Global Ecology and Conservation 51 (2024) e02949

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Short communication

The effect of COVID-19 movement restriction on Korean expressway wildlife–vehicle collisions

Hyomin Park, Sangdon Lee *

Department of Environmental Science & Engineering, College of Engineering, Ewha Womans University, Seoul 03760, South Korea

A R T I C L E I N F O

Keywords:
Wildlife management
Conservation strategy
Roadkill
Road ecology
Hotspots
ICT-Environmental Impact Assessment

A B S T R A C T

The construction of roads obstructs animal movement, which directly results in fatal wildlife–vehicle collisions (WVCs). Owing to the worldwide COVID-19 outbreak in 2020, movement restrictions were imposed by the Korean government between February and March 2020, which represented the beginning of the COVID-19 pandemic. During this period, this study examined the effects of reduced traffic volume on WVCs. The study selected the Dangjin–Yeongdeok, Jungang, and Jungbu Expressways as study sites since they have the highest occurrence of WVCs in Korea. The sections of these expressways with the highest densities of WVCs were denoted as WVC hotspots. We categorized the period from February to March 2020 as 'strict pandemic'. In addition, the period from February to March 2015–2019 was categorized as "pre-strict pandemic", and between April 2020 and December 2020 was classified as the "pandemic period". We analyzed the relationship between WVC and traffic volume for each period in the designated hotspots. As a result, there were statistically significant differences in WVCs and traffic volumes across all routes for different periods. WVCs and traffic volume showed a strong negative correlation during the strict pandemic period. WVC per traffic volume was positively correlated between the strict pandemic period and the pandemic period, while it was negatively correlated between pre-strict pandemic and strict pandemic periods. The deceleration in WVC continued after all routes were out of strict pandemic. This study shows that WVC and traffic volume are negatively correlated and that a strong, albeit temporary, traffic reduction can help reduce WVC. Therefore, the overall quantitative conclusion of this study on the interaction can serve as a valuable reference to develop practical strategies for preventing WVCs.

1. Introduction

The increasing number of new roadways has become a considerable threat to wildlife globally (Primack et al., 2021). With the continuous expansion of towns and heavier traffic between cities, newly constructed roads have increasingly fragmented wildlife habitats (Forman et al., 2003), eventually, isolating, and confining wildlife. Roadways obstruct animal movement, influence species diversity, and directly result in fatal wildlife–vehicle collisions (WVCs) (Forman et al., 2003; Laurance et al., 2009; Van der Ree et al., 2015). Due to the use of wider lanes and adjacency to forests, expressways have higher traffic speeds and volumes than other road types, thereby making them more prone to WVCs, and thus, a significant threat to wildlife (Park et al., 2021). This problem is exemplified in South Korea, where persistent industrial growth necessitates the construction of additional expressways, which

* Corresponding author.
E-mail address: lsd@ewha.ac.kr (S. Lee).

https://doi.org/10.1016/j.gecco.2024.e02949
Received 30 October 2023; Received in revised form 8 April 2024; Accepted 10 April 2024
Available online 10 April 2024

increases the threat to wildlife.

Wildlife–vehicle collisions (WVCs) are a significant threat to many species, causing financial loss, and posing a serious risk to driver safety (Laube et al., 2023). Since WVCs have caused severe problems worldwide, researchers have actively investigated various associated issues, including the socioeconomic costs of WVCs (Huijser et al., 2009) and mitigation measures (Lester, 2015). Several

