nighttime speed limit was 55 mph compared to when the posted nighttime speed limit was 70 mph. At night, this difference was about 4-5 mph, and at dawn and dusk, when drivers were typically traveling slightly faster than during the night, this difference was about 3 mph. These patterns were clearly due to the reduced posted speed limit at night, since they were consistent across all sites, did not occur in the control stretches or in the "reduced" stretches of road when the flashing beacons were turned off (in other words, when the speed limit reduction was not in effect), and did not occur during the daytime.

Driver responses to reduced nighttime speed limit were surprisingly similar between winter sites, where the reduction was in effect for seven months, and migration sites, where the reduction was in effect for only two months. We had predicted that drivers at migration sites would be more responsive to the reduced speed limit because it was in effect intermittently and only for a limited duration at a time—both of which meant less time for drivers to habituate to the change in speed limit. However, drivers in both types of sites slowed down by a similar amount when the speed limit reduction was in effect.

Our results were mixed in terms of whether drivers' responses to the reduced speed limit depended on road surface and/or atmospheric conditions. We had predicted that drivers might modify their speed either more or less under more adverse conditions. For example, drivers might be more likely to comply with the 55 mph speed limit at night if road conditions were poor, as was found in a study of driver responses to animal detection system.[31] Alternatively, drivers might all be traveling slowly under poor road conditions regardless of the posted speed limit. Our results from winter sites, which experienced a variety of road and atmospheric conditions, showed that drivers did travel at lower speeds overall in year one of the study, which was a winter with very heavy snowfall, compared to year two of the study, which was a much milder winter. At one winter site (LaBarge), drivers responded equally to the reduced nighttime speed limit in good and poor road and atmospheric conditions. At another winter site (Kemmerer West), drivers had similar speeds under poor conditions regardless of the posted speed limit, but different speeds when conditions were good (lower speeds when the posted speed limit was 55 mph compared to 70 mph). It is possible that drivers in LaBarge, who were likely a higher percentage of local drivers than at Kemmerer West, were more familiar with the speed limit reductions, and therefore, more consistent in when they adhered to them.

We also found that drivers maintained their reduced speeds throughout the reduced speed limit zone, regardless of how close or far they were from the start of the zone. We had predicted that drivers would slow more after entering the reduced speed limit zone and encountering the first set of flashing beacons, but that their speeds would increase after several miles. This prediction was based on the assumption that drivers would forget about the reduced speed limit several miles into the reduced speed limit stretch. However, we did not find any consistent pattern to support this prediction. This may be because flashing beacons and speed limit signs were positioned every 5 mi in the reduced speed limit stretches, serving as reminders to drivers that the 55 mph speed limit was still in effect.

Although drivers did consistently reduce their speed when the posted speed limit was reduced to 55 mph, the average vehicle was still traveling at 60-65 mph, well above the speed limit. This finding supports the idea that drivers tend to drive at the speed at which they feel safe and comfortable, rather than adhering to the posted speed limit, unless there is a high presence of law enforcement.[22,23] Our results do not support the idea that posting a lower nighttime speed limit, without other interventions to modify driver behavior, is an effective way to substantially reduce vehicle speeds on rural two-lane highways with a high design speed.

Patterns of law enforcement activity in our study sites did not indicate any direct relationship with vehicle speed patterns. The number of citations and warnings per day was higher when the 55 mph speed limit was in effect relative to the 70 mph speed limit only at some locations, and there was no pattern of these locations having lower driver speeds, which would indicate higher rates of driver compliance to the posted speed limit, than other locations. Although we would expect higher rates of law enforcement presence—imperfectly measured by law enforcement activity—to translate to lower vehicle speeds when the 55 mph speed limit was in effect, the data from our study sites do not conclusively indicate that law enforcement affected driver speeds.

Although drivers did slow down consistently when nighttime speed limit was reduced, this did not translate to a reduced risk of deer-vehicle collisions at winter sites. If roads were safer for deer when there was a nighttime speed limit of 55 mph, compared to 70 mph, in effect, then we would expect that relatively fewer deer-vehicle interactions would be “high-risk” interactions—situations where deer and vehicles collided, narrowly avoided colliding with each other, or where deer crossed the road in front of an oncoming vehicle. However, observations of deer-vehicles interactions at winter sites showed similar proportions of high-risk interactions under both speed limit conditions. Consistent with this, there was also no evidence that the number of deer hit by vehicles—crashes and deer carcasses along roadsides—was lower at any of the three winter sites when the reduced nighttime speed limit was in effect.

At migration sites, there was a slight, but not statistically significant, reduction in the proportion of high-risk deer-vehicle interactions when the nighttime speed limit of 55 mph was in effect. There were also significantly fewer crashes and marginally significantly fewer carcasses at migration sites when the speed limit reduction was in effect. The behavior data pattern may have occurred because of disproportionate representation of data from a site that had generally fewer high-risk deer-vehicle interactions, but the patterns of fewer crashes and carcasses were fairly consistent across sites, lending support to the argument that the lower crash and carcass rates were due to the reduced speed limit.

