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Received: 7 December 2020 | Revised: 24 November 2021 | Accepted: 2 December 2021

DOI: 10.1111/csp2.618

CONTRIBUTED PAPER

Conservation Science and Practice
A journal of the Society for Conservation Biology
Open Access

WILEY

Reduced speed limit is ineffective for mitigating the effects of roads on ungulates

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Funding information
Wyoming Department of Transportation, Grant/Award Number: RS11216

Abstract

Roads obstruct wildlife movements, and wildlife-vehicle collisions are a hazard to both animals and humans. Wildlife and transportation managers often consider reducing the speed limit to reduce wildlife-vehicle collisions, but there is little empirical data to support or refute this measure. We experimentally reduced the nighttime speed limit from 70 to 55 mph on six stretches of highway that cross mule deer (*Odocoileus hemionus*) winter range or migration paths. Drivers consistently reduced their speeds, but only by 3–5 mi/h. Reduced speed limit did not make it any easier for deer to cross the road, indicating no benefit for habitat connectivity. At winter sites, the number of deer-vehicle collisions was not affected by the reduced speed limit whereas at migration sites, collisions were modestly lower under the reduced speed limit. Given the small reduction in vehicle speeds, it is not surprising that there was little benefit of reduced speed limit for deer or people. We conclude that reduced nighttime speed limit is not an effective way to reduce wildlife-vehicle collisions or make roads more permeable to wildlife due to poor compliance from motorists.

KEYWORDS

habitat connectivity, linear infrastructure, mule deer, *Odocoileus hemionus*, road ecology, transportation ecology, wildlife-vehicle collisions

1 | INTRODUCTION

Roads negatively impact wildlife populations in many ways: they result in wildlife mortality associated with wildlife-vehicle collisions (WVCs), impede animal movements across the landscape, and cause habitat loss and quality reduction along transportation corridors (Beckmann et al., 2010; Forman & Alexander, 1998). Collisions with wildlife also affect human safety and result in property damage. In the United States alone, an estimated 1–2 million (WVCs occur every year, costing $6–12 billion per year in vehicle damage, human injuries and fatalities as well as the lost value of the animal (Huijser et al., 2009). Finding ways to reduce WVCs and minimize the barrier effects of roads is a high priority for wildlife and transportation managers in many parts of the world.

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Measures aimed at reducing WVCs and creating safe crossing opportunities for wildlife vary widely in both cost and effectiveness. WVCs can typically be reduced by >80% through the use of wildlife-exclusion fencing to prevent animals from entering the highway, coupled with overpasses and underpasses that allow wildlife to cross safely (Huijser et al., 2009; Huijser, Fairbank, et al., 2016; Rytwinski et al., 2016; Sawyer et al., 2012; Sawyer et al., 2016). The combination of fencing and crossing structures is also very effective at maintaining, and potentially even improving, habitat connectivity for large mammals (Huijser, Camel-Means, et al., 2016; Sawyer et al., 2016). However, these measures require lengthy planning and typically cost many millions of dollars to build (Huijser et al., 2009). Consequently, managers often seek less expensive measures that can be installed relatively quickly and cover long stretches of road.

One possible 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 (Huijser et al., 2008). The logic underpinning this measure is simple: if drivers comply with the reduced posted speed limit, they will be traveling at lower speeds and will have a shorter stopping distance (Huijser et al., 2017). Since the relationship between vehicle speed and stopping distance is exponential, small reductions in vehicle speed can result in substantial decreases in stopping distance (Huijser et al., 2017). Thus, if drivers comply with a lower legal posted speed limit, the reduced operating speed of the vehicles could potentially lead to a reduced risk of WVCs. Slower moving traffic could also ameliorate the barrier effect of roads, if it translates to more opportunities for animals to safely cross roads. In addition to cost considerations, reduced speed limit is particularly appealing to managers in places where driveways and access roads make fencing difficult.

A number of broad-scale analyses of the landscape variables associated with high WVC rates have shown that higher posted speed limits are positively correlated with higher collision rates (Danks & Porter, 2010; Gunson et al., 2011; Meisingset et al., 2014; Ng et al., 2008; Seiler, 2005). Although these findings seem to suggest that reducing speed limits will reduce WVCs, an alternative possibility is that posted speed limits and WVC rates are both correlated with the typical operating speed (the observed actual speed) of vehicles on the road, and it is operating speed rather than speed limit that influences WVC rates. Speed limits are typically set using a combination of the design speed of the road (the selected speed used to determine the geometric features of a road during road design) and the 85th percentile of driver operating speeds (Fitzpatrick et al., 1997). Drivers tend to drive at the speed they feel is safe and socially acceptable (Bissonette & Kassar, 2008; Elliott et al., 2005; Mannering, 2009; Shinar, 2007), rather than the posted speed limit. Thus, reducing the posted speed limit well below the design speed may not result in reduced operating speeds. Greater enforcement of a speed limit can result in greater compliance, but is effective only in the immediate vicinity of law enforcement personnel or speed cameras (Soole et al., 2013; Vaa, 1997; Wasson et al., 2011). Thus, if the posted speed limit is reduced far below the design speed of a highway, law enforcement may not have the capacity to ensure driver compliance, especially in expansive rural landscapes.

These concerns raise questions about whether reducing the posted speed limit is an effective way to reduce driver operating speeds and WVC rates. Yet, empirical data are very limited. To our knowledge, there are no peer-reviewed studies on the effectiveness of speed limit reduction. In response to this knowledge gap, we tested the effectiveness of reducing the nighttime speed limit using a rigorous before-after-control-impact (BACI) study design at multiple sites in Wyoming. WVCs make up 18–22% of all reported vehicle crashes annually in Wyoming (Wyoming Department of Transportation, 2020). At the same time, the state is home to some of the longest-distance and most intact large ungulate migrations in the world (Berger, 2004; Kauffman et al., 2018; Middleton et al., 2019). While fencing and crossing structures have been installed in several locations in Wyoming and shown to be highly effective at reducing WVCs and connecting habitat for a variety of large mammals (Sawyer et al., 2012, 2016), the public continues to exert pressure to try other, less costly measures such as reducing the posted speed limit at night.