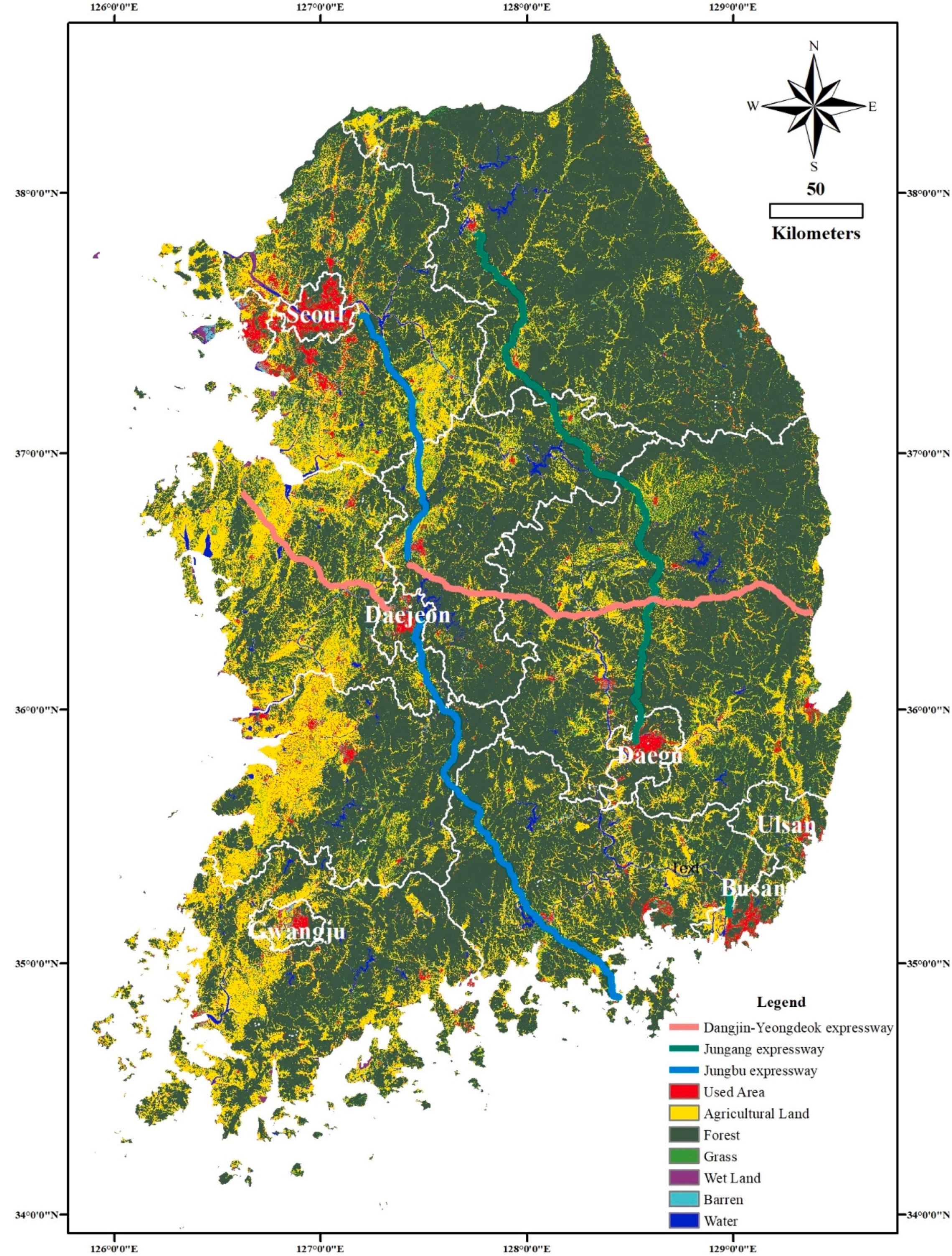

Fig. 1. A map of study sites in South Korea showing sections of the surveyed expressways.

factors affect the incidence of WVCs, including spatial characteristics (Park et al., 2021), traffic volume changes (Bencin et al., 2019), and seasonal migrations of wildlife (Main and Allen, 2002). Among these, traffic volume is a critical predictor of wildlife roadkill rates (Taylor and Goldingay, 2010; Visintin et al., 2017; Pagany, 2020). The presence of roadways generally affects wildlife (Fahrig and Rytwinski, 2009), and traffic volume is strongly correlated to the frequency and potential risks of WVCs (Litvaitis and Tash, 2008). In South Korea, the escalating incidence of WVCs has also become a nationwide problem, thereby prompting further research. However, the relationship between WVCs on expressways and traffic volume in the country requires further investigation.

Owing to the worldwide COVID-19 outbreak in 2020, movement restrictions were imposed by the Korean government between February and March 2020 to curb the spread of the virus—the beginning of the COVID-19 pandemic. These restrictions significantly reduced human activities (Primack et al., 2021), thereby providing opportunities to observe the human influence on WVCs (Driessen, 2021). Several studies have reported that changes in human activity during the pandemic altered the behavior of wild animals (Manenti et al., 2020; Rutz et al., 2020). Thus, during this period, this study examined the effects of reduced traffic volume on WVCs.

Based on nationwide WVC data from 2015 to 2020, this study selected the Dangjin−Yeongdeok, Jungang, and Jungbu Expressways as study sites since they have the highest occurrence of WVCs in Korea. The sections of these expressways with the highest densities of WVCs were denoted as WVC hotspots, meaning that in these hotspots, the risk of a collision was statistically higher than in any other section of the expressway (Seiler et al., 2016). The identification of the hotspot locations is important for the effective application of mitigation measures (Bíl et al., 2016). Therefore, we analyzed the relationship between the WVCs and traffic volume in these hotspots. To our knowledge, there has been no previous study conducted in Korea on the changes in the occurrence of WVCs during the pandemic period. Therefore, this study seeks to establish important basic data necessary for the management plan of WVC occurrences on expressways.

2. Materials and methods

2.1. Study sites

To choose the appropriate areas for this study, we analyzed the annual numbers of WVCs per kilometer of expressway in Korea between 2015 and 2019. Expressways under 100 km in length were excluded owing to suggestions that the WVC rate for short roadways is often overestimated (Lee et al., 2014). Based on this analysis, Dangjin−Yeongdeok Expressway (DYE), Jungang Expressway (JAE), and Jungbu Expressway (JBE) were included in the study (Fig. 1, Appendix 1). All expressways selected in this study have maximum and minimum speed limits of 110 km/h and 50 km/h, respectively.

The DYE (route number 30) has a total length of 278.6 km and connects the eastern and western regions of South Korea, thereby traversing the central inland regions of Chungcheongnam-do, Chungcheongbuk-do, and Gyeongsangbuk-do. Its first section opened in November 2007, with subsequent additional sections being completed in stages thereafter.

Next, the JAE (route number 55) passes through Gyeongsangbuk-do, Chungcheongbuk-do, and Gangwon-do, cutting across the eastern inland area of the country, north to south. These regions are enclosed by the Taebaek and Sobaek Mountain Ranges. The JAE is 288.9 km long, while the first section of the expressway opened to traffic in December 1994.

