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Nighttime traffic volume predicts risk of deer–vehicle collisions

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Abstract: Annually, in the United States, >1 million deer (*Odocoileus* spp.)–vehicle collisions are reported, resulting in losses of $4.6 billion in vehicle damage and medical expenses. Wildlife and transportation managers require better information about traffic volumes relative to seasonal and diurnal deer movement patterns to appropriately evaluate the risks associated with deer–vehicle collisions (DVCs). We incorporated traffic volume data with DVC data and the movement rates and incidences of road crossings by white-tailed deer (*O. virginianus*) to evaluate if traffic volume or deer behaviors mediate the incidence of DVCs along a high-volume interstate highway in Morgan County in central Georgia, USA. From May 2012 to July 2014, we monitored the movements and survival of 25 deer (13 males, 12 females) instrumented with global positioning system (GPS) collars in an area 1.6 km north and south of a 7.7-km section of Interstate 20 in our study area. We used a linear mixed model to quantify the effects of mean traffic volume and total road crossings on DVCs for each hour of the day. Deer movements and DVCs were primarily crepuscular. Approximately 60% of GPS-collared deer crossed roads; 7 deer accounted for >90% of all road crossings. Approximately 73% of daily traffic occurred between 0700 and 1859 hours. Nearly twice the number of daily DVCs occurred during the fall (9.8 DVCs/day) than during the next highest season (winter; 4.9 DVCs/day). Although DVCs occurred at greater frequencies during crepuscular periods, results of our linear mixed model suggested only nighttime traffic volume predicted DVCs. The relationship between nighttime DVCs and traffic volume is likely due to the inability of drivers to perceive deer in a roadway during this time. We recommend mitigation efforts focus on increasing driver vigilance and reducing vehicle speed during nighttime periods, especially during the fall season.

Key words: animal–vehicle collisions, deer–vehicle collisions, Georgia, interstate highway, mitigation, *Odocoileus virginianus*, risk evaluation, traffic volumes, white-tailed deer

Each year in the United States, >1 million deer (*Odocoileus* spp.)–vehicle collisions (DVCs; State Farm Insurance Company 2020) cause an estimated 29,000 injuries, up to 200 deaths (Conover et al. 1995), and losses of $4.6 billion in vehicle damage and medical expenses (Insurance Information Institute 2020). In Georgia, USA, insurance claims related to DVCs totaled >53,000 during 2018, representing an increase of 40% from 2003 (Quality Deer Management Association 2019). Georgia consistently ranks among the top 10 states for numbers of reported DVCs (State Farm Insurance Company 2020). Deer–vehicle collisions in Georgia are spatially clustered. For example, 13% of Georgia's counties accounted for 55% of reported DVCs

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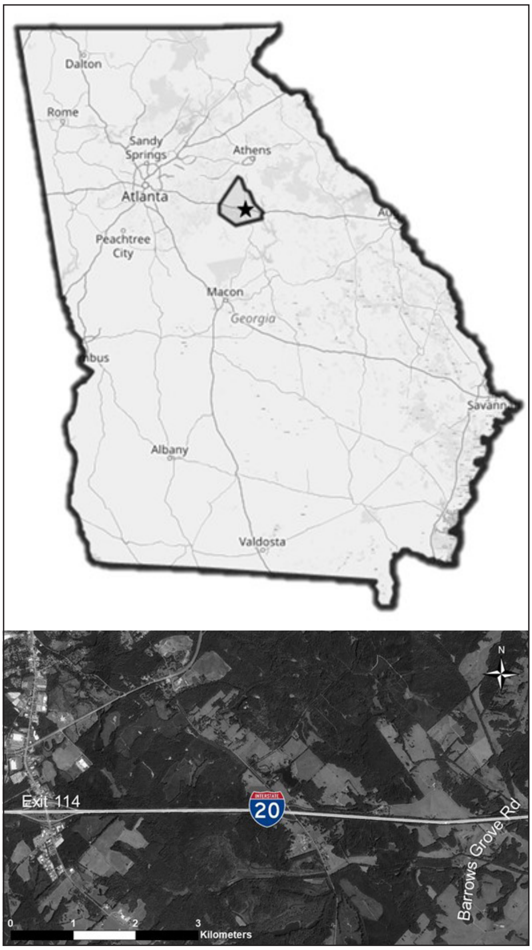