In partnership with the Wyoming Department of Transportation (WYDOT), we experimentally reduced the posted nighttime speed limit from 70 to 55 mi/h (112 to 88 km/h) on six stretches of highway with high rates of deer-vehicle collisions (DVCs). Through this study, we asked: (1) Did drivers reduce their operating speed in response to posted night and twilight speed limit reductions? (2) Did reduced posted speed limit affect deer road-crossing behavior—specifically, the proportion of road crossings that carried high risk of vehicle collision and the ease with which deer crossed the highway? And, (3) Did reduced posted speed limit reduce the number of DVCs?

2 | METHODS

2.1 | Study area

We selected six sections of highway in southwestern Wyoming with high rates of DVCs (Figure S1) (Riginos

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et al., 2016). Based on prior patterns of DVCs and our knowledge of local ecology (Riginos et al., 2016), we considered three of these (La Barge, Kemmerer South, and Kemmerer West) to be "winter" collision sites and three (Warren Bridge, Cokeville, and Evanston) to be "migration" sites—where deer were primarily hit in the fall and spring but not winter. Data collection took place during 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 with posted daytime speed limits of 70 mi/h (112 km/h).

2.2 | Study design

At all sites, we collected data before and after the posted speed limits were reduced to 55 mi/hi (88 km/h) during nighttime (30 min before sunset to 30 min after sunrise). For full details of the signage used to reduce the speed limit, see the Supporting Information. At the winter sites, we used a BACI study design over two winters (Table 1) with data collection in fall–winter 2016–2017 (Y1) before the nighttime speed limit signs were installed, and in fall–winter 2017–2018 (Y2), when WYDOT posted reduced nighttime speed limits in half of each study site (Figure S1b; Table 1). This allowed us to compare differences in vehicle speeds, deer behavior, and collisions before and after reduced speed limits were implemented while controlling for both spatial and temporal variability in road conditions and deer numbers. At migration sites, we collected data in fall 2016, before nighttime speed limit signs were installed, in spring 2017 and fall 2017 with nighttime speed limits in effect, and in spring 2018 after the nighttime speed limit signs were removed. Both fall 2016 and spring 2018 served as "before" measurements and were compared against the two "after" time periods with the experimental nighttime speed limit reduction in 2017 (spring and fall). Because there were beacon malfunctions in spring 2017 at Cokeville and Evanston, we did not use those data in our analyses.

2.3 | Vehicle speed data

We measured vehicle speeds using five radar recorders (JAMAR Technologies Inc., Hatfield, PA) for four to five 24-h periods per month at each site. These included locations in reduced and control stretches at winter sites and reduced and adjacent locations outside of the reduced speed limit stretch at migration sites (Figure S1b,c; Supplemental Information). We classified vehicles into two categories: passenger vehicles = 2–6.7 m in length and cargo vehicles are those >6.7 m in length. Here, we present results only for passenger vehicles; cargo vehicles showed the same patterns but with slightly lower overall speeds (Riginos et al., 2019). We classified all speed observations into three time windows: "night" = 30 min post-sunset until 30 min pre-sunrise, "daytime" = 30 min post-sunrise until 30 min pre-sunset, and "twilight" = 30 min on either side of sunset and sunrise. Finally, we removed all vehicles that had <10 s following distance from the preceding vehicle—whose speeds were likely being influenced by the vehicle(s) in front of them. Thus, we focus on assessing the effect of reduced posted speed limit on the speeds of independently acting drivers. We also used enforcement records from the Wyoming Highway Patrol to indicate law

TABLE 1 Study site locations and months of data collection

Highway	Site name	Length—Control stretch	Length—Impact stretch	AADT	Site type	Study design	Months of study
US 189	La Barge	10.0 mi (16.0 km)	12.5 mi (20.0 km)	1392	Winter	BACI	November–April
US 30	Kemmerer West	4.0 mi (6.4 km)	4.3 mi (6.9 km)	1508	Winter	BACI	November–April
US 189	Kemmerer South	8.0 mi (12.8 km)	8.0 mi (12.8 km)	1094	Winter	BACI	November–April
US 30	Cokeville	Same stretch as impact	3.5 mi (5.6 km)	1871	Migration	Before-after	October–November and April–May
US 191	Warren Bridge	Same stretch as impact	6.5 mi (10.5 km)	1855	Migration	Before-after	October-November and May–June (2017) or April–May (2018)
WYO 89	Evanston	Same stretch as impact	9.6 mi (15.4 km)	2490	Migration	Before-after	October–November and March–April

Abbreviation: BACI, before-after-control-impact.

enforcement activity levels during our study period (see Supplemental Information).

We analyzed speed data from winter sites using a two-way ANOVA with main and interacting effects of year and treatment (control vs. reduced, where "control" refers to the stretch where the speed limit was never reduced, and "reduced" refers to the stretch where speed limit was reduced in Y2), looking particularly for any interactions between year and treatment that would indicate an effect of reduced nighttime posted speed limit. For migration site data, we analyzed all combinations of time (fall 2016, spring 2017, fall 2017, spring 2018) and whether the radar recorder was inside or outside the reduced speed limit stretch as one-way ANOVAs, using Tukey's HSD test to compare speeds inside versus outside the reduced stretch at each time period. We conducted these analyses separately for each site, since the patterns were somewhat different from site to site, and separately for night, twilight, and daytime data.

