Exploring Apex Predator Effects on Wildlife-Vehicle Collisions: A Case Study on Wolf Reintroductions in Yellowstone

Final Report

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16. Abstract

This study investigates the impact of wolf reintroduction on wildlife-vehicle collisions (WVCs) along a segment of US-191 bordering Yellowstone National Park. Wolves were reintroduced in 1995–1996, and subsequent wolf pack establishment may have influenced the behavior and population dynamics of prey species, potentially altering WVC patterns. Using carcass data collected from 1989 to 2021, the analysis was divided into two primary phases: before wolves (1989–1996) and after wolves (1997–2021). A series of linear mixed-effects models were developed to assess changes in WVCs across these time periods. Predictor variables included average annual daily traffic (AADT), elk population estimates, and wolf counts. Results showed that WVCs significantly declined in the post-wolf period, suggesting that the presence of wolves may reduce WVCs directly by modifying prey behavior and movement patterns, or indirectly by reducing prey population densities. Further analysis revealed that while elk populations were a significant predictor of WVCs before wolves were reintroduced, this relationship weakened post-reintroduction. Traffic volume did not significantly influence WVC patterns in either period, nor did it interact significantly with wolf presence. The inclusion of wolf counts as a continuous variable showed a negative relationship with WVCs, indicating that higher wolf densities may contribute to a further reduction in collisions over time. These findings suggest that apex predators can play a role in mitigating human-wildlife conflicts, such as WVCs, by influencing prey species' behavior and distribution. The study provides valuable insights for wildlife managers and transportation planners, highlighting the potential benefits of predator conservation for road safety and ecosystem health.

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About the Small Urban, Rural and Tribal Center on Mobility

The mission of the Small Urban, Rural and Tribal Center on Mobility (SURTCOM) is to conduct research and provide leadership, education, workforce development and technology transfer in all transportation-related aspects of mobility for people and goods, focusing specifically on small urban, rural and tribal areas. Member institutions include the Western Transportation Institute at Montana State University, the Upper Great Plains Transportation Institute at North Dakota State University, and the Urban and Regional Planning program at Eastern Washington University.

Disclaimer

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1 Introduction

The presence of an apex predator within the trophic scale of wildlife species can affect the density, behavior, and physiology of an ungulate population (Warren, 2011). This was witnessed in Yellowstone National Park (YNP) when wolves were reintroduced to the landscape starting in 1995. Wolves forced elk, their main food source, to stay alert and continue to move, which therefore reestablished the natural structure and function of plant communities (Laundré et al. 2001). The presence of an apex predator can also create healthier ungulate populations by preying on the sick, weak, and dying animals.

Reductions in wildlife-vehicle collisions (WVCs) has been witnessed in studies where ungulate herds were reduced by culling, or killing, to reduce population size. Depending on the amount a deer population is reduced, WVCs with deer were reduced 30-94% (Doerr et al. 2001; DeNicola and Williams 2008; Warren et al. 2011; D'Angelo et al. 2012). It has been theorized that the reintroduction of an apex predator can also reduce WVCs by creating smaller, more healthy ungulate populations that are more alert and continually move through the landscape. When a predator is present in a landscape, ungulates are forced to keep moving and cannot linger in an area (i.e., road right-of-way) for too long.

In addition to human culling, large wild ungulate populations can also be regulated through the reintroduction of predators. For example, the reintroduction of bobcats to Cumberland Island led to a 50% reduction in the deer population within a few years, and significant increases in age- and sex-specific body weights due to reduced competition. The primary cause of this reduced growth rate was bobcats targeting fawns (Warren, 2011).

Similarly, the modeling and empirical evidence provided by Gilbert et al. (2017) support the idea that apex predators, such as cougars, can help control prey populations and reduce WVCs. Using population models, the researchers demonstrated that reintroducing cougars to the eastern United States could reduce deer densities and, consequently, WVCs involving deer by 22%, potentially preventing over 21,000 human injuries and 155 fatalities within 30 years (Gilbert et al. 2017). The study also included a before-after-control-impact analysis of recently established cougar populations in South Dakota, which showed a 9% decrease in deer-vehicle collisions within eight years of cougar re-establishment.

This research aims to build on these findings by exploring whether the presence of an apex predator, such as wolves, could similarly decrease WVCs along a section of road in the Greater Yellowstone Ecosystem. It is essential to note that the impact of apex predators on wildlife-vehicle collision rates can vary depending on several factors, including the specific predator and prey species involved, the density of both predators and prey, the overall landscape configuration, and the level of human development and traffic in the area. Therefore, the relationship between apex predators and wildlife-vehicle collisions can be complex and context-dependent. Conservation efforts and understanding the ecological dynamics of an area are critical to managing and mitigating wildlife-vehicle collisions effectively.

1.1 Background

The history of wolves in Yellowstone National Park and the surrounding area is marked by a rise, fall, and subsequent restoration of the population. Historically, grey wolves (*Canis lupus*) thrived in the region but were relentlessly hunted and persecuted by settlers, leading to their local extinction by the early 20th century. As attitudes towards predators shifted, conservation efforts aimed to restore wolf populations.

In January 1995, eight gray wolves from Jasper National Park in Canada were released into YNP. By the end of 1996, a total of 31 wolves were reintroduced to YNP. This endeavor had a profound ecological impact, as wolves played a crucial role in controlling unnaturally high elk populations, leading to habitat restoration, and benefiting various species. The reintroduction was widely considered a successful restoration effort, illustrating the importance of apex predators in maintaining ecological balance. Over time, wolf populations grew and expanded beyond Yellowstone, leading to their removal from the Endangered Species Act in 2011 and management by individual states. However, this decision has sparked debates and challenges concerning wolf conservation and human-wildlife interactions.