Figure 1. Location of study area (star in top panel) in Morgan County, Georgia, USA. We monitored white-tailed deer (*Odocoileus virginianus*) fitted with global positioning system transmitters in an area 1.6 km north and south of a 7.7-km section of Interstate 20 extending from Exit 114 to the Barrows Grove Road underpass near Madison, Georgia, USA. Besides Interstate 20, the study area included primarily secondary 2-lane roads.

(Bowers et al. 2005). Other studies have described clustering of DVCs along specific sections of highway or identifiable landscape features (Hussain et al. 2007, Grovenburg et al. 2008, McShea et al. 2008, Ng et al. 2008, Gunson et al. 2011, Chen and Wu 2014). The uneven spatial distribution of DVCs suggested mitigation efforts directed at the most problematic sections of roadway may reduce the incidence of DVCs (Hubbard et al. 2000, Gunson et al. 2011, McCance et al. 2015).

Management strategies for minimizing DVCs should consider biological influences (e.g., deer density, deer movements) and human factors (e.g., traffic volume, land use; Sullivan and Messmer 2003). Deer behavior is reportedly the most reliable predictor of DVCs (Steiner et al. 2014, Hothorn et al. 2015). On both diurnal and seasonal scales, peaks in DVC occurrence coincide with periods of increased deer movements (Allen and McCullough 1976, Haikonen and Summala 2001, Steiner et al. 2014, Braden et al. 2020). Previous studies have used frequency of DVCs to assess motorist risk (Allen and McCullough 1976, Haikonen and Summala 2001). But more recently, global positioning system (GPS) technology has been used to study behavior of white-tailed deer (*O. virginianus*; Kramer et al. 2016), Florida key deer (*O. v. clavium*; Braden et al. 2020), and elk (*Cervus canadensis*; Dodd et al. 2007, Gagnon et al. 2007) relative to roads to assess risks and to implement mitigation techniques.

We examined the underlying processes (e.g., human and animal behavior) contributing to DVCs. Our objective was to assess relationships among vehicle traffic, deer movements, time of day, and DVCs and to provide recommendations for strategies to minimize DVCs. Because deer behavior purportedly predicts DVCs (Steiner et al. 2014), we hypothesized deer crossing rates would predict the incidence of DVCs. Because driver visibility is limited during nighttime hours and may hinder reaction times when deer are in the roadway, we also predicted traffic volume would predict DVCs, but only during sunrise, sunset, and nighttime.

Study area

We monitored GPS-instrumented deer in an area 1.6 km north and south of a 7.7-km section of Interstate 20 (I-20) extending from Exit 114 to the Barrows Grove Road underpass near Madison, in Morgan County, Georgia (Figure 1). Outside of the rights-of-way (ROW), the western portion of the study area was primarily forested on both sides of the highway with planted loblolly pines (*Pinus taeda*) and mixed pine-hardwoods. The eastern portion of the study area consisted of agricultural fields, planted pines, mixed pine-hardwoods, and pasture on both sides of the highway. Along both sides of I-20 was a 1.2-m woven-wire fence built by the Georgia Department of Transportation (GDOT) in 1979. Due to lack of maintenance, the fence was in various stages of disrepair, leaving numerous breaches for deer to access the I-20 ROW.