2.4 | Deer behavior data

We collected data on deer behavior to complement data on deer collision rates; deer behavior data can inform us about the frequency of near-missed collisions and the degree to which the road was or was not challenging for deer to cross. We recorded deer road crossings using four forward looking infrared (FLIR) thermal monoculars (FLIR Systems, Inc., Stillwater, OK) for four to five nights per month of the study at each site (see Supplemental Information for more detail) and reviewed footage to find deer-road interactions during the dusk-dawn period. We identified a total of 350 "deer-road interactions" in which a deer and a vehicle were close enough to each other that there was potential for an unsafe interaction or collision. Each deer-road interaction started when a deer in the right-of-way (ROW) moved directionally toward the pavement edge—indicating intent to cross—and ended with either a successful crossing or a failure to cross. In a successful crossing, the deer exited the pavement edge on the other side of the road, completing the deer-road interaction. In a failed crossing, the deer never reached the other side of the road, and the deer-road interaction ended when the deer (a) exited the ROW on the same side where it entered, (b) stopped showing intent to cross, or (c) was hit by a vehicle. During 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 pavement and either continuing onto the road or turning away from the road. For each deer-road interaction, we recorded the number of attempts to cross, the number of vehicles that passed during the interaction ("traffic count"), and the overall risk level of the interaction. "High-risk" interactions included collisions and narrowly avoided collisions where the deer and vehicle were in close proximity and modified their behavior to avoid each other. "Low risk" interactions were those where the deer crossed in front of a vehicle but was not immediately threatened by it, or where the deer waited for the vehicle to pass before attempting to cross.

We fitted logistic regressions of risk level as a function of site, year, treatment, year × treatment, and traffic count (log-transformed) for winter sites and as a function of site, time period, and traffic count for migration sites. Number of attempts to cross at migration sites ranged from one to six, and we fitted this response using a generalized linear model with a Poisson distribution using the same set of predictors as used for risk level. At winter sites, only one observation involved more than two attempts to cross, making a Poisson distribution inappropriate; instead we fitted a logistic regression using the same predictors as for risk level, with a binary response variable of one versus more than one attempt to cross. To facilitate visualization of deer behaviors in response to traffic variables, we divided traffic count data into quartiles and plotted deer behavior for each traffic quartile.

2.5 | DVC data

We used two sources of data to examine the effects of reduced posted speed limit on the number of DVCs: WYDOT's animal-vehicle crash data (from collisions reported to highway patrol) and WYDOT's roadside carcass count data collected by highway maintenance crews. Collection methods and a comparison of these data sets can be found in the Supplemental Information. Due to sample size, statistical power to detect changes in crashes is more limited than for carcasses.

For winter sites, we analyzed crash and carcass data in two ways. First, we used chi-squared tests to assess whether the proportional distribution of crashes and carcasses was equal or unequal among the 4-year-treatment combinations; this is detailed in the Supplemental Information and allowed more power to detect effects. Second, we used an ANOVA for crash and carcass data from all three winter sites, standardized to a per-mile rate over the 6-month winter period, with site as a random effect and year, treatment, and the year × treatment interaction as fixed effects. This had less power but allowed us to account for site differences in the model. Because results were consistent between both methods, we focus on the results of the ANOVA.

For the migration sites, we used paired *t*-tests to analyze crash and carcass data, including fall data from all three sites and spring data from Warren Bridge. Data were again standardized to per-mile rates of crashes and carcasses over the 2-month migration period. We paired data by sites and compared them between conditions of 70 mi/h (112 km/h) and 55 mi/h (88 km/h; reduced night speed limit). 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." All data analyses were conducted using R (version 3.5.2, R Core Team 2018) and JMP (Version 13.0, SAS Institute, Inc., Cary, NC).

3 | RESULTS

3.1 | Vehicle speeds and enforcement

At all three winter sites, during the periods when the posted speed limit was 70 mi/h (112 km/h), drivers traveled slightly faster at twilight than at night, and slightly faster during daytime hours than at twilight hours (Figure 1). At Kemmerer West and South, vehicles traveled faster in Y2 than in Y1, which may have been due