The JBE (route number 35) connects Tongyeong-si, Gyeongsangnam-do, Hanam-si, and Gyeonggi-do. Initially, it was 117.2 km long between Hanam-si, Gyeonggi-do, Nami-myeon, Cheongwon-gun, and Chungcheongbuk-do. The Tongyeong–Daejeon Expressway was built and joined to the original JBE; therefore, the current total length of the expressway is now 332.5 km, and it has been renamed the Tongyeong–Daejeon Jungbu Expressway. Notably, it was first opened in December 1987.

2.2. Data collection

The analysis was conducted based on the nationwide data for traffic volume and WVCs provided by the Korea Expressway Corporation (KEC) (http://data.ex.co.kr) and spanned six years from January 2015 to December 2020. WVC investigation methods are investigated in accordance with the 'Guidelines for Roadkill Investigation and Management' set by the government as administrative rules. WVC data are collected by the Safety Patrol of the KEC, which records the number of carcasses discovered along with other related information during their expressway patrol, which occurs three times a day. Carcasses found are photographed by safety patrols and sent to the 'Animal Roadkill Information System', and the National Institute of Ecology uses the photos to identify the animal species. The recorded items are as follows: the date; the jurisdictional authority; the route name; the distance from the expressway starting point; the direction; the species of the animal killed in the WVC; the longitude and latitude of the WVC location. Following the analysis, the carcass was removed from the site to prevent the formation of duplicate records. WVC investigations were conducted in the same way as before, even when government movement restrictions due to COVID-19 were in place.

Toll collection system (TCS) data from the KEC was used to measure the traffic volume. TCS data contain detailed information regarding the vehicles entering and leaving the expressways via the toll booths. Such data facilitates the easy and precise identification of expressway usage patterns.

2.3. Data analysis

2.3.1. WVC hotspot modelling

Kernel density estimations (KDEs) were used to identify specific WVC hotspots in each expressway (Eq. 1). KDE calculates the spatial density based on the distribution of individual points within a specific search radius (bandwidth) and generates kernel function

K. In the estimation process, the larger the bandwidth, the greater the hotspot area (Da Silva et al., 2022). Thus, the spatial relevance decreases as the distance between the center and an individual point increases.

$$f(x,y) = \frac{1}{nh^2} = \sum_{i=1}^{n} K\left(\frac{d_i}{h}\right) \quad (1)$$

where f (x, y) is the density estimation at (x, y), n is the number of WVCs, h is the bandwidth, di is the location (x, y), and i is the distance between occurrence points (Eq.1). A Gaussian kernel function is used to determine K (Eq. 2):

$$K(u) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}u^2} \quad (2)$$

where u is the ratio of the distance at location (x, y) within the bandwidth.

To identify specific WVC hotspots in the expressways, the WVC density was estimated using KDEs based on the WVC data from 2015 to 2019. The WVC data used for the KDEs was based on the longitude and latitude of the WVC occurrence points to obtain cumulative data for each WVC occurrence point. KDE was then used to estimate the WVC density for the entire route, which was then categorized into five sections (I, II, III, IV, and V) with equal ranges for WVC density using the equal interval method: Section I with a WVC density ranging from 100% to 80%; Section II from 80% to 60%; Section III from 60% to 40%; Section IV from 40% to 20%; Section V from 20% to 0%. Section I covers the areas with extremely high WVC occurrence densities (top 20%). By contrast, Section V covers the areas with extremely low or zero WVC occurrence density (bottom 20%) (Park et al., 2021). Therefore, we classified Section I as the highest WVC occurrence, Section II as high WVC occurrence, Section III as medium, Section IV as low, and Section V as very low.

We identified the Section I regions with the highest WVC density in DYE, JAE, and JBE. We extracted the roads passing between the toll booths located within the Section I as hotspot areas. This is to measure the traffic volume of hotspots accurately. Subsequently, the traffic volume and WVCs within the hotspot zone between 2015 and 2020 were analyzed by period (before, during and after restrictions).

2.3.2. Statistical Analysis

Owing to the severe risk of COVID-19, governments implemented strict restrictions during the initial stage of the pandemic to contain the spread of the virus (Rilett et al., 2021). A wide range of studies has been conducted worldwide that have focused on the early stages of the pandemic. Similarly, in Korea, strict regulations were implemented, particularly between February and March 2020. Thus, this study focused on the initial period of the pandemic in Korea. We categorized the period from February to March 2020, when strong measures were implemented to contain COVID-19 infections, as a 'strict pandemic'. In addition, the period from February to March between 2015 and 2019 was categorized as pre-strict pandemic, and between April 2020 and December 2020, when strong measures were lifted, was categorized as the pandemic period.

We conducted an analysis of ANOVA by a period (strict pandemic, pre-pandemic, and pandemic) on WVC data from all routes to determine whether there were statistically significant differences in WVC incidence due to the COVID-19 pandemic. Paired t-test were also used to identify periods with statistically significant differences in WVC. Additionally, a paired t-test was conducted for each period of each route using WVC data. This derived the period when differences in WVC occurrence for each route were observed. In addition, we derived the traffic volume for each route to determine whether there is a statistically significant difference in the change in traffic volume due to the COVID-19 pandemic by period (DYE, JAE, JBE). Then, we derived traffic volumes by period (strict pandemic, pre-pandemic, pandemic) and conducted an ANOVA analysis.