The presence of an apex predator in an area can influence WVC rates through several mechanisms:

- **Changes in Animal Behavior:** Apex predators can induce behavioral changes in prey species, often referred to as the "ecology of fear" (Ripple & Beschta, 2004). Prey animals may avoid areas where predators are known to be present or alter their movement patterns to reduce the risk of encounters. For instance, prey species might reduce time spent in open areas, such as road corridors, which could lead to fewer WVCs as animals avoid crossing roads in predator-rich areas (Ripple & Beschta, 2012; Ford et al., 2017).
- **Population Dynamics:** Apex predators play a crucial role in regulating prey populations, often preventing overpopulation and reducing the likelihood of WVCs. For example, the reintroduction of wolves in Yellowstone led to a decline in elk populations, which has been linked to changes in elk movement and road-crossing behavior (Ripple & Beschta, 2012). Similarly, Gilbert et al. (2017) found that cougar re-establishment in the eastern United States could reduce deer densities and, consequently, deer-vehicle collisions by 22% within 30 years. However, the effectiveness of predator presence in controlling WVCs depends on the predator's population density and other ecological factors.
- **Habitat Selection:** The presence of apex predators can influence prey species' habitat selection, leading prey to avoid areas with high predator activity (Ripple & Beschta, 2004). This avoidance may include roads or areas with high traffic, indirectly reducing the risk of collisions as prey shift their distribution to safer habitats (Clevenger & Huijser, 2011; Ford et al., 2017).
- **Scavenger Behavior:** Apex predators may leave remains of their kills near roads, which can attract scavengers such as vultures, coyotes, or smaller carnivores. This attraction to road-adjacent carcasses can increase the likelihood of WVCs as scavengers are drawn to feed on the remains (Huijser et al., 2016).
- **Road Avoidance:** Some apex predators, such as large cats or wolves, may actively avoid roads due to human activity and associated disturbances (Clevenger & Huijser, 2011). This avoidance behavior could lead to increased prey activity near roads, as prey may perceive these areas as relatively safer due to the absence of predators, potentially increasing the likelihood of WVCs (Ford et al., 2017).

Wolves are carnivorous predators and primarily hunt a variety of ungulate species. The main prey of wolves can vary depending on their geographic location and the availability of different prey species. In YNP, wolves’ primary prey is elk (*Cervus canadensis*), mule deer (Odocoileus hemionus), white-tailed deer (*Odocoileus virginianus*), moose (*Alces alces*), and bison (*Bison bison*) (National Park Service, 2024).

1.2 Research Objectives

The primary objective of this project is to explore the impact of the wolf reintroduction into Yellowstone National Park on WVCs along US-191. The study area is along the western edge of YNP, specifically from reference marker 10.5 to 32.3 (US-191 RM10.5 - RM32.3) where the highway crosses into the park boundary for a short distance. While many factors influence WVCs and animal behavior, the presence of an apex predator, such as wolves, is believed to play a key role. This project aims to explore potential correlations between the reintroduction of wolves and changes in WVC patterns. Using carcass data collected by Yellowstone National Park and the Montana Department of Transportation (MDT) from 1989 to 2021, the study employs a linear mixed-effects model to examine the relationship between WVCs, elk population estimates, and annual average daily traffic (AADT) volume. By comparing the pre- and post-wolf reintroduction periods, this project seeks to provide further evidence that the presence of an apex predator may reduce WVCs. This research aims to address three hypotheses, 1) the presence of wolves reduces WVCs directly, or indirectly; 2) wolve presence modifies the impact of traffic volume (AADT) on WVCs; and 3) wolf presence affects elk-specific collision. If such a correlation is found, it would suggest that predator restoration not only promotes ecological balance within the food web but may also offer additional benefits to public safety and transportation infrastructure by reducing the frequency of wildlife-vehicle interactions.

2 Methods

This chapter focuses on the data and statistical analysis used to explore the effects of wolves on large mammal WVCs. All spatial data were projected using the NAD 1983 StatePlane Montana FIPS 2500 coordinate system, with meters as the unit of measurement. The data variables were processed using ArcGIS Pro 3.1.2 (ESRI, 2024), while statistical analyses were conducted using RStudio 4.4.1 (Posit Team, 2023).

2.1 Geographic Location

The study is located along US-191, extending from reference marker (RM) 10.5 to RM 32.3, which follows the western edge of Yellowstone National Park. This section of road passes through the park boundaries between RM 14.9 and RM 20.9. To facilitate the analysis, the section of US-191 was divided into 0.1-mile segments, each assigned a unique identifier. Carcass data was mapped to these segments (*n* = 219) and categorized by species, as well as the total number of WVCs per segment. Road segments within the study area were included if they have at least one carcass from 1989 to 2021 (*n* = 172).