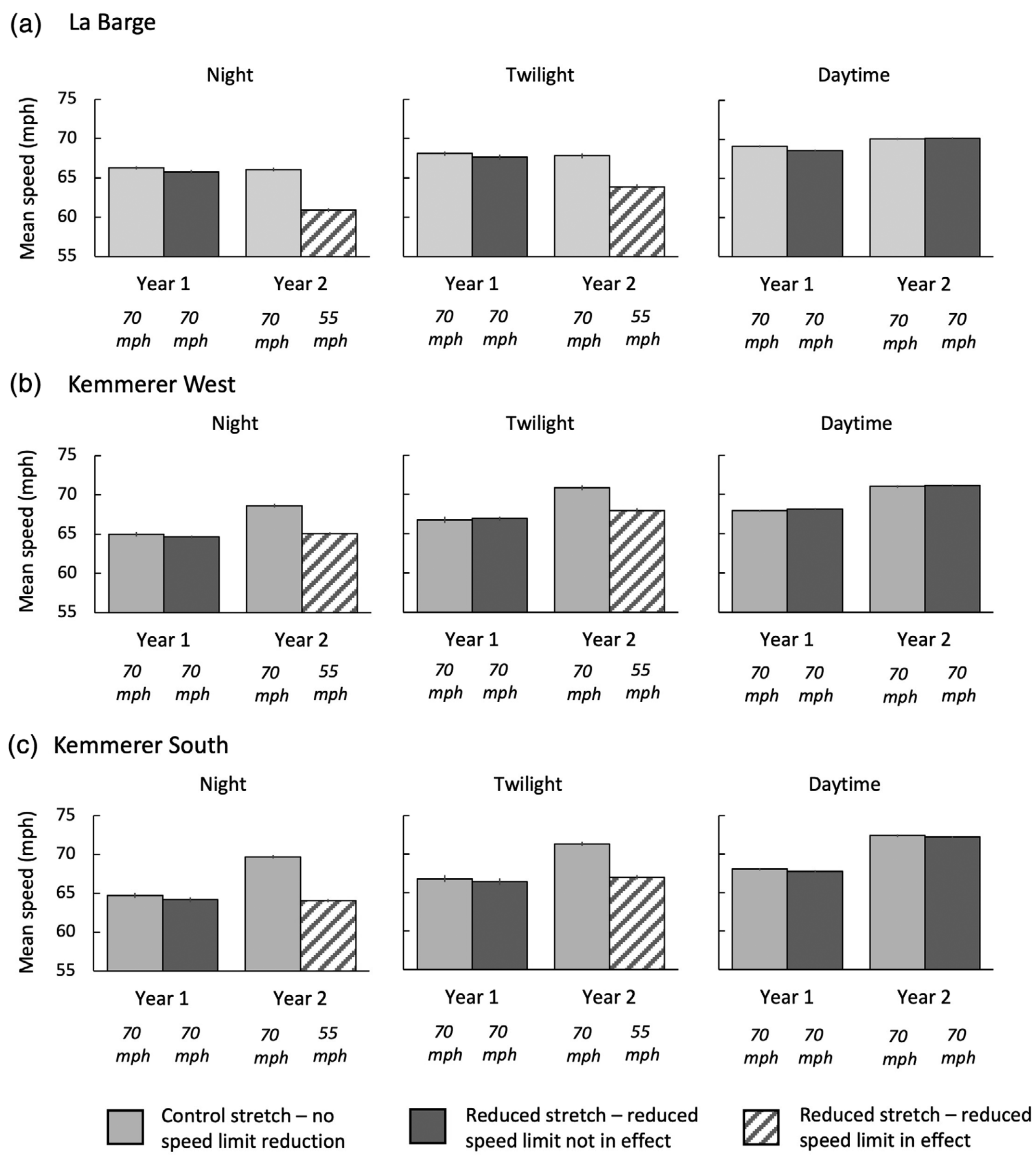

FIGURE 1 Mean vehicle speeds (±95% CIs) at night, twilight, and daytime for three winter sites, (a) La Barge, (b) Kemmerer West, and (c) Kemmerer South. Data were collected over two winters, with speed limit reduced to 55 mph at night and twilight in one stretch per site

to the more benign weather conditions in the winter of Y2 compared to Y1 (NOAA, 2017, 2018). Against the background of these sources of variation, there was a consistent pattern that drivers at night traveled, on average, 3–6 mph (5–10 kph) slower when the posted speed limit was 55 mi/h (88 km/h) compared to when there was a posted speed limit of 70 mi/h (112 km/h) (Figure 1). While drivers responded to the lower posted speed limit by reducing their speeds, their average nighttime speeds were still well above the posted 55 mph speed limit. At all three winter sites, the interactions between year and treatment were significant, both during night and twilight hours (Table S1; Figure 1). These interactions were not significant during daytime hours—when the posted speed limit was always 70 mi/h (112 km/h)—at two sites and significant but minimal in magnitude at the third site (Table S1, Figure 1).

At migration sites, the effect of reduced posted nighttime speed limit on vehicle operating speed was similar to patterns at winter sites (Figure 2). At all three migration sites, overall one-way ANOVAs showed significant differences among all combinations of radar locations (inside the reduced speed limit stretch versus adjacent outside stretch) and time periods (fall 2016, spring 2017, fall 2017, spring 2018) at all three times of day (Table S2). At Warren Bridge, the consistently lower speed inside the reduced speed limit stretch compared to outside, even during the day, may have occurred because the road in this stretch is more curved compared to the outside area where radar recorders were placed.

The rate of warnings and citations issued by law enforcement personnel was not associated in any clear way with the reduced speed limit being in effect. The rate