Meanwhile, we analyzed the correlation between WVC and traffic volume during the strict pandemic using Pearson's correlation coefficient. To examine the relationship between the changes in traffic volume and WVCs during the COVID-19 pandemic, we obtained monthly data on the traffic volume and WVCs for the study routes for each period (strict pandemic, pre-strict pandemic, and pandemic). To analyze the changes in WVCs per traffic volume, the percentage of WVCs per traffic volume was derived using monthly data on traffic volume and WVCs. Then, a paired *t*-test was used to examine the difference in the percentage change of the percentage of WVCs per traffic volume during each period. The correlation between WVC and traffic volume was analyzed for each period using the Pearson correlation coefficient. All statistical analyses were performed using R (ver. 4.1.2).

3. Results and discussion

3.1. WVC hotspots

The roads passing between the toll booths located within the Section I derived using the KDE method were identified as hotspots. The WVC hotspots for each study site were identified as follows: DYE: Gongju–Namsejong IC; JAE: Hoengseong–Namwonju IC; JBE: Gonjiam-Seoicheon IC (Fig. 2).

WVCs per kilometer have been decreasing steadily since 2015 throughout the total length of the DYE and JAE, whereas they have increased since 2017 for the JBE. This trend was the same in the hotspots for each expressway. Despite this trend, the WVC/km of the hotspots was observed to be higher than that of the WVC/km for the total length of the expressways. The percentage of WVCs that occurred at each hotspot relative to the entire expressway has also grown (Table 1).

Therefore, the WVCs in the hotspots have remained high, so we analyzed the WVC characteristics of each hotspot. We analyzed the WVCs on the DYE, JAE, and JBE from 2015 to 2019 and our findings revealed that water deer (*Hydropotes inermis*) were the most frequently involved in collisions (Table 2), while April, May, and June were the months that exhibited the highest number of WVCs. This suggests that WVCs exhibit seasonality, which is associated with the behavioral characteristics of water deer. According to Garrah et al., (2015), WVCs are strongly seasonal, and this seasonality is extensively species-specific. The Korean water deer have a high population density and are widely distributed throughout the country. During their breeding season in spring, they tend to expand their home range (Park and Lee, 2013). Thus, during this time of year, young deer are more likely to be involved in vehicle accidents compared to other seasons, thereby contributing to the high rate of WVCs in spring.

3.2. The effect of the COVID-19 movement restriction on WVCs

To examine the impact on WVCs by the pandemic, we analyzed the relative change in the monthly number of WVCs during the pandemic period versus that during the pre-pandemic period, focusing specifically on the period from February to March 2020, when the Korean government implemented movement restrictions. The WVCs recorded on all studied routes were analyzed by dividing them into pre-COVID (2015–2019), strict pandemic (February–March 2020), and pandemic (April–December 2020). Thereafter, it was confirmed that during the strict pandemic period, the number of WVCs increased compared to pre-COVID, and during the pandemic, WVCs decreased compared to pre-COVID (Table 3). An ANOVA test was conducted to evaluate the differences in WVCs by period for all