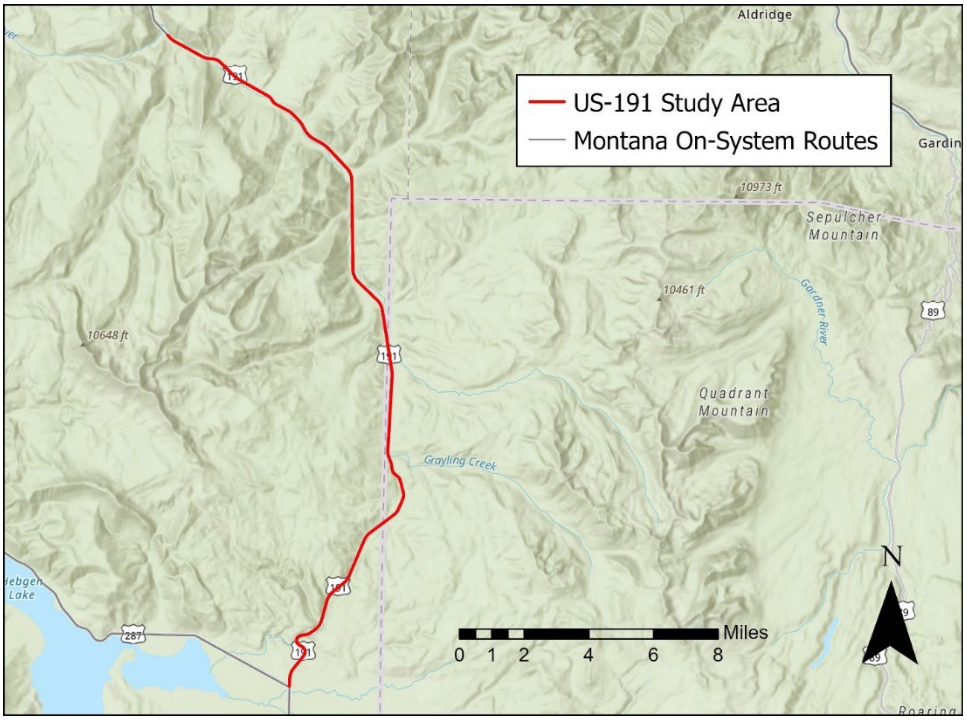

Figure 1: Study area along US-191 along the western boundary of Yellowstone National Park.

2.2 Data Variables

Carcass data for this area was collected by YNP and Montana Department of Transportation (MDT) employees from 1989 to 2021. There is a total of 771 large mammal carcasses within the study area: 453 elk (58.75%), 197 deer (25.55%), 77 moose (9.99%), 12 bison (1.56%), 16 wolves (2.08%), 13 black bear (1.69%), and 2 grizzly bear (0.26%). The data was filtered to focus solely on large mammal carcasses along US-191, with records for smaller mammals and adjacent roads removed. The number of carcasses per year can be seen in Figure 2.

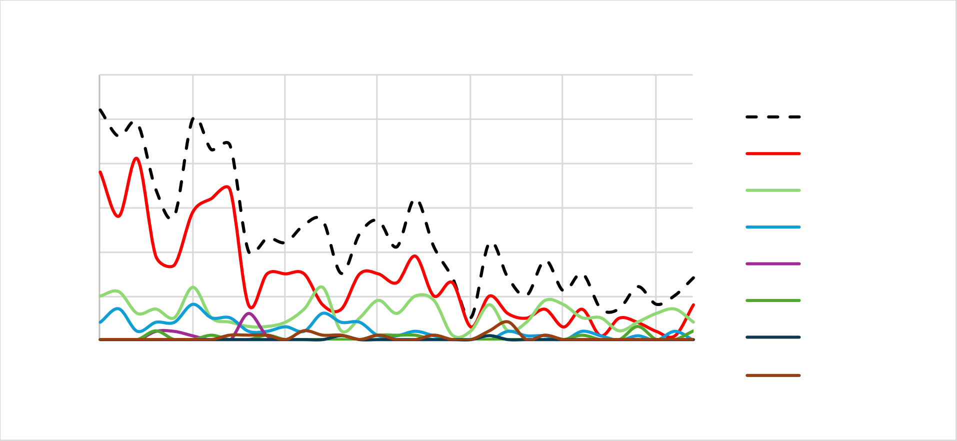

Figure 2: WVCs by species from 1989 to 2021.

The majority of WVCs occurred during the summer months of June and July (Figure 3). This trend differs from the patterns observed in carcass data for the entire Gallatin County, where this study area is located. Typically, the highest number of WVCs in Montana occurs during the fall and winter months, particularly around November. The shift in this study area’s peak WVC period may be influenced by increased tourism and associated traffic during the summer months.

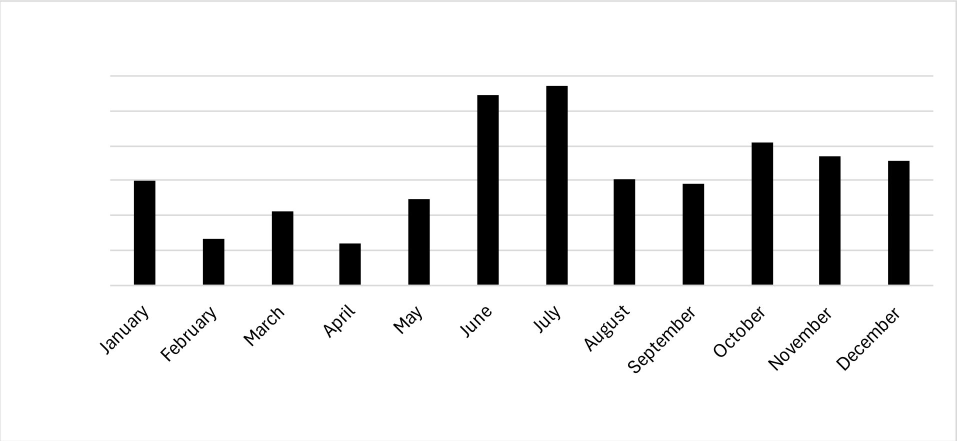

Figure 3: Distribution of WVC carcasses by month of the year.

Wolves were reintroduced into the study area in 1996, initially establishing the Chief Joseph Pack, followed in subsequent years by the Cougar Creek Pack and, temporarily, the Grayling Pack. This research divides the data into two periods: before wolf reintroduction (1989–1996) and after reintroduction (1997–2021). Carcass data, provided by Yellowstone National Park (YNP) biologists, was supplemented with information on wolf pack numbers. Each year, the Yellowstone Wolf Project publishes an annual report detailing wolf pack locations and population sizes within YNP (National Park Service, 2024). The number of adult wolves (≥ 2 years old) in packs within the study area was summed to create an annual wolf count variable.