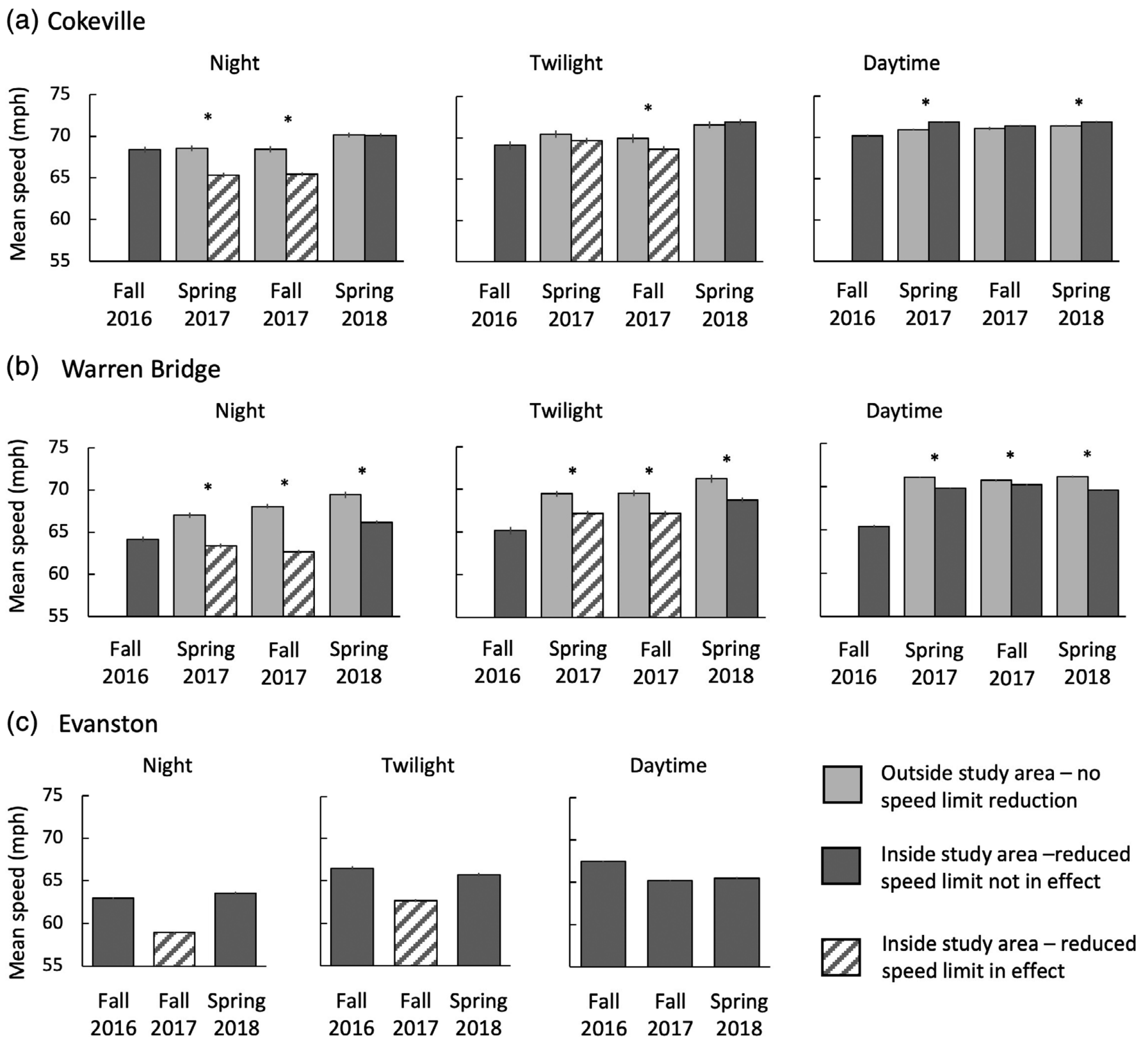

FIGURE 2 Mean vehicle speeds (±95% CIs) at night, twilight, and daytime for three migration sites, (a) Cokeville, (b) Warren Bridge, and (c) Evanston. Data were collected over four time periods (three at Evanston), with speed limit reduced inside the study stretch in spring 2017 and fall 2017. Speed data were collected simultaneously in a 70 mph zone outside but adjacent to each study stretch, except Evanston where no 70 mph zone existed nearby

of warnings and citations varied among sites, with overall higher rates at migration sites than winter sites (Figure S2). For several (but not all) sites, this rate was higher when the 55 mph (88 kph) speed limit was in effect.

3.2 | Deer behavior

Whether a deer engaged in a high-risk or low-risk road crossing varied depending on site and time period, but there was little evidence of fewer high-risk crossings when the reduced speed limit was in effect. At winter sites, site was the only statistically significantly predictor of crossing risk ($z = -2.2$, $n = 112$, $p = .02$). The percentage of interactions that were high-risk at La Barge (32%) was much higher than Kemmerer South (7%) or Kemmerer West (0%). In the pooled crossing risk dataset used for analysis, there was an overall pattern, albeit not significant, of fewer high-risk crossings in the reduced speed limit stretches in both years (Figure 3a); this likely occurred because those stretches had a much lower representation of deer-vehicle interactions from La Barge than the control stretches (Figure S3). For migration sites, time period was the only significant predictor of crossing risk, with fall 2016 (reduced speed limit not in effect) having a higher likelihood of high-risk interactions than fall 2017 (reduced speed limit in effect; $z = -2.02$, $n = 203$, $p = .04$) and a marginally significant higher likelihood than spring 2018 (reduced speed limit not in effect; $z = -1.83$, $n = 203$, $p = .07$; Figure 3b). The lower proportion of high-risk interactions in fall 2017 than fall 2016 suggests a potential benefit of reduced speed limit, but this is not fully conclusive since high-risk interactions were also somewhat lower in spring 2018 relative to fall 2016. Traffic volume during the deer-road interaction was also a marginally significant predictor of the likelihood of high-risk interactions ($z = 1.69$, $n = 203$, $p = .09$).

At winter sites, whether deer made one vs. multiple attempts to cross was positively affected by traffic count during the deer-road interaction ($z = 2.2$, $n = 112$, $p = .03$) and, marginally affected by a year × treatment interaction with the lowest likelihood of multiple attempts in the Y2-reduced treatment combination (Figure 3c; $z = -2.0$, $n = 112$, $p = .05$). The latter suggests a possible benefit of the reduced speed limit; however, it could also be an artifact of the high

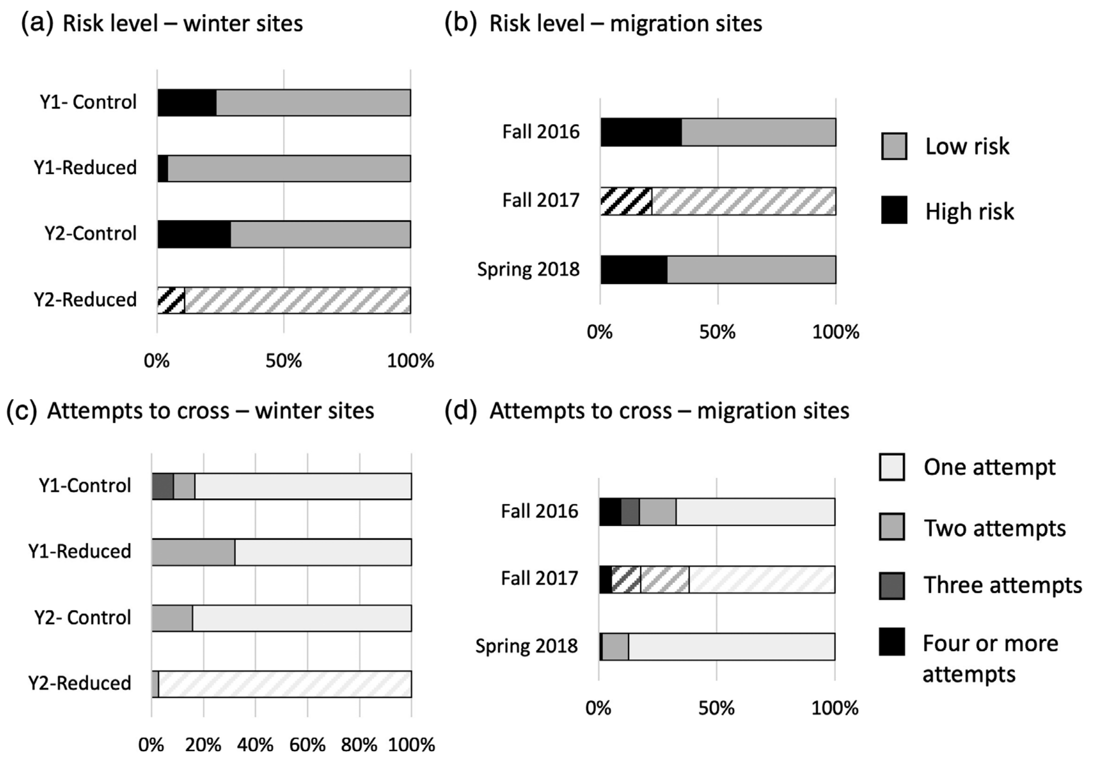

FIGURE 3 Percentage of deer-vehicle interactions that (a) were high versus low risk of collision in each of the four combinations of year and treatment at winter sites, where speed limit was reduced from 70 to 55 mph in Y2 reduced, (b) were high versus low risk in each of the three time periods at migration sites, where speed limit was reduced in fall 2017, (c) number of attempts deer made to cross the road in each of the four combinations of year and treatment at winter sites, where speed limit was reduced in Y2 reduced, and (d) number of attempts deer made to cross the road in each of the three time periods at migration sites, where speed limit was reduced in fall 2017