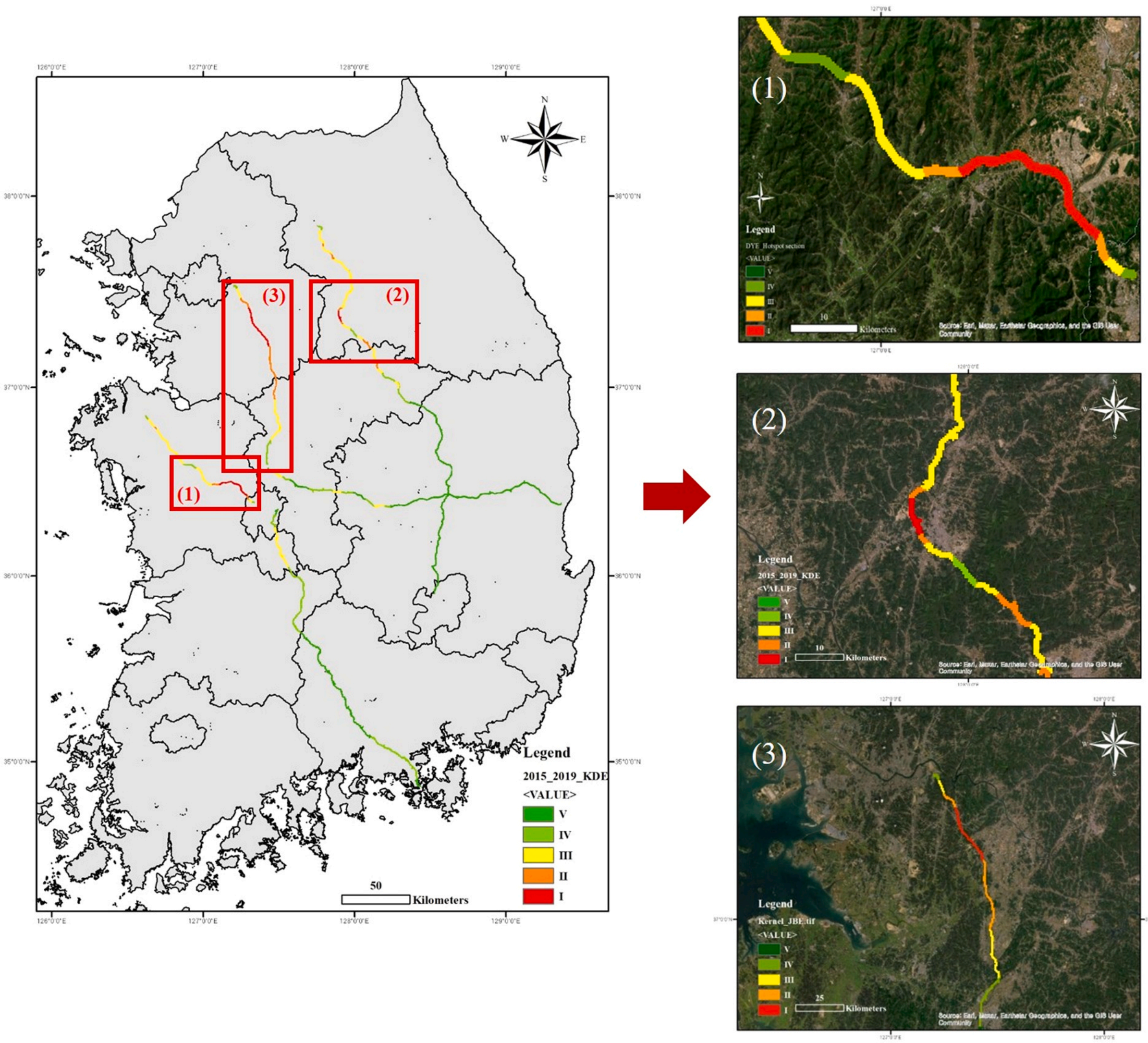

Fig. 2. Categorization of the Wildlife density into five sections (I, II, III, IV, V) for the (1) Dangjin−Yeongdeok Expressway (DYE), (2) Jungang Expressway (JAE), and (3) Jungbu Expressway (JBE), using kernel density estimations (KDEs). Sections with a high WVC density are marked in red (I), while those with a low WVC density are marked in green (V). (I: 100–80%, II: 80–60%, III: 60–40%, IV: 40–20%, and V: 20–0%).

Table 1
Wildlife–vehicle collision (WVC) analysis results in each study site and hotspot: WVC occurs per 1 km on the entire route, WVC occurs per 1 km in each hotspot, and percentage of WVCs occurring at hotspots relative to total routes.

	Year	Entire expressway (WVC/km)	Hotspot (WVC/km)	WVC rate in hotspots (%)
Dangjin−Yeongdeok Expressway (DYE)	2015	2.83	4.24	17.96
	2016	1.92	4.1	25.63
	2017	1.06	2.9	21.38
	2018	0.79	3.03	29.82
	2019	0.85	2.72	24.9
Jungang Expressway (JAE)	2015	0.35	4.74	10.86
	2016	0.22	2.78	12.33
	2017	0.18	1.76	15.38
	2018	0.16	2.75	19.3
	2019	0.16	2.33	17.54
Jungbu Expressway (JBE)	2015	0.1	1.95	22.12
	2016	0.08	1.67	17.52
	2017	0.08	1.56	17.69
	2018	0.09	1.37	19.9
	2019	0.14	2.19	20.41

study routes. As a result, the difference in the number of WVCs according to the period (pre-COVID, strict pandemic, and pandemic) was statistically significant (df=2, F value=4.772, $p = 0.012$). Paired t-test were used to identify periods with statistically significant differences in WVC. There was a statistically significant difference in the WVCs between the strict pandemic (February–March 2020) and the pandemic period (April–December 2020) (t=–2.988, df=5, $p = 0.031$).

After the strict pandemic, the WVCs continued to decrease on all routes in this study compared to the previous year (Fig. 3). A study from northwest Spain demonstrated results similar to our study, whereby an increase in WVCs was observed during the early months of 2020 before becoming reduced following the enforced COVID-19 lockdowns. Moreover, this trend persisted following the end of the COVID-19 lockdown. According to that study, the number of WVCs was 30.22% lower in 2020 than in 2019, with a considerable decline of 66.77% observed during the strictest lockdown period (García-Martínez-de-Albéniz et al., 2022). This study also revealed a significant reduction in WVCs on the DYE, JAE, and JBE during 2020 (Jan–Dec) compared to 2019 (Jan–Dec), with declines of 50.09%, 42.55%, and 57.78%, respectively.

Meanwhile, the WVCs recorded for studied routes were analyzed by dividing them into pre-COVID (2015–2019), strict pandemic (February–March 2020), and pandemic (April–December 2020). On DYE and JAE, the number of WVCs increased during the strict pandemic (February to March 2020) compared to the pre-pandemic period. Specifically, the DYE exhibited a 66.67% and 25% increase, and the JAE exhibited a 100% and 42.86% increase. However, during this period, the number of WVCs on the JBE significantly decreased to 0. The number of WVCs showed a decreasing trend during the pandemic period (April to December 2020), compared to the pre-COVID period, except for specific months, which were October for the DYE, November for the JAE, and August and December for the JBE (Fig. 3).

Therefore, the results from the paired t-test to compare WVCs between the pre-strict pandemic and strict pandemic periods for each study route revealed a statistically significant difference in WVCs for the DYE (t=2.360, df=10, p=0.040) and JAE (t=2.562, df=10, p=0.028). Contrastingly, for the JBE, the difference in WVCs during the same period was not statistically significant (t=1.854, df=10, p=0.093).

Numerous studies have investigated the potential impact of reduced human activities during various periods of the COVID-19 pandemic on worldwide incidences of WVCs. In this study, WVCs increased during the strict pandemic period on the DYE and JAE. In Scotland, WVCs increased during the COVID-19 lockdown (Bíl et al., 2021), and in some states in the US, WVCs increased during the pandemic (Abraham and Mumma, 2021). This suggests that wildlife may have increased their use of roads and areas near roads during the pandemic in response to reduced traffic (Rutz et al., 2020).