Methods

Deer capture and monitoring

From February to June 2012 and January to April 2013, we captured adult deer within 0.5 km of I-20 using 3 mL transmitter darts (Pneu-dart Inc., Williamsport, Pennsylvania, USA) containing Telazol® (500 mg; tiletamine hydrochloride and zolazepam hydrochloride; Fort Dodge Animal Health, Fort Dodge, Iowa, USA) and AnaSed® (450 mg; xylazine hydrochloride; Congaree Veterinary Pharmacy, Cayce, South Carolina, USA). We identified deer as adults (≥1.0 years old at time of capture) based upon tooth replacement and wear (Severinghaus 1949). We collared each deer with a FOLLOWiT Tellus GPS collar (FOLLOWiT Wildlife, Lindesberg, Sweden) programmed to collect 1 location per hour throughout the study period. After 80 minutes, we injected deer with 300 mg of Tolazine® (tolazoline hydrochloride; Congaree Veterinary Pharmacy, Cayce, South Carolina; 150 mg [IV] + 150 mg [IM]) and monitored deer until ambulatory. Animal handling procedures were approved by the University of Georgia Institutional Animal Care and Use Committee (#A2011 08-023-R1).

From May 2012 to July 2014, we monitored survival of each deer weekly via very high frequency telemetry via mortality signals from collars triggered by >6 hours of inactivity. We downloaded GPS data from each deer's collar every 4–6 months. We calculated mean collar error ($\bar{x}$ = 24.2 m) by placing 1 collar at 2 surveyed GPS test sites at the University of Georgia, Athens, Georgia (n = 252 points).

Deer–vehicle collisions

We obtained DVC data for May 1, 2012 to July 31, 2014 from GDOT from 19 counties (Baldwin, Barrow, Butts, Clarke, Greene, Gwinnett, Hancock, Henry, Jackson, Jasper, Jones, Monroe, Morgan, Newton, Oconee, Oglethorpe, Putnam, Rockdale, and Walton) surrounding our study site. We assumed deer behavior in these counties was similar to our study site because each is located in the Piedmont physiographic region with similar landscape composition, road types, and deer densities (Georgia Department of Natural Resources 2015). Therefore, we assumed temporal patterns of DVCs would also be similar. The DVC data were collected by law enforcement agencies and reported to GDOT. We calculated the number of DVCs occurring within each 1-hour period, starting at 0000–0059 hours and ending at 2300–2359 hours. Because the time of DVCs was grouped into 1-hour periods, we calculated deer movements and traffic volume at similar intervals, as we explain in more detail below. We assumed that any potential bias in unreported DVCs was consistent among seasons and years in our study.

Deer movements and road crossings

We used ArcGIS 10.2 (Environmental Systems Research Institute, Inc., Redlands, California, USA) to view GPS locations. We removed erroneous locations involving impossible dates, times, or coordinates. To calculate movement rates, we excluded locations with >1 hour between successive points. For individual deer, we excluded months with >12% data loss, and we excluded deer with <4 months of qualifying data. Herein, a calendar month with ≥88% of hourly locations for an individual deer is referred to as a "deer-month." We determined hourly distance traveled by calculating the distance between successive points for individual deer. We then calculated a monthly mean distance traveled per hour for each deer and used the hourly means to calculate an overall mean across all deer by month. Mean daily distance for each deer was calculated as the sum of all hourly movements divided by the total number of days represented by the data for the individual animal. Because deer behavior may be the most reliable predictor of DVCs (Steiner et al. 2014) and the seasonal distribution of DVCs tends to be consistent among years (Allen and McCullough 1976, Bashore et al. 1985), we pooled monthly data into 4 biologically meaningful seasons with regard to deer movements in our study area (see DeYoung and Miller 2011 for more details): spring (April to June), summer (July to September), fall (October to December), and winter (January to March).

To identify road-crossing events, we converted points to lines using Geospatial Modeling Environment (Beyer 2014) to create hourly movement paths between successive points for each deer. We then used ArcGIS 10.2 to spatially select and export data from the line segments that crossed roads. To account for unequal numbers of deer-months within seasons, we calculated the percent of the total road crossings that occurred during each hour.

Traffic

We obtained traffic volume from a permanent traffic counter located near the center of the segment of I-20 that represented our study area. We calculated mean traffic volume per hour for each month from May 1, 2012 to July 31, 2014. Although traffic patterns may influence deer behavior along roads (Killmaster et al. 2006) and different types of roads have different traffic volumes, the pattern of traffic is likely similar on different road types due to the diurnal pattern of human activity. Therefore, we assumed that the diel distribution of traffic on secondary roads was similar to the distribution on our study site on I-20. Traffic was reported as number of vehicles per hour; therefore, we could not determine hourly changes in traffic speed or the types of vehicles used.