representation of Kemmerer South, where 93% of deer-road interactions involved only one attempt to cross, in the Y2-reduced behavior data (Figure S3). At migration sites, number of attempts to cross was strongly related to traffic count ($z = 3.8$, $n = 203$, $p < .001$) and time period, with spring 2018 (no speed limit reduction) having fewer attempts to cross than fall 2016 (no speed limit reduction) or fall 2017 (speed limit reduction in effect) ($z = -2.4$, $n = 203$, $p = .01$; Figure 3d), suggesting that annual variation in crossing attempts were likely due to causes other than speed limit reduction. At both winter and migration sites, higher traffic volume was associated with deer making a larger number of attempts to cross per deer-road interaction (Figure 4).

3.3 | Crashes and carcasses

Analysis of variance on winter sites using the BACI design showed no evidence of an effect of reduced posted speed limit. For both crashes and carcasses, there was no significant year × treatment interaction (crashes: $F = 0.91$, df = 1, $p = 0.37$; carcasses: $F = 0.008$, df = 1, $p = .93$). Crash rates were actually 20–70 percent higher under reduced posted speed limit (Y2-reduced) compared to the other 3-year-treatment combinations, while carcass rates were almost identical across year and treatment combinations (Figure 5a,b).

In contrast, migration sites showed some indication that the reduced posted speed limit resulted in fewer

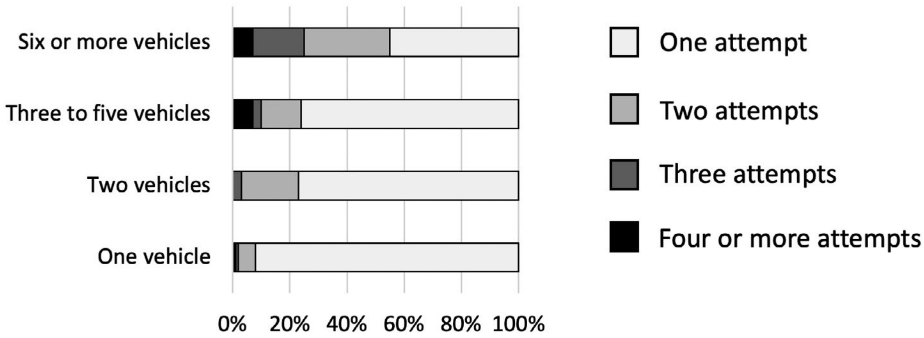

FIGURE 4 Percentage of deer that made one, two, three, or four or more attempts to cross the highway by number of vehicles that passed during the deer-road interaction. Data from all sites and time periods are pooled

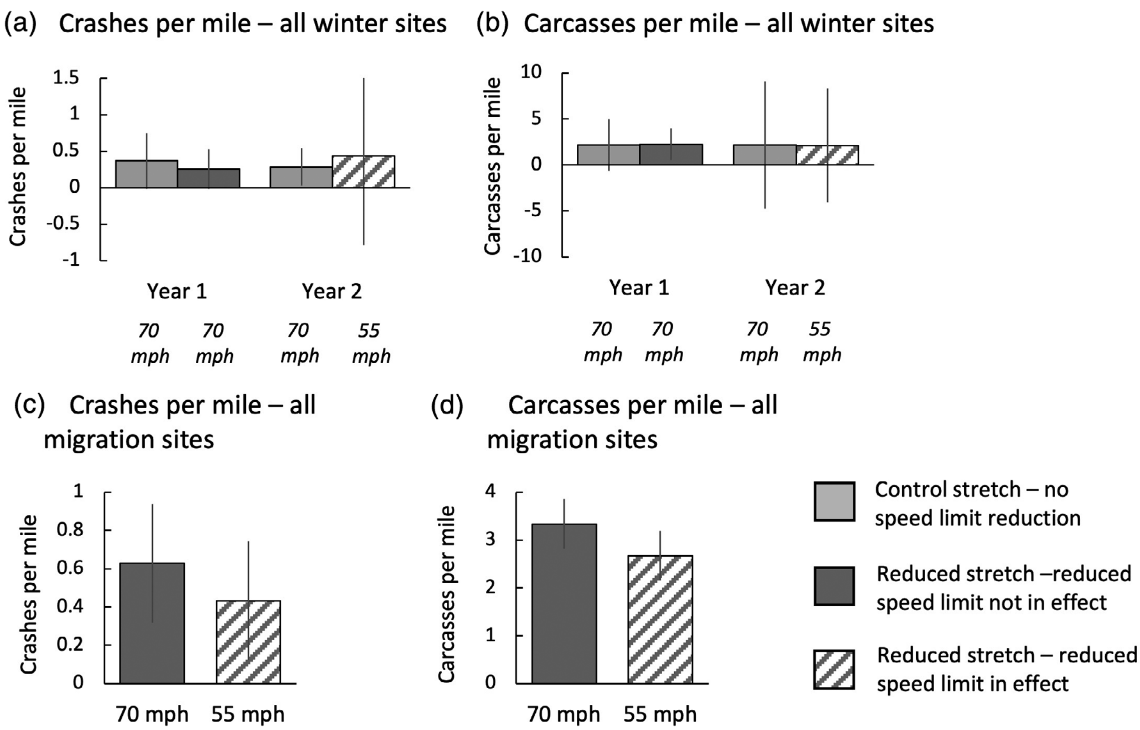

FIGURE 5 (a) Mean (±95% CIs) deer-vehicle crashes per mile averaged across all winter sites, by year and posted speed limit, (b) mean (±95% CIs) deer carcasses per mile averaged across all winter sites, by year and posted speed limit, (c) mean (±95% CIs) deer-vehicle crashes per mile averaged across all migration sites, by posted speed limit, and (d) mean (±95% CIs) deer carcasses per mile averaged across all migration sites, by posted speed limit

crashes and carcasses. The average number of crashes per mile across all four pairs of data was 37% lower in reduced speed limit conditions relative to 70 mph (112 kph) speed limit conditions (Figure 5c), and this difference was statistically significant ($t = 2.28$, df = 6, $p = .03$). The pattern was consistent for three of the four pairs of data (Figure S4e). Similarly, the average number of carcasses per mile across all four pairs of data was 31% lower in reduced speed limit conditions relative to 70 mph speed limit conditions (Figure 5d). Although this difference was not statistically significant at the $p < .05$ level ($t = 1.42$, df = 6, $p = .10$), 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 (Figure S4f).