While in this study, WVCs decreased during the strict pandemic period on the JBE. A study conducted in several US states reported a decline in WVCs of 34% during the pandemic period, while some states showed a significant relationship between the implementation of COVID-19 restrictions and the change in WVCs (Shilling et al., 2021). Additionally, there was a 48% decrease in WVCs in Tasmania, Australia, during the pandemic, with statistically significant changes observed between WVCs during the pre-pandemic and pandemic periods. Furthermore, a study conducted across 11 European countries revealed a 40% decrease in WVCs during the pandemic period in Spain, Israel, Estonia, and the Czech Republic compared to previous periods (Driessen, 2021).

In this study, we found that WVCs differed by the duration of travel restrictions due to COVID-19, and the differences in WVCs by duration were statistically significant for each study route. Therefore, we can confirm that travel restrictions due to COVID-19 affect the occurrence of WVCs.

3.3. Relationship between traffic volume and WVCs

To analyze the change in traffic volume due to the COVID-19 restriction, we compared the change in traffic volume in 2020 to the average traffic volume from 2015 to 2019. We found that compared to pre-COVID-19, traffic volume on DYE and JAE decreased during the COVID-19 restriction, while traffic volume on JBE increased. The decrease in traffic volume on JAE has been maintained even after

Table 2
The status of wildlife involved in wildlife–vehicle collisions (WVCs) in each hotspot zone.

Species	DYE					JAE					JBE				
	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019
Water deer (*Hydropotes inermis*)	91	88	59	66	57	92	55	41	40	40	33	24	27	30	40
Raccoon dog (*Nyctereutes procyonoides*)	3	2	2	1	2	8	5	3	5	5	1	1			1
Wild boar (*Sus scrofa*)		1	1	1			2	6		1		1			4
eopard cat (*Prionailurus bengalensis*)		1					1								
Asian badger (*Meles leucurus*)	1		2		2	1		1		1					
Korean hare (*Lepus coreanus*)								2							
Others			1												
Total	95	92	65	68	61	101	63	53	45	47	34	26	27	30	45

Table 3
Monthly WVC average across the entire study route. The gray blocks represent the period when strict restrictions began in Korea during the COVID-19 pandemic (February–March 2020).

	2015–2019		2020	
month	average	variance	average	variance
Jan	1.867	1.310	2.333	0.943
Feb	0.800	0.980	1.333	0.943
Mar	1.067	1.236	1.333	0.943
Apr	4.667	2.936	1.667	1.247
May	17.533	9.142	6.000	0.816
Jun	13.667	5.861	4.000	0.816
Jul	5.533	3.964	2.000	0.816
Aug	2.467	2.306	1.667	1.247
Sep	1.867	1.454	0.667	0.471
Oct	2.000	1.461	1.333	0.471
Nov	2.667	1.776	1.000	1.414
Dec	2.667	2.119	1.333	1.247