Additionally, historic elk population counts were supplied by Montana Fish, Wildlife, and Parks (MTFWP) based on annual aerial surveys over the designated hunting district. While these elk counts do not represent precise population estimates, they effectively indicate population trends for the area (Figure 4). Traffic data, specifically average annual daily traffic (AADT) volumes, was obtained from the Montana Department of Transportation (MDT) GIS Portal for this section of US-191. The trend in elk counts and AADT averages from 1989 to 2021 are presented in Figure 4.

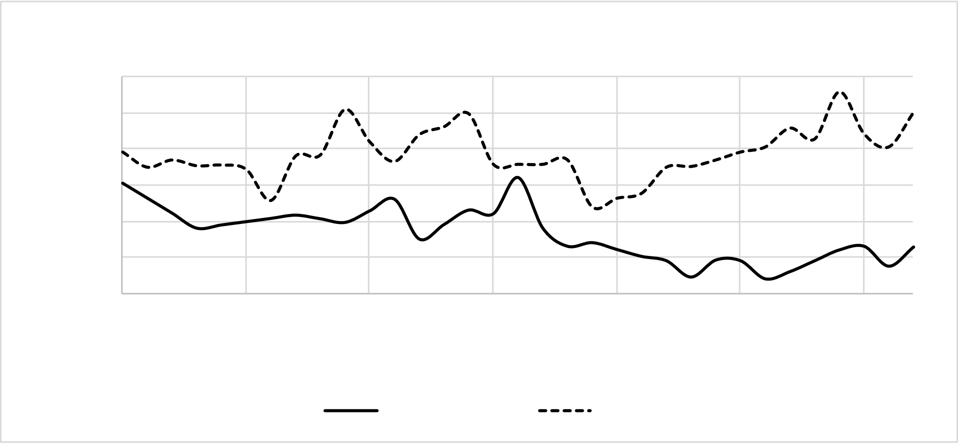

Figure 4: Aerial yearly elk counts for Montana Hunting District 310 and AADT from 1989 to 2021.

2.3 Statistical Analysis

To evaluate the impact of wolf reintroduction on WVCs and to explore the relationships between wolf presence, elk populations, and WVC trends, a series of six linear mixed-effects models were created using carcass data from 1989 to 2021 along US-191 (RM10.5 – RM32.3). The analysis was divided into two main phases: before wolf reintroduction (1989–1996) and after wolf reintroduction (1997–2021). The models were designed to identify changes in WVC dynamics between these periods, assess interactions between wolf presence and other variables, and evaluate the influence of increasing wolf numbers. A description of the six models is provided below.

Before and after wolves WVC models were developed for two baseline models to analyze general trends in WVCs before and after wolves were reintroduced.

1. Before Wolves WVC Model (bw96_1): This model used WVCs as the response variable, with predictors including average annual daily traffic (AADT), elk population numbers (Elk_Count), and year (Year). A random intercept for road segments was included to account for segment-

level variability. The model aimed to establish baseline WVC patterns prior to wolf reintroduction. The full model was specified as:

$$WVC \sim AADT + Elk_{Count} + Year + (1|Segment)$$

2. After Wolves WVC Model (aw97_1): This model used the same structure as bw96_1 but was applied to data from 1997 to 2021, capturing changes in WVC patterns following the reintroduction of wolves. The objective was to assess temporal trends in WVCs post-reintroduction and evaluate whether the relationship between elk counts and WVCs shifted after wolf presence was established. The full model was specified as:

$$WVC \sim AADT + Elk_{Count} + Year + (1|Segment)$$

3. Interaction Model with Wolf Presence (wint_1): An interaction model was developed to investigate whether the presence of wolves modified the relationship between elk populations, traffic volume, and WVCs. In this model, wolf presence was incorporated as a binary variable (Wolves; 0 = no wolves, 1 = wolves present). Interaction terms between wolf presence and elk counts (Elk_Count * Wolves) as well as wolf presence and traffic volume (AADT * Wolves) were included to test for differential effects of these variables depending on wolf presence. The full model was specified as:

$$WVC \sim AADT * Wolves + Elk_{Count} * Wolves + Year + (1|Segment)$$

Elk-vehicle collision (EVC) models were created to isolate the impact of wolves on their primary prey species. Two elk-specific collision models were constructed:

4. Before Wolves Elk Model (bw96_e1): This model examined only elk-specific collisions as the response variable for the pre-wolf period (1989–1996), using AADT, elk counts, and year as predictors. The objective was to identify the baseline relationship between elk populations and elk-vehicle collisions in the absence of wolves. The full model was specified as:

$$EVC \sim AADT + Elk_{Count} + Year + (1|Segment)$$

5. After Wolves Elk Model (aw97_e1): This model used the same structure as bw96_e1 but for the post-wolf period (1997–2021). The aim was to determine whether the reintroduction of wolves influenced elk-specific collision patterns over time. The full model was specified as:

$$EVC \sim AADT + Elk_{Count} + Year + (1|Segment)$$

6. Continuous Wolf Count Model (wolf_1) incorporated wolf population counts (Wolf_Counts) as a continuous predictor to evaluate the relationship between increasing wolf numbers and WVCs over the entire study period (1989–2021). This model allowed for a more detailed exploration of whether higher wolf densities were associated with changes in WVC frequency. The full model was specified as:

$$WVC \sim AADT + Elk_{Count} + Wolf_{Counts} + Year + (1|Segment)$$

P-value calculation for fixed effects were calculated based on the t-values obtained from each model. The p-values were derived using the formula:

$$p - value = 2 * (1 - pt(|t|, df)$$

where pt() is the cumulative probability function of the t-distribution, |t| is the absolute value of the t-statistic, and df is the degrees of freedom. An approximate degrees of freedom value of 100 was used for all calculations. This method provided an approximation of statistical significance for each fixed effect coefficient, allowing for comparison of effects across models. Comparisons between models were made using the significance of fixed effects, changes in residual variance, and trends observed in the random intercept variance for road segments.