4 | DISCUSSION

Wildlife and transportation managers, as well as the public, often propose reducing the speed limit as a measure to reduce WVCs on highways, despite little empirical evidence to support the effectiveness of this measure. Here, we tested the whole causal chain from reduced posted nighttime speed limit to vehicle operating speed, deer-vehicle interaction dynamics, and the number of DVCs, using experimental speed limit reduction with controls in both time and space.

4.1 | Vehicle operating speed

At all sites, independently acting (non-platooned) drivers drove more slowly during dusk, dawn, and night when the posted nighttime speed limit was 55 mi/h compared to when it was 70 mi/h. However, the reduction in speed was relatively small; at night, this difference was about 4–5 mi/h (6.5–8 km/h), and at dawn and dusk this difference was about 3 mi/h (4.8 km/h). These patterns were clearly associated with the reduced posted nighttime speed limit, since they were consistent across all sites, did not occur in the control stretches or in the reduced speed limit stretches of road when the flashing beacons were turned off, 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 7 months, and migration sites, where the reduction was in effect for only 2 months. We expected that drivers would habituate to reduced speed limit signs and stop heeding them at the winter sites. However, drivers in both types of sites slowed down by a similar amount over the entire time that the reduced speed limit was in effect.

Although drivers did consistently reduce their speeds, the average vehicle was still traveling at 60–65 mi/h (96–105 km/h), 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 given the design and surroundings of a road, rather than adhering to the posted speed limit, unless there is a high presence of law enforcement (Elliott et al., 2005; Mannering, 2009; Shinar, 2007; Soole et al., 2013). Law enforcement presence is generally positively related with driver compliance to posted speed limits (Soole et al., 2013; Vaa, 1997; Wasson et al., 2011); however, the rate of traffic warnings and citations at our sites had no clear relationship with vehicle operating speeds. Enforcement presence may have been too low in the study sites to routinely affect driver speeds. In rural Wyoming, a small number of highway patrol cars must cover a large network of two-lane highways, and patrol presence on most roads is scant. Additionally, the rate of warnings and citations is an imperfect proxy for true enforcement presence, which may also explain the lack of pattern between enforcement and speeds.

These results are consistent with findings from the only other comprehensive test of reduced nighttime speed limit as a means of reducing WVCs that we are aware of, which was conducted by CDOT (Colorado Department of Transportation, 2014). This study found that vehicle operating speeds at 14 sites averaged 62 mi/h (100 km/h) when the posted speed limit was reduced from 70 or 65 mi/h to 55 mi/h (112.5 or 104.5 to 88.5 km/h). CDOT reported a 43% increase in the number of law enforcement citations distributed during the study period, indicating that law enforcement was at least present and attempting to influence driver compliance to the posted speed limit.

4.2 | Deer behavior and road permeability

We expected that, if roads were safer for deer and drivers when the nighttime speed limit was reduced, we would find relatively fewer deer-vehicle interactions to be “high-risk” (situations where deer and vehicles collided or narrowly avoided colliding with each other) under this situation. However, we found no effect of reduced nighttime speed limit on the rate of high versus low risk deer-vehicle interactions at winter sites and an equivocal effect at migration sites. This is not surprising given the relatively small change in overall vehicle operating speeds that we observed. We did find strong effects of site, indicating that some areas have more frequent high-risk deer-vehicle interactions than others, perhaps related to unmeasured variables such as road curvature or driver and deer viewshed in specific locations.

We also hypothesized that if drivers reduced their speed in response to reduced posted nighttime speed limit, this might make roads easier for deer to cross. However, there was no evidence to support this hypothesis at migration sites, and an unclear outcome at winter sites given highly variable representation of data from the three sites across year-treatment combinations. We did find that traffic volume had a substantial impact on deer behavior. The more vehicles that passed during the deer-road interaction, the more attempts the deer made to cross. Further, the more attempts a deer made to cross, the higher the chances that the deer would ultimately abandon its effort and fail to cross. The rate of successfully completed crossings was 84% when the deer made only one attempt, 87% for two attempts, 71% for three attempts, and 58% for four attempts ($\chi^2 = 8.1$, $n = 341$, $p = .04$). The idea that roads can pose a partial or even complete barrier to wildlife movements is widely accepted (Beckmann et al., 2010; Coe et al., 2015; Jacobson et al., 2016), but evidence for how this barrier effect manifests at an individual animal level is scarce. Our results show how instantaneous traffic volume creates conditions that enable or hinder deer road crossings.

4.3 | Deer-vehicle collisions

We found 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, we did find 37% fewer crashes and 31% fewer carcasses when the speed limit reduction was in effect. These results seem to suggest that reduced nighttime speed limits were effective at reducing WVCs at migration sites but not winter sites. It is important to keep in mind that we employed a robust BACI design at winter sites but were only able to use a weaker before-after design at migration sites. DVC rates are well-known to differ from one season or year to another, since deer behavior varies seasonally (Relyea & Demarais, 1994) and herd sizes and other risk factors such as snow depth fluctuate from year to year. While we could effectively rule out such fluctuations as the cause of collision patterns at winter sites, we could not do this for migration sites. Consequently, we have higher overall confidence in the winter site results that indicate no reduction in collisions.