On the surface, these results seem to support our original prediction that reduced nighttime speed limits were more likely to be an effective tool for reducing WVCs at migration sites than winter sites. However, there are two important considerations that weaken that conclusion. First, we were able to employ a much better experimental design at winter sites, which allowed us to compare deer behavior and collision rates under 55 mph posted speed limit conditions relative to 70 mph conditions at the same time (comparing against the control stretch), and at the same location (comparing against the reduced stretch in Y1, when the speed limit was not reduced). In contrast, at migration sites, we could only compare the same location against itself at a different time of year. It would not be surprising for deer-vehicle interactions to differ in risk level between fall and spring seasons, since deer are widely-observed to have more erratic behavior during the fall rut and hunting season than other times of year.[32] Similarly, it would not be surprising for rates of deer-vehicle collisions to differ from one season or year to another, since herd sizes fluctuate from year to year.

Second, and perhaps more importantly, vehicle speeds were not any lower at migration sites than at winter sites when the posted speed limit was 55 mph. At all six sites, vehicle speeds were very similar and only a few miles per hour slower than vehicle speeds under the 70 mph speed limit. We would therefore expect that the effect of speed limit reduction on deer-vehicle interaction dynamics and number of collisions would be the same at all locations.

In general, given the relatively small decrease in average vehicle speed and that vehicles at all sites were still traveling 60-65 mph, even when posted speed limits were 55 mph, we would expect that there would be little to no impact of these slower speeds on the risk of deer-vehicle collisions. In a separate analysis of vehicle stopping distance, several authors of this report showed that a vehicle traveling at 60 mph has a stopping distance of 477.5-566.0 ft after the driver first detects an animal in the road.[33] This is a longer distance than the detection distance afforded by most vehicle's high beam headlights and all vehicles' low beam headlights.[33] In other words, at this speed, most vehicles are outrunning their headlights and their drivers cannot avoid a collision with the animal unless the animal moves out of the path of the vehicle or the vehicle deviates from its path. Vehicle operating speeds would have to be much lower, 45 mph or slower, for about half the drivers to be able to avoid collisions with very large mammals (moose size). To achieve a similar theoretical reduction in collisions with deer, operating speeds would have to be even lower as deer are smaller and are likely to have a shorter detection range than larger species such as moose.

We had also predicted that if drivers reduced their speed in response to reduced posted speed limit, this might make roads easier for deer to cross. There was no evidence to support this prediction, again most likely because the actual reduction in vehicle speed was small. Instead, however, we found that the number of vehicles that passed during the course of a deer group attempting to cross had a substantial impact on deer behavior. More vehicles during the group-road interaction led to the deer making more attempts to cross. The more attempts to cross, the higher the chances that the deer would ultimately abandon its efforts to cross, leading to a failure to cross. There was also a non-significant trend that more vehicles during the group-road interaction led to more risky deer-road interactions. These findings support our prior findings

that the traffic volume and duration of gaps between consecutive vehicles that deer experience at the time of attempted crossing play an important role in the risk of deer-vehicle collisions.[34]

Overall, our results do not indicate that reduced nighttime speed limit is an effective means to reduce WVCs under the conditions represented in this study: rural two-lane highways with high design speeds. These results are consistent with the only other comprehensive test of reduced nighttime speed limit as a means of reducing WVCs, conducted by the Colorado Department of Transportation (CDOT).[25] The CDOT study resulting from the passing of a "wildlife crossing zones" bill, which included provisions to implement and enforce reduced nighttime speed limits at over 100 mi of known wildlife crossing zones throughout the state. In 14 locations, posted speed limits were reduced to 55 mph from dusk to dawn, a 10-15 mph decrease from daytime posted speed limits. Rates of WVCs were compared for two years before and two years after the posted speed limit reductions. The study found the reduced posted nighttime speed limits were ineffective in providing the desired reduction in operating speed, with drivers exceeding the 55 mph speed limit by an average of 7 mph, even with a 43 percent increase in the number of law enforcement citations distributed during the study period. In 8 of the 14 study areas, WVCs decreased during the study, while in the other 6 study areas WVCs increased. Overall, the authors of the report concluded that the night-time posted speed limit reductions were ineffective due to poor driver compliance and variable results in WVCs.[25]

Another study in Jasper National Park, Canada compared bighorn sheep crash rates for eight years before and eight years after reductions in posted speed limit.[26] The authors of this study found a slight increase in the number of crashes after the speed limit was reduced, but this was complicated by significant increases in traffic volume and changes in bighorn sheep behavior, such as habituation to vehicles and failure to leave the road. The results of this study were relatively inconclusive but overall did not indicate that reduced speed limit translated to reduced rates of WVCs.