This multi-model approach was created to try and capture both direct and indirect effects of wolf reintroduction on WVCs, providing a comprehensive assessment of changes in collision patterns before and after wolves were reintroduced into the study area.

2.4 Research Limitations

This study has some limitations. There is no direct control study area with comparable carcass data over the same time period, which makes it difficult to establish causal relationships. Additionally, correlation does not imply causation; multiple factors can influence WVCs, and any identified relationships may not be the primary cause. Nonetheless, the study aims to provide valuable insights into how the presence of wolves might interact with other variables to affect wildlife-vehicle collisions.

3 Results

The results of the linear mixed-effects models demonstrate distinct patterns in wildlife-vehicle collisions before and after the reintroduction of wolves in the study area. The before-wolves WVC model (bw96_1), which includes data from 1989 to 1996, reveals a positive relationship between elk populations and WVCs, with the coefficient for elk counts approaching statistical significance ($p \approx 0.068$) (Table 1). This indicates that higher elk populations were linked to an increase in WVCs during this period. No significant effects were observed for traffic volume (AADT) or year, suggesting that these factors did not meaningfully influence variations in collision rates in the absence of wolves. Additionally, the variance in WVCs between road segments was higher during this period, as indicated by the segment-level random effect variance (Table 2).

Table 1: Fixed effects summary results for the before and after WVC models analyzed.

Model	Variable	Coefficient Estimate	Standard Error	t-value	Significance
bw96_1	(Intercept)	-11.872798	19.04705	-0.623	0.5345
bw96_1	AADT	-0.000008	0.00009	-0.092	0.9270
bw96_1	Elk_Count	0.000200	0.00011	1.845	0.0680
bw96_1	Year	0.005981	0.00950	0.630	0.5304
aw97_1	(Intercept)	6.095489	2.15914	2.823	0.0057
aw97_1	AADT	0.000003	0.00001	0.201	0.8415
aw97_1	Elk_Count	0.000032	0.00002	1.442	0.1524
aw97_1	Year	-0.002999	0.00107	-2.797	0.0062

Table 2: Random effects summary results for six models analyzed.

Model	Group	Variance	Standard Deviation
bw96_1	Segment	0.075	0.273
bw96_1	Residual	0.331	0.575
aw97_1	Segment	0.005	0.068
aw97_1	Residual	0.115	0.339
wint_1	Segment	0.013	0.115
wint_1	Residual	0.175	0.419
bw96_e1	Segment	0.057	0.238
bw96_e1	Residual	0.216	0.464
aw97_e1	Segment	0.002	0.047
aw97_e1	Residual	0.057	0.240
wolf_1	Segment	0.013	0.115
wolf_1	Residual	0.176	0.420

In contrast, the after-wolves WVC model (aw97_1), which includes data from 1997 to 2021, shows a significant negative trend for the year variable ($p \approx 0.006$) (Table 1), indicating that WVCs decreased over time in the post-wolf period. The relationship between elk populations and WVCs was weaker and not statistically significant compared to the pre-wolf period, suggesting a shift in collision dynamics after wolves were reintroduced. This decline is further visualized in Figure 5, which depicts the overall reduction in WVCs over the entire study period, with a clear drop in segment variance (0.075 to 0.005) after the reintroduction of wolves in 1996. The variability between road segments in the post-wolf period was also reduced compared to the pre-wolf period (Table 2), indicating more consistent WVC rates across the study area after wolves became established.

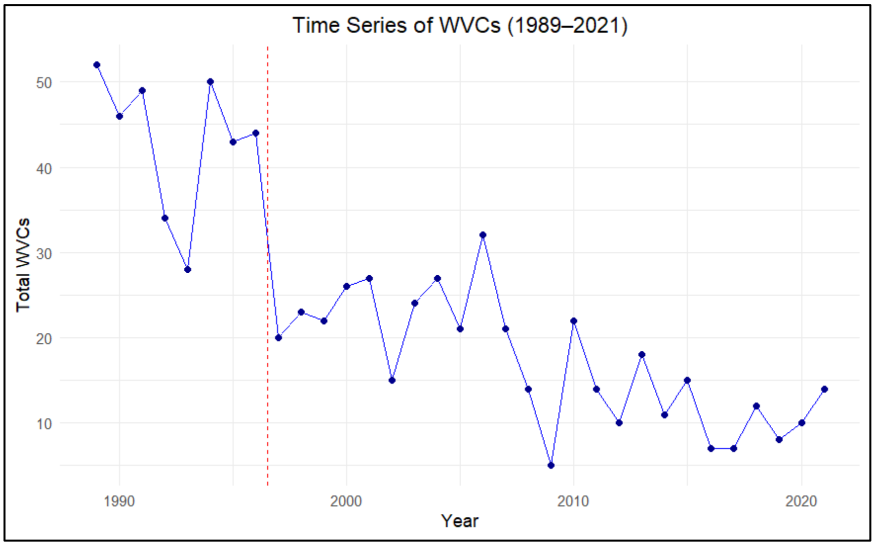

Figure 5: WVCs per year from 1989-2021. Red-dashed line depicts when wolves were introduced to Yellowstone.