Given the relatively small effect of speed limit on operating speeds and that vehicles were still traveling 60–65 mi/h (96–105 km/h) at all sites, we would expect there to be little to no impact of these slower speeds on the risk of DVCs at night. A vehicle traveling at 60 mi/h (96 km/h) has a stopping distance of 145–172 m after the driver first detects an animal in the road (Huijser et al., 2017). This is a longer distance than the detection distance afforded by most vehicle high beam headlights and all vehicles' low beam headlights. In other words, at this speed, most vehicles are outrunning their headlights and drivers cannot avoid a collision unless the animal or vehicle moves out of its current path (Huijser et al., 2017). Vehicle operating speeds would need to be below 55 and 35 mi/h for most vehicles to avoid outrunning median high and low beam headlights, respectively.

However, it is possible that modest reductions in vehicle speed could translate to increased ability to avoid collisions with deer at dawn and dusk. It is also possible that a higher fraction of our deer road crossings and collisions occurred during crepuscular hours at migration sites than at winter sites, which could explain why WVC rates were lower under reduced speed limit at migration sites despite vehicle speeds similar to speeds at winter sites. It could also be that driver awareness of the collision hotspot and alertness for deer was heightened at migration sites, which were more discrete stretches than the diffuse winter sites. Alternatively, the WVC pattern at migration sites could have been an artifact of differences in deer activity and numbers from time period to time period.

Like this study, the CDOT study also failed to find any consistent effect of reduced speed limit on collisions with animals. CDOT found that WVCs decreased during the study in eight of the 14 study areas following speed limit reduction, while they increased in the other six study areas that received the same speed limit reduction (Colorado Department of Transportation, 2014). The study design was a before-after comparison, and the variation in WVC rates probably reflects interannual fluctuations in WVC rates due to reasons other than the reduced speed limit. From their study, CDOT concluded that the nighttime posted speed limit reductions were ineffective due to poor driver compliance and variable results in WVCs.

4.4 | Management implications

Overall, our results do not indicate that reduced posted nighttime speed limit is an effective means to reduce WVCs on rural two-lane highways with high design speeds. However, there are several caveats and areas for potential further research. First, there is an important 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 if the vehicle's operating speed is reduced sufficiently to bring its stopping distance within the visibility range of its headlights at night (with potentially less reduction in speed needed during crepuscular hours). However, reducing the speed limit to below 55 mi/h on rural highways without changing the design speed is neither practical nor safe; drivers will not comply uniformly, leading to a high risk of speed dispersion and risky overtakes that would lead to more head-on collisions between vehicles. Large reductions in speed limit are likely to be socially unpalatable, and law enforcement agents may have low willingness to enforce them. Further, there are economic cost impacts of slowing the speed of transportation, especially the transportation of goods.

Second, there may be more effective ways to influence driver behavior than the methods used in this study. Drivers were alerted to the risk of wildlife collisions by a single, permanent sign at the start of each study stretch, whereas seasonally placed signs and variable messages may be more effective (Huijser et al., 2015). Reduced speed limits were indicated with static speed limit signs and flashing beacons; variable speed limit signs, where drivers see only the speed limit currently in effect, might be less confusing and result in higher driver compliance rates. Greater enforcement presence or automated enforcement systems such as “average speed enforcement”—which uses a network of speed cameras to calculate a vehicle's average speed over a larger stretch (Soole et al., 2013)—could be tested as a means to increase driver compliance with reduced speed limit. Additionally, driver culture—awareness of the problem of WVCs, attitudes toward this problem, and compliance with speed limits for the purpose of reducing WVCs—could possibly be altered over time with heavy and sustained investment in public outreach and education (Elliott et al., 2005).

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 mi/h, 72 km/h), such as in or near towns, where drivers are accustomed to traveling more slowly and a reduction of 5–10 mi/h (8–16 km/h) could make a substantial difference in drivers' ability to detect and avoid animals in the road.

One further caveat is that reducing driver operating speeds, even if achievable, is not likely to make high traffic volume highways any more passable to large mammals, as our results also indicate. For higher traffic volume roads, separated crossings (highway underpasses and overpasses) with wildlife fencing are the only proven way to ensure that roads do not obstruct large mammal movements, while also reducing WVC rates. Separated crossing structures with >3 mi (5 km) of fencing are consistently >80% effective at reducing WVCs (Huijser, Fairbank, et al., 2016; Rytwinski et al., 2016; Sawyer et al., 2012, 2016) and once accustomed to them, large mammals cross them regularly (Sawyer et al., 2016). 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. However, we also recognize that crossing structures and fences are not possible in some places and that speed limit reduction will remain appealing for these places. We recommend that any use of reduced speed limit should be combined with other measures to reduce operating speeds and treated as experimental, with sufficient data gathered so that we can increase our understanding of whether reduced speed limit can ever be effective at reducing WVCs, and if so, under what circumstances.

ACKNOWLEDGMENTS

This research was funded by grant RS11216 from the Wyoming Department of Transportation (WYDOT) to C. Riginos and M. Huijser, and a full account of results was published as WYDOT Final Report 1904F (Riginos et al., 2019). This study would not have been possible without the logistical support of numerous WYDOT staff, with special thanks to Keith Compton, Darin Kauffman, Raymond Avery and Enid White. We also thank Maggie Schilling at the Northern Rockies Conservation Cooperative for grant administration and support. Courtney Larson, Trevor Bloom, Maggie Eshleman and three anonymous reviewers provided valuable comments on earlier drafts of this manuscript.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

Corinna Riginos and Marcel P. Huijser designed the study, with on the ground modifications by Elizabeth Fairbank and Erica Hansen. Elizabeth Fairbank, Erica Hansen, and Jaron Kolek collected field data and deer behavior data from video footage. Corinna Riginos, Erica Hansen, and Marcel P. Huijser analyzed the data. Corinna Riginos wrote the manuscript, with input from all authors.

DATA AVAILABILITY STATEMENT

Data are publically available via FigShare at: https://doi.org/10.6084/m9.figshare.17269046.

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How to cite this article: Riginos, C., Fairbank, E., Hansen, E., Kolek, J., & Huijser, M. P. (2022). Reduced speed limit is ineffective for mitigating the effects of roads on ungulates. *Conservation Science and Practice*, e618. https://doi.org/10.1111/csp2.618