Data analysis

We used a linear mixed model to quantify the effects of mean traffic volume and total road crossings on the incidences of DVCs for each hour of the day. Our response variable was the number of DVCs occurring at each 1-hour period for each month. Our predictor variables were the number of vehicles counted and the number of road crossings at each 1-hour period for each month. Because we were interested in delineating the effects of time of day on DVCs, we assigned each 1-hour period into 1 of 3 categories. We used National Oceanic and Atmospheric Administration sunrise and sunset tables to divide days into 3 periods based on the amount of light available (Endler 1993). The sunrise/sunset period was the 6-hour period that included dawn (the hour bisected by sunrise and the hours immediately before and after sunrise) and dusk (the hour bisected by sunset and the hours immediately before and after sunset). The day period was the hours between dawn and dusk, and night period was the hours between dusk and dawn. To aid in model convergence, we scaled number of vehicles counted by 100. Because physiological cues may affect how deer behavior and vigilance change across a year (DeYoung and Miller 2011), we treated season as a random effect. We conducted statistical analyses using program R version 3.0.2 (R Development Core Team 2013).

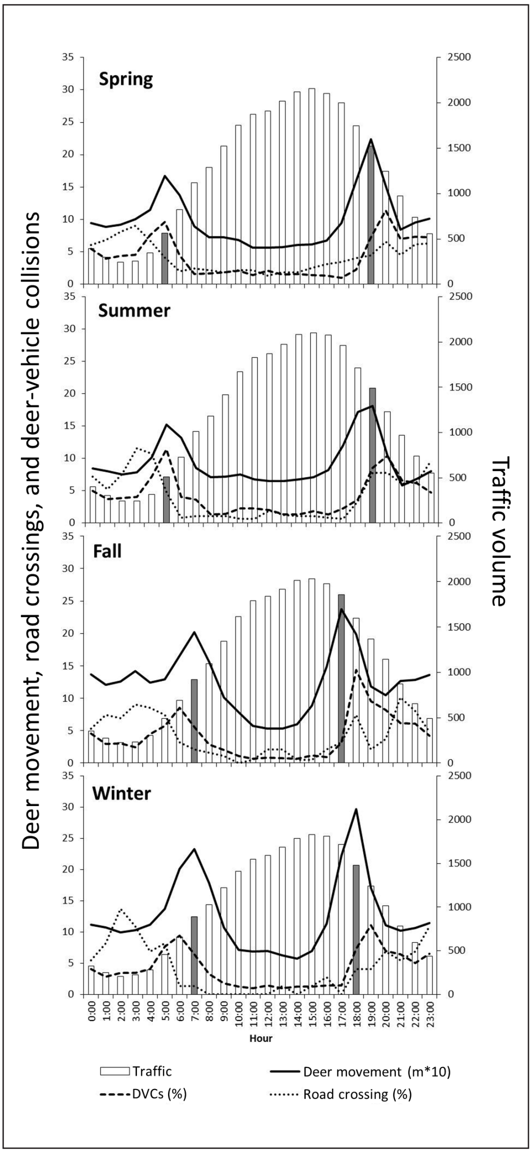

Figure 2. Seasonal mean hourly traffic volume, percent of total hourly deer–vehicle collisions (DVCs), mean hourly distance moved (m*10) and percent of total road crossings for 25 adult white-tailed deer (*Odocoileus virginianus*; 13 males, 12 females) from May 1, 2012 to July 31, 2014. Gray traffic bars indicate the hours of sunrise and sunset.