The interaction model (wint_1), which used wolf presence as a binary variable (0 = no wolves, 1 = wolves present) across the entire dataset (1989–2021), did not reveal significant interaction terms between wolf presence and either elk populations or traffic volume. The positive relationship between elk populations and WVCs remained significant ($p \approx 0.029$) (Table 3). Similar trends are observed with and without wolves present, however WVCs were more frequent before wolves were reintroduced (Figure 6). The negative trend for the year variable persisted ($p \approx 0.042$), indicating a decline in WVCs over time, independent of wolf presence. These results suggest that wolf presence alone does not significantly modify the impact of elk populations or traffic volume on WVCs. However, the overall downward trend in WVCs post-wolf reintroduction is visualized in Figure 7, which compares WVC distributions before and after wolves, showing a clear reduction in WVCs after 1997.

Table 3: Fixed effects summary results for the interaction model with wolf presence.

Model	Variable	Coefficient Estimate	Standard Error	t-value	Significance
wint_1	(Intercept)	5.493862	2.61165	2.104	0.0379
wint_1	AADT	-0.000031	0.00006	-0.487	0.6275
wint_1	Wolves	-0.038014	0.11445	-0.332	0.7405
wint_1	Elk_Count	0.000139	0.00006	2.210	0.0294
wint_1	Year	-0.002682	0.00130	-2.060	0.0420
wint_1	AADT:Wolves	0.000033	0.00007	0.495	0.6216
wint_1	Wolves:Elk_Count	-0.000103	0.00007	-1.560	0.1218

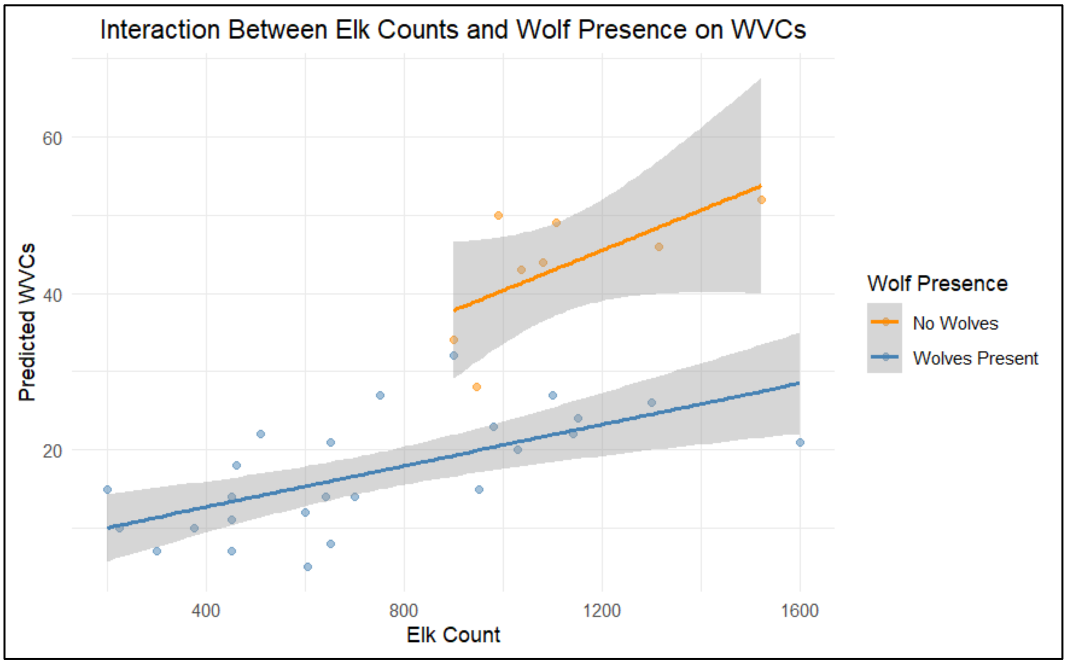

Figure 6: Interaction between aerial elk counts and WVCs with and without the presence of wolves.

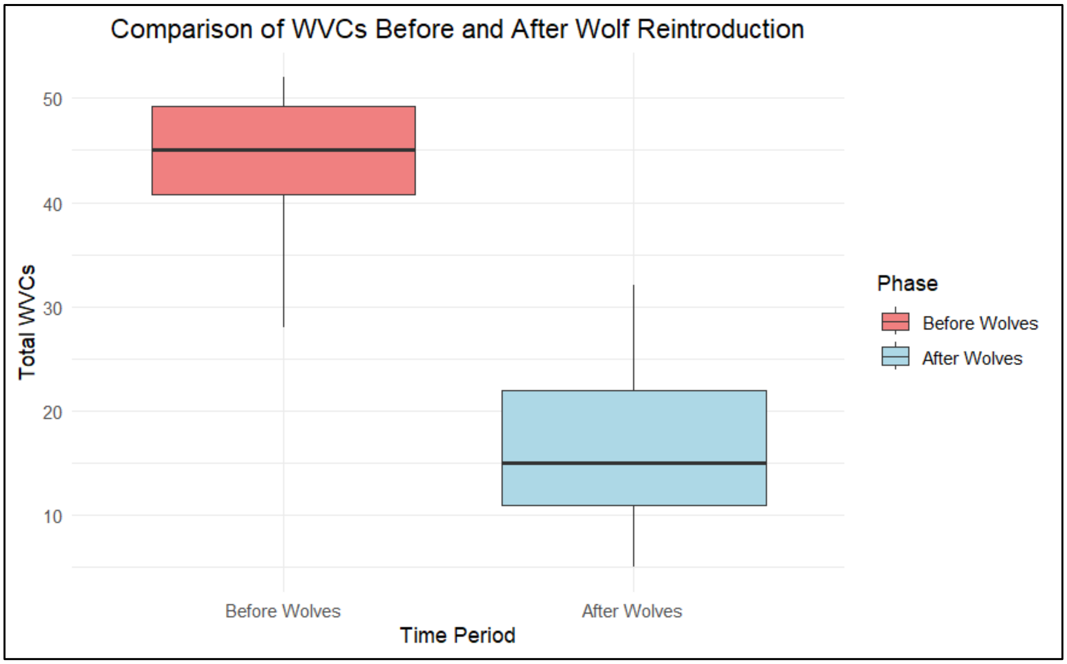

Figure 7: Comparison of the number of WVCs per year before and after wolf reintroductions.