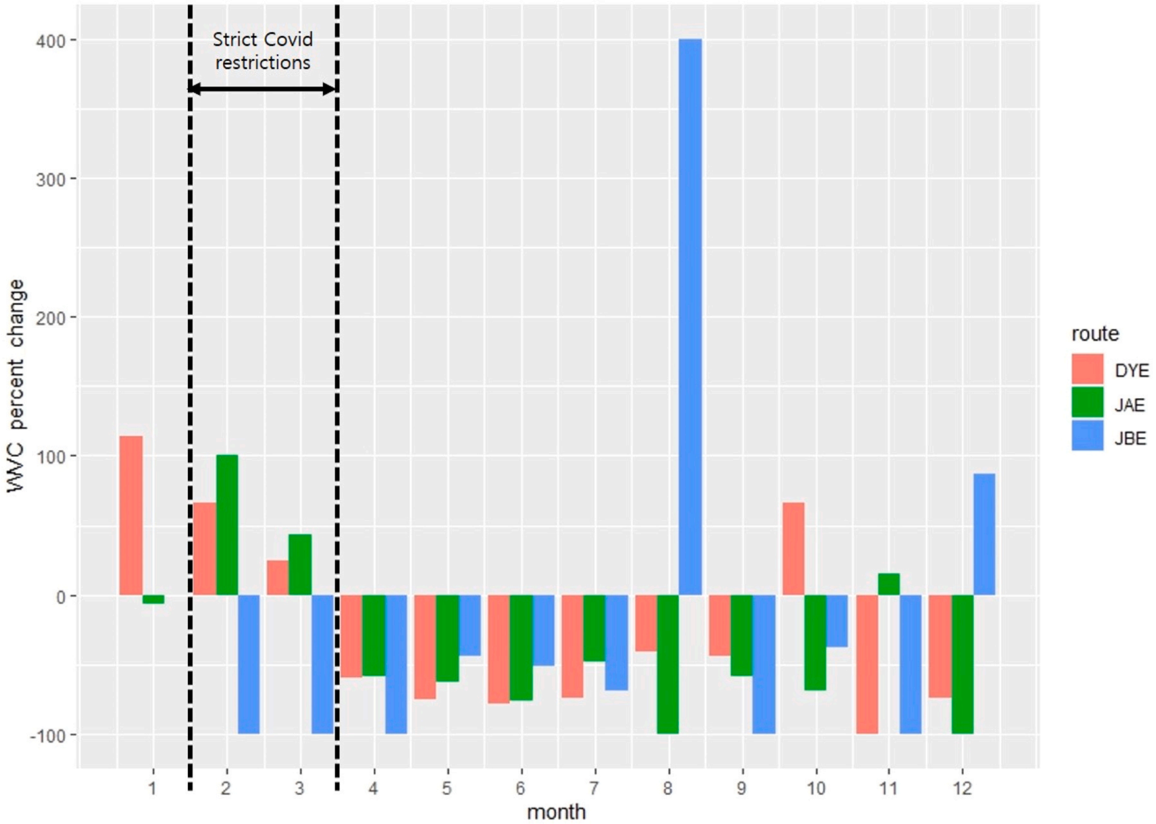

Fig. 3. Monthly percentage change in wildlife–vehicle collisions (WVCs) from the pre-pandemic period to the pandemic period on the Dangjin−Yeongdeok Expressway (DYE), Jungang Expressway (JAE), and Jungbu Expressway (JBE). The area within the black dotted lines refers to the period from February to April 2020, when strict COVID-19 restrictions were implemented to prevent the spread of the virus.

the restrictions were lifted (Fig. 4).

Therefore, we analyzed the traffic volume of each route during the COVID-19 restrictions by dividing it into pre-strict pandemic (February –March 2015–2019), strict pandemic (February-March 2020), and pandemic (April-December 2020) (Fig. 5). The results show that traffic volume on DYE and JAE decreased significantly during the strict pandemic compared to pre-strict pandemic traffic volume. In contrast, after the strict pandemic, traffic volume increased significantly. For JBE, traffic volume during the strict pandemic tended to be higher than the pre-strict pandemic, and traffic volume continued to increase during the pandemic.

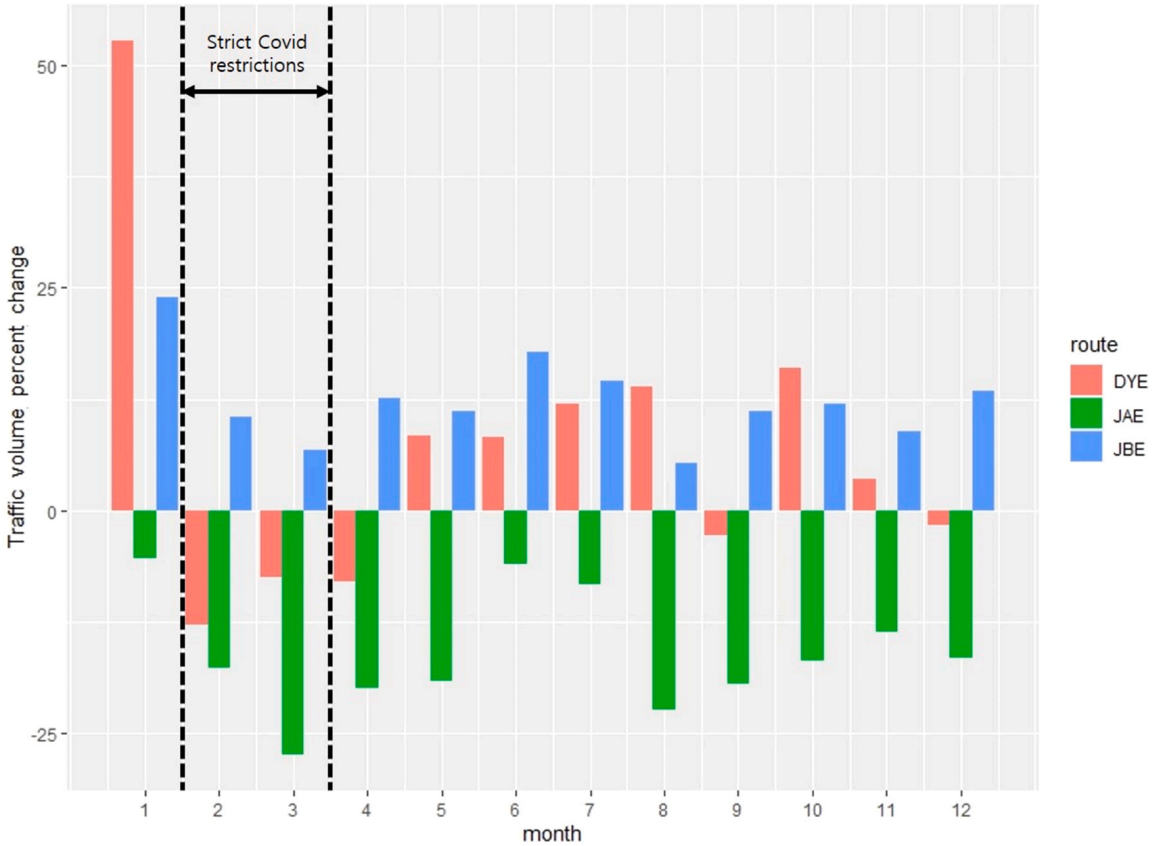

Fig. 4. Monthly percentage changes in traffic volume from the pre-pandemic period to the pandemic period on the Dangjin−Yeongdeok Expressway (DYE), Jungang Expressway (JAE), and Jungbu Expressway (JBE). The area within the black dotted lines refers to the period from February to April 2020, when strict COVID restrictions were implemented to curb the spread of the virus.

In the case of JAE, traffic volume has declined during and after the strict pandemic. This is due to the continuous dispersion of vehicles due to the opening of the Jungbu Naeryuk Expressway near JAE. For this reason, it can be seen that the JAE route shows a decreasing traffic volume trend every year (Appendix 2). On the other hand, it can be seen that the JBE has seen a decrease in the peak value of traffic volume during the strict pandemic but an increase in the median and minimum values. The JBE is an expressway connecting the capital region, and the hotspot section is located close to Seoul, which tends to show a significant increase in traffic volume every year (Appendix 2). In addition, the JBE is an expressway with high freight traffic volume, with more than 30% of the traffic volume being trucks (https://stat.molit.go.kr/). While human movement has decreased during the COVID-19 lockdown, freight transportation has expanded globally. JBE is also an expressway with a high proportion of freight vehicles, which may explain the increase in traffic volume on JBE during this period.

Therefore, we used ANOVA analysis to determine if there was a statistically significant difference in the traffic volume of each route by period. As a result, we found that the difference in traffic volume by period was statistically significant for DYE, JAE, and JBE routes (DYE: df=2, F value= 9.679, p=0.001**, JAE: df=2, F value=10.696, p=0.001**, JBE: df=2, F value=16.183, p=0.000***). Therefore, the study found that COVID-19 restrictions impacted traffic volume.

To analyze the impact of traffic volume changes on WVCs due to movement restrictions during the COVID-19 pandemic, this study analyzed the Pearson correlation between WVCs and traffic volume for all routes during the strict pandemic. The results showed a strong negative correlation between WVCs and traffic volume during the strict pandemic (Pearson correlation coefficient =-0.873).

To analyze the influence of traffic volume changes due to the COVID-19 pandemic on WVCs, our study calculated the WVCs by traffic volume for each period over the entire route. This analysis found that the mean of the pre-strict pandemic was 0.329 (SD = 0.642), the strict pandemic was 0.541 (SD = 0.675), and the pandemic was 0.499 (SD = 0.784). Thus, the strict pandemic period exhibited the highest mean as well as a greater range of change in WVC occurrences per traffic (Fig. 6). This is because traffic volume and WVCs are strongly negatively correlated, with the decrease in traffic volume during the strict pandemic period leading to an increase in WVCs.

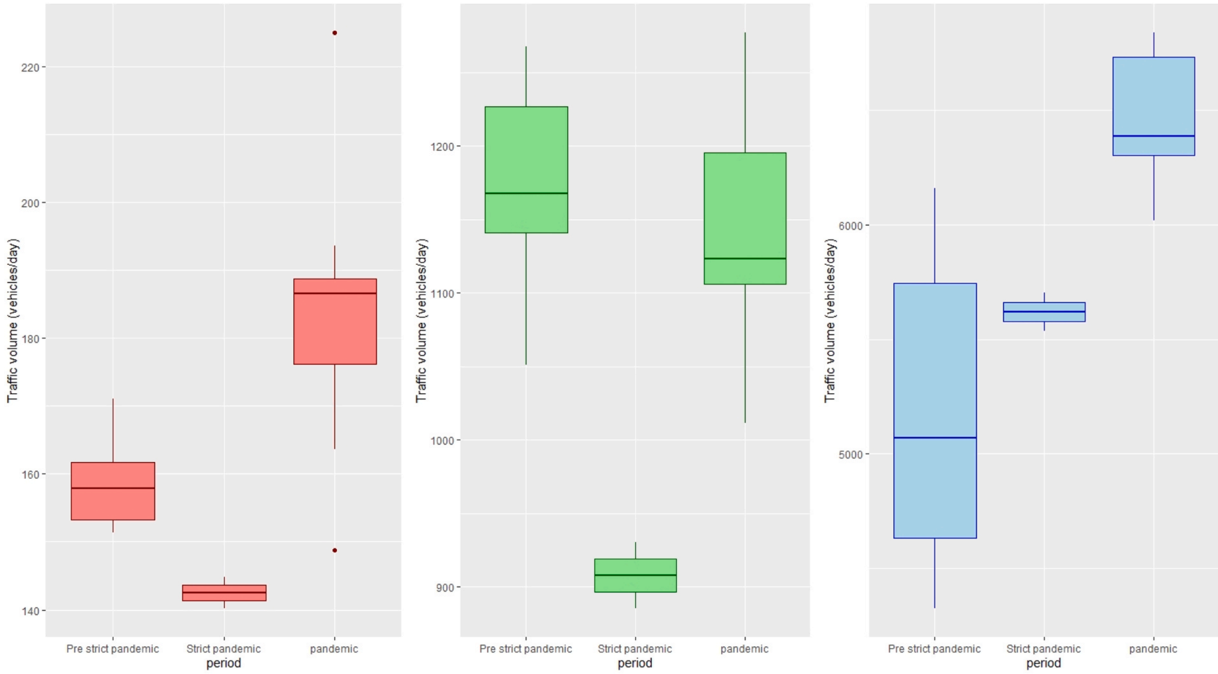

Fig. 5. Traffic volume from 2015 to 2020 on each route, broken down by pre-strict COVID (February-March 2015–2019), strict pandemic (February-March 2020), and pandemic (April-December 2020) (Left is Dangjin–Yeongdeok Expressway (DYE), center is Jungang Expressway (JAE) and right is Jungbu Expressway (JBE).