Table 1. Parameter estimates the model estimating risk of a deer–vehicle collision (DVC) based on traffic volume along an interstate highway, the number of road crossings made by 15 adult white-tailed deer (*Odocoileus virginianus*), and their interaction with time of day (daytime, nighttime, or sunrise/sunset) along a 7.7-km stretch of Interstate 20 in Madison, Georgia, USA, 2012–2014. Traffic volume at night was the only significant predictor of DVC occurrence ($P < 0.05$). Interactions effects are demarcated by colons between 2 covariates. Standard errors (SE), *t*-values, and *P*-values are also presented. Degrees of freedom were 276 for all covariates in the model.

Covariate	Estimate	Coefficient (SE)	*t*-value	*P*-value
(Intercept)	8.44	8.55	0.99	0.32
Traffic volume[a]	-0.20	0.44	-0.44	0.66
Nighttime	-2.00	8.29	-0.24	0.81
Sunrise/sunset	14.1	9.25	1.52	0.13
Road crossings	0.27	0.32	0.85	0.40
Traffic volume[a]:nighttime	2.48	0.64	3.87	<0.01
Traffic volume[a]:sunrise/sunset	0.30	0.59	0.50	0.61
Road crossings:nighttime	0.66	0.33	0.20	0.84
Road crossings:sunrise/sunset	0.16	0.36	0.45	0.64
Season[b]	41.76	N/A	N/A	N/A

[a] Traffic volume was calculated as the number of cars crossing a vehicle counter for each hour across a day. For this analysis, traffic volume was scaled by 100 to help with model convergence.
[b] Season was considered a random effect in the model. Thus, it is a variance estimate.

Results

The obtained data from GPS radio-marked deer included 151,873 hourly locations over 223 deer-months (spring: 13 males, 12 females, 76 deer-months; summer: 13 males, 9 females, 64 deer-months; fall: 7 males, 8 females, 39 deer-months; winter: 4 males, 11 females, 44 deer-months). Deer were primarily crepuscular during all seasons, with peak movement occurring at sunrise and sunset (Figure 2). We recorded 1,429 road crossings by 15 deer (8 males, 7 females). A majority of road crossings ($n = 919$) were contributed by 1 female (#47). This female crossed roads frequently throughout the year, with 421 crossings occurring outside the months of May and June. Despite the large number of crossings made by deer #47, she survived through the study period. Seven deer accounted for >90% of all road crossings. Two of those 7 deer that crossed roads regularly (male #65, $n = 43$, 0.47 crossings/day; female #85, $n = 17$, 0.07 crossings/day) were killed by vehicles during the study. Road crossings were mostly nocturnal, with 60%, 72%, 80%, and 89% of all crossings occurring at nighttime hours during spring, summer, fall, and winter, respectively. Approximately 44% of all road crossings occurred from 0000–0559 hours, when traffic volume tended to be at its lowest.

For all seasons, greatest traffic volume occurred from 1500–1559 hours, and the lowest occurred from 0200–0259 hours. During the time of our study, approximately 73% of daily traffic occurred between 0700 and 1859 hours. There were 4,531 reported DVCs within the counties that comprised our study area. For all seasons, the distribution of DVCs was crepuscular, with morning peaks in DVCs occurring concurrently with deer movement at sunrise for spring and summer and 1 hour prior to sunrise during fall and winter. Evening peaks in DVCs occurred 1 hour after sunset for all seasons. The fall season accounted for 44% of the DVCs during our study, with November alone accounting for 20%.

Although DVCs occurred at greater frequencies during crepuscular periods, results of our linear mixed model suggested only nighttime traffic volume predicted the incidence of DVCs (Table 1). Seasons were assigned large intercept values ranging from 8.80 in fall to -5.69 in winter. The large amount of variance seen in these random effects underscores the seasonal variability in the occurrence of DVCs.

Discussion

Although deer movement is an important variable in the occurrence of DVCs, deer are only a traffic hazard when they are crossing roads. Although deer in our study were moving at a greater rate at sunset, a majority of road crossings did not occur until 1 hour after sunset. Road crossings remained elevated throughout the night, even when deer movement had declined to near daytime levels. As morning traffic increased, road crossings declined rapidly, concurrent with DVCs. Surprisingly, the number of road-crossing events, throughout all periods of the day, was not predictive of the number of DVCs occurring in our study area. Traffic volume during sunrise, sunset, and daytime was not a significant predictor of DVCs. However, traffic volume at nighttime was the only factor in our analysis that statistically predicted the incidence of DVCs.