Although our findings and the findings of others provide little compelling evidence that reducing the posted speed limit can substantially reduce WVCs, there are several caveats and areas in need of further research:

- First, it is important to keep in mind the distinction between posted speed limit and vehicle operating speed. If drivers can be influenced to reduce their vehicle operating speed, this should translate to fewer WVCs. However, in the studies conducted so far, reduced posted speed limit did not translate to substantially reduce operating speeds.
- Second, there may be more effective ways to influence driver behavior than the methods used in this study. At our study sites, drivers were alerted to the risk of wildlife collisions by a single, permanent sign at the start of each study stretch. This kind of permanent signage has been shown to be ineffective at reducing WVC rates, while seasonally placed signs (at specific locations for specific seasonal durations) and possibly variable message signs with custom warnings may be more effective.[28] In our study, reduced speed limits were indicated with static speed limit signs and flashing beacons to indicate that the reduced speed limit was in effect. Variable speed limit signs or digital dual speed limit signs, where drivers see only the speed limit currently in effect, might be less confusing to drivers and might result in higher driver compliance rates. Additionally, it is

possible that driver culture—awareness of the problem of WVCs and attitudes toward this problem—could possibly be altered over time with heavy investment in public outreach and education. This could, in turn, contribute to greater driver compliance with reduced posted speed limits for the purpose of reducing WVCs. The potential for these measures to contribute to reduced driver operating speeds is not well known and in need of further study before DOTs adopt them widely. A more certain, but difficult to implement, means of reducing driver operating speed would be to alter the geometry and design of the road.

- Third, it is possible that reduced posted speed limits could be more effective at reducing driver operating speeds and WVCs under different road conditions. For example, this measure might have greater effectiveness on roads with lower design speeds (< 45 mph), where drivers are accustomed to traveling more slowly and a reduction of 5-10 mph could make a substantial difference in drivers' ability to detect and avoid animals in the road. This possibility is also in need of further study.

One important further caveat is that reducing driver operating speeds on high-speed highways (for example, from 70 to 55 mph, as the posted reductions in this study were intended to do) is not likely to make roads more passable to large mammals. In our prior work, we showed that deer need >30 seconds between consecutive vehicles to cross highways in Wyoming safely, without high risk of WVC or without abandoning the attempt to cross.[34] A high traffic volume with vehicles closely spaced together is likely to create a substantial barrier for large mammal movements, even if those vehicles are traveling somewhat slower than they otherwise would. For higher traffic volume roads, separated crossings (highway underpasses and overpasses) with wildlife fencing are the only effective way to ensure that roads do not obstruct large mammal movements, while also reducing WVC rates. Separated crossing structures with >5 mi of fencing are consistently >80 percent effective at reducing WVCs[9-14] and once accustomed to them, large mammals cross them regularly. [10] In the long-term, crossing structures with fencing, though costly, are the most effective way to increase road safety for large mammals and the traveling public alike and to also allow wildlife to continue to move across the road.

We recommend that reduced nighttime speed limit should not be considered an effective measure for reducing WVCs on rural high-speed highways. If the objective is to substantially reduce WVCs on roads with high vehicle speeds and high traffic volume, reducing speed limit should not be considered a measure for meeting this objective. If the objective is to obtain more data on the possible benefits of reduced speed limit, then it could be considered only where (a) crossing structures are not possible, (b) other measures such as enhanced seasonal signage, public awareness, and/or a sustainably high level of law-enforcement presence are also employed simultaneously, and (c) the effectiveness of these combined measures is studied so as to improve our understanding of whether reduced nighttime speed limit can ever be an effective means of reducing WVCs and increasing driver safety, and if so, under what circumstances.

APPENDIX A

WYDOT surface and atmospheric conditions and the simplified categories used in this report for each WYDOT condition.

WYDOT Surface Conditions	Simplified Category
Dry	Good
Wet	Moderate
Wet, slick in spots	Moderate
Slick in spots	Moderate
Wet, slick in spots, drifted snow	Moderate
Slick in spots, drifted snow	Moderate
Slick	Poor
Slick, drifted snow	Poor
Road closed	Poor

WYDOT Atmospheric Conditions	Simplified Category
Favorable	Good
Blowing Snow	Poor
Fog	Moderate
Rain	Moderate
Rain, fog	Moderate
Rain, strong winds	Poor
Snowfall	Moderate
Snowfall, blowing snow	Poor
Snowfall, fog	Poor
Snowfall, strong winds	Poor
Snowfall, strong winds, blowing snow	Poor
Strong winds	Poor
Strong winds, blowing snow	Poor
Blowing snow, limited visibility	Poor
Fog, limited visibility	Poor
Limited visibility	Poor
Snowfall, blowing snow, limited visibility	Poor
Snowfall, fog, blowing snow, limited visibility	Poor
Snowfall, fog, limited visibility	Poor
Snowfall, strong winds, blowing snow, limited visibility	Poor
Strong winds, blowing snow, limited visibility	Poor

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