The elk-specific collision models (bw96_e1 and aw97_e1) demonstrate that elk counts were consistently significant predictors of elk-vehicle collisions in both the pre-wolf and post-wolf periods (p ≈ 0.022 and p ≈ 0.01, respectively) (Table 4). The positive relationship between elk counts and elk-specific collisions is consistent with the expectation that more elk increase the likelihood of elk-vehicle interactions. In the post-wolf model (aw97_e1), a marginally significant negative trend for the year variable (p ≈ 0.078) was observed, indicating a slight decrease in elk-vehicle collisions over time in the presence of wolves. This reduction in EVCs is further illustrated in Figure 7, where boxplots show the decline in WVCs after wolves were established.

Table 4: Fixed effects summary results for the elk-vehicle collision models.

Model	Variable	Coefficient Estimate	Standard Error	t-value	Significance
bw96_e1	(Intercept)	-17.369737	15.38034	-1.129	0.2615
bw96_e1	AADT	0.000007	0.00007	0.089	0.9295
bw96_e1	Elk_Count	0.000203	0.00009	2.330	0.0218
bw96_e1	Year	0.008685	0.00767	1.132	0.2603
aw97_e1	(Intercept)	2.751795	1.52601	1.803	0.0744
aw97_e1	AADT	-0.000009	0.00001	-0.849	0.3977
aw97_e1	Elk_Count	0.000041	0.00002	2.618	0.0102
aw97_e1	Year	-0.001351	0.00076	-1.783	0.0776

The model incorporating wolf counts as a continuous variable (wolf_1) showed a significant negative relationship between wolf counts and WVCs (p ≈ 0.027), indicating that higher wolf numbers are associated with a decrease in WVCs over time (Table 5). The year variable also remained significant and negative (p ≈ 0.001), suggesting a general decline in WVCs during the study period. The scatter plot in Figure 8 further illustrates this relationship, showing a clear downward trend in WVCs as wolf counts increase. These results support the hypothesis that increasing wolf densities may influence prey behavior, particularly elk, leading to fewer WVCs over time.

Table 5: Fixed effects results summary for continuous wolf count model.

Model	Variable	Coefficient Estimate	Standard Error	t-value	Significance
wolf_1	(Intercept)	9.065147	2.55206	3.552	0.0006
wolf_1	AADT	-0.000004	0.00002	-0.244	0.8081
wolf_1	Elk_Count	0.000053	0.00003	1.851	0.0671
wolf_1	Wolf_Counts	-0.004488	0.00200	-2.247	0.0269
wolf_1	Year	-0.004460	0.00127	-3.511	0.0007

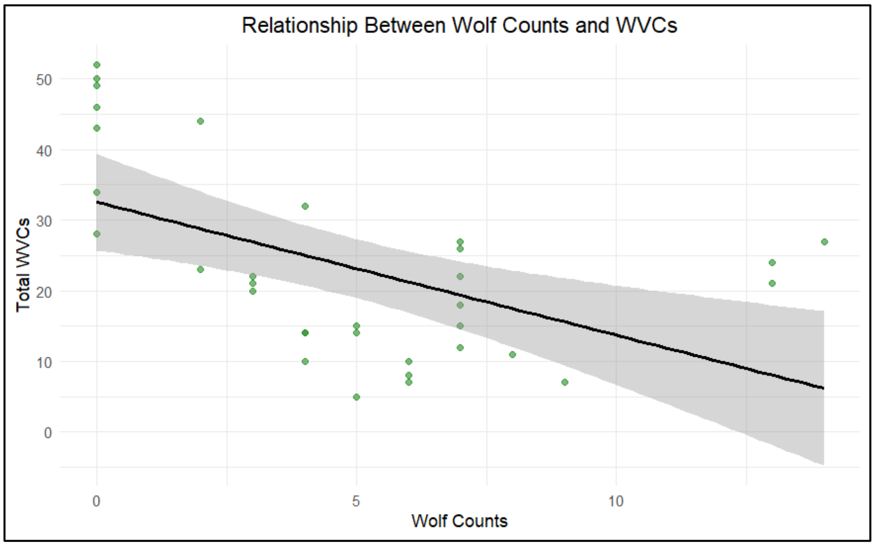

Figure 8: Relationship of adult wolves identified in packs near the study area and WVCs per year.

Overall, the models demonstrate a clear shift in WVC dynamics between the pre- and post-wolf periods, with a notable decline in WVCs after wolves were reintroduced. The effect of elk populations on WVCs was significant in the pre-wolf period but became weaker and less consistent in the post-wolf period. The inclusion of wolf counts as a continuous variable further emphasizes the potential role of wolves in reducing WVCs over time.

4 Discussion and Conclusion

The results of this study offer several key insights into the impact of wolf reintroduction on wildlife-vehicle collisions, as well as the interactions between predator presence, prey populations, and collision frequencies. This research provides a deeper understanding of the complex factors influencing WVCs by examining patterns before and after the reintroduction of wolves along a segment of US-191 near Yellowstone National Park.