Although 60% of the deer in our study crossed roads, the fact that most of the crossings were represented by a few deer indicates that there are individual differences among deer with regard to crossing roads. In the years immediately after new roads are opened, there is generally a sharp increase in DVC mortality that eventually decreases and then stabilizes (Reilly and Green 1974, Falk et al. 1978). This pattern suggests that DVC mortality may remove individuals that cross roads frequently or those that cross roads during periods of high risk. In the interest of public safety, maintaining lowered deer densities along roads with DVC hotspots would be beneficial. Targeted removal of deer in areas of high DVC risk, including sharpshooting along road rights-of-way, has been shown to be an effective management strategy where practical (DeNicola and Williams 2008, Kilgo et al. 2020). Additionally, roadside fencing is a viable option for preventing deer access to roads and directing them to safe crossing areas such as overpasses or underpasses (Gulsby et al. 2011).

Insurance companies, law enforcement agencies, natural resource agencies, and transportation departments often warn motorists of DVC risk during dawn and dusk, but these warnings fail to recognize that deer frequently cross and interact with roads throughout the entire night, as we observed. In Austria, accidents with roe deer (*Capreolus capreolus*) coincided with times of peak traffic volume and roe deer activity (Steiner et al. 2021). Similarly, Daylight Saving Time clock-shifts in New York, USA, resulted in an increase in DVCs because commuter traffic coincided with peak DVC risk (Abeyrathna and Langen 2021). Studies from Michigan and Pennsylvania, USA, also showed that white-tailed deer activity relative to roads appeared constant from dusk to dawn (Carbaugh et al. 1975, Allen and McCullough 1976), and researchers in Tennessee who surveyed deer with aerial infrared imaging observed that deer congregated along roads during nighttime survey periods (Beaver et al. 2014). Our findings, in concert with these previous studies, warrant additional preventive actions and updates to messaging to minimize risk of DVCs.

We recommend that driver education programs warn motorists of the increased risk of encountering deer crossing roadways during nighttime travel from dusk to dawn during the fall breeding season. Changeable message signs have been shown to be effective in reducing vehicle speeds and number of DVCs (Donaldson and Kweon 2018). Limited forward vision of drivers at night and their inability to perceive animals in a roadway is an important factor contributing to collisions (Sullivan 2011). Reduced speed limits allow drivers to identify obstacles (e.g., deer) with more time to react before reaching the object, and lower speeds lessen the severity of collisions (Sullivan 2011). Advancements in night-vision technology, such as infrared or thermographic cameras, have the potential to be integrated with modern vehicles. Advanced roadside warning systems to detect wildlife standing in or along roads, and possibly give motorists more time to reduce their speed, also show promise (Zhou 2013). Future research should consider development and testing such systems for the purpose of DVC mitigation.

Our study was limited by the sample size of GPS-collared deer. Also, we observed substantial inter-individual variation with only a few individuals making the majority of road crossings. However, our results provide evidence that the DVC risk posed by even a small proportion of a deer population is significant. Also, scaling the number of crossings we observed to a broader spatial scale points to the challenge of attempting to mitigate DVCs across the landscape by altering deer behavior using roadside devices. From a management perspective, focusing efforts on enhancing driver awareness may be most beneficial.

Management implications

This study highlights aspects of risk that are important in terms of driver education but that are overlooked in annual information campaigns about deer–vehicle collisions. We found that highest movements and road crossings of deer occurred primarily during crepuscular periods, as expected. However, traffic volume at night was the most important predictor of risk, and deer–vehicle collisions remained high during overnight hours. Strategies including altering the roadway lighting environment and education aimed at increasing driver vigilance at night should become common practice.

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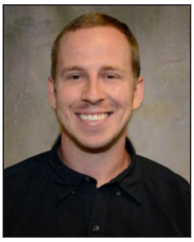

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