4.1 Presence of Wolves Reduces WVCs Directly or Indirectly

The analysis revealed a significant negative trend in WVCs over time during the post-wolf period (1997–2021). This decline, evident in both the after-wolves WVC model (aw97_1) and the interaction model (wint_1), suggests that WVCs have decreased since wolves were reintroduced. Furthermore, the model incorporating wolf counts as a continuous variable (wolf_1) indicated a significant negative relationship between increasing wolf numbers and WVCs. These findings support the hypothesis that wolf presence—particularly as wolf populations increased—may contribute to a reduction in WVCs, either through direct or indirect effects. Similar patterns have been observed in other studies, where the reintroduction of apex predators such as wolves and cougars led to reductions in ungulate populations and subsequent declines in ungulate-vehicle collisions (Gilbert et al., 2017; Ripple & Beschta, 2004).

The mechanisms behind this trend could include changes in prey behavior and movement patterns in response to wolf presence, such as a reduction in time spent near roadways or more cautious crossing behavior. This aligns with previous research suggesting that prey species may alter their spatial use and movement patterns to avoid predation risk, thereby reducing interactions with roadways and vehicle collisions (Ripple & Beschta, 2012; Ford et al., 2017). However, because the direct interactions between wolves and roads were not part of the analysis, we cannot definitively conclude that wolf presence alone is the primary factor driving the observed reduction in WVCs. Other factors, such as changes in habitat use, prey distribution, or road management practices, may also play a role.

4.2 Wolf Presence Modifies the Impact of Traffic Volume (AADT) on WVCs

The interaction model (wint_1) did not reveal significant interaction effects between wolf presence and traffic volume (AADT), indicating that the presence of wolves does not significantly alter the relationship between traffic volume and WVCs. In both the before-wolves and after-wolves models (bw96_1 and aw97_1), traffic volume was not a significant predictor of WVCs, and this relationship did not change meaningfully with the presence or absence of wolves. This is consistent with findings from previous studies that have shown traffic volume to be a weaker predictor of collision rates compared to factors like wildlife movement and habitat use (Clevenger & Huijser, 2011; Huijser et al., 2016).

This finding suggests that while wolf presence may influence overall WVC trends, it does not modify the effect of traffic volume on collision rates. In other words, WVCs are not more or less likely to occur at higher or lower traffic volumes depending on wolf presence. This lack of interaction effect could be due to the fact that traffic volume and wolf presence influence WVCs through different mechanisms: traffic volume is primarily a function of human activity, while wolf presence affects prey behavior and distribution.

4.3 Wolf Presence Affects Elk-Specific Collisions

The elk-specific models revealed a consistent positive relationship between elk populations and elk-vehicle collisions, both before and after wolves were reintroduced. However, the post-wolf model (aw97_e1) showed a marginally significant negative trend for the year variable, suggesting a slight reduction in elk-specific collisions over time in the presence of wolves. This decline, combined with the significant negative relationship between wolf counts and WVCs observed in the wolf_1 model, supports the hypothesis that wolf presence may influence elk-specific collisions, potentially by altering elk behavior, movement patterns, or distribution.

The reduction in elk-vehicle collisions could be attributed to several factors: (1) increased vigilance and reduced movement near roadways due to the risk of predation, (2) avoidance of open areas, including road corridors, or (3) a shift in habitat use to less accessible areas when wolves are present. These behavioral changes could result in fewer elk crossing roads, thereby reducing the likelihood of elk-vehicle collisions. Previous studies have documented similar behavioral responses in ungulates exposed to predation risk, leading to changes in habitat use and reduced time spent in risky areas like roads (Ford et al., 2017; Gagnon et al., 2010).

4.4 Key Interpretations and Implications

Overall Reduction in WVCs: The significant negative trend in WVCs during the post-wolf period and the negative relationship between wolf counts and WVCs suggest that wolf presence may contribute to a reduction in overall WVCs. This finding aligns with studies that have demonstrated predator-induced behavioral changes in prey species, leading to reduced road-crossing activity and fewer collisions (Ripple & Beschta, 2012; Ford et al., 2017).

Lack of Impact of Traffic Volume: Traffic volume did not significantly influence WVCs in either the before- or after-wolf models, nor did it interact with wolf presence. This indicates that the primary factors driving WVC patterns in this area may be more related to wildlife behavior and distribution rather than traffic density alone. Previous research has also shown that traffic volume is often a secondary factor compared to ecological and behavioral influences when assessing WVC risk (Clevenger & Huijser, 2011; Huijser et al., 2016).

Indirect Effects on Elk-Specific Collisions: Although the presence of wolves did not directly alter the relationship between elk populations and elk-vehicle collisions, the post-wolf trend of decreasing elk-specific collisions suggests an indirect influence. Changes in elk behavior in response to wolves could be contributing to fewer elk-vehicle interactions, highlighting that apex predators can influence prey dynamics and interactions with human infrastructure in complex ways (Ripple & Beschta, 2012; Ford et al., 2017).

Management and Conservation Implications: The observed reduction in WVCs in the presence of wolves underscores the broader ecological benefits of restoring apex predators to ecosystems. Beyond ecological balance and biodiversity conservation, wolves may provide additional benefits by reducing human-wildlife conflicts, such as WVCs. This finding supports previous suggestions that predator restoration can help mitigate human-wildlife interactions (Ripple & Beschta, 2012; Gilbert et al., 2017) and should inform road safety and wildlife management strategies.

4.5 Conclusion

This study demonstrates that the reintroduction of wolves in the Greater Yellowstone Ecosystem has influenced wildlife-vehicle collision dynamics, particularly in relation to elk populations. The presence of wolves, especially as wolf numbers increased over time, appears to contribute to a reduction in overall WVCs, supporting the idea that predator-induced behavioral changes in prey can have cascading effects on road safety. While traffic volume did not significantly influence WVC patterns, the reduction in elk-specific collisions over time suggests that wolf presence may indirectly affect prey behavior near roadways. Future research should continue to explore these dynamics and consider the broader implications of predator-prey interactions for road safety and wildlife management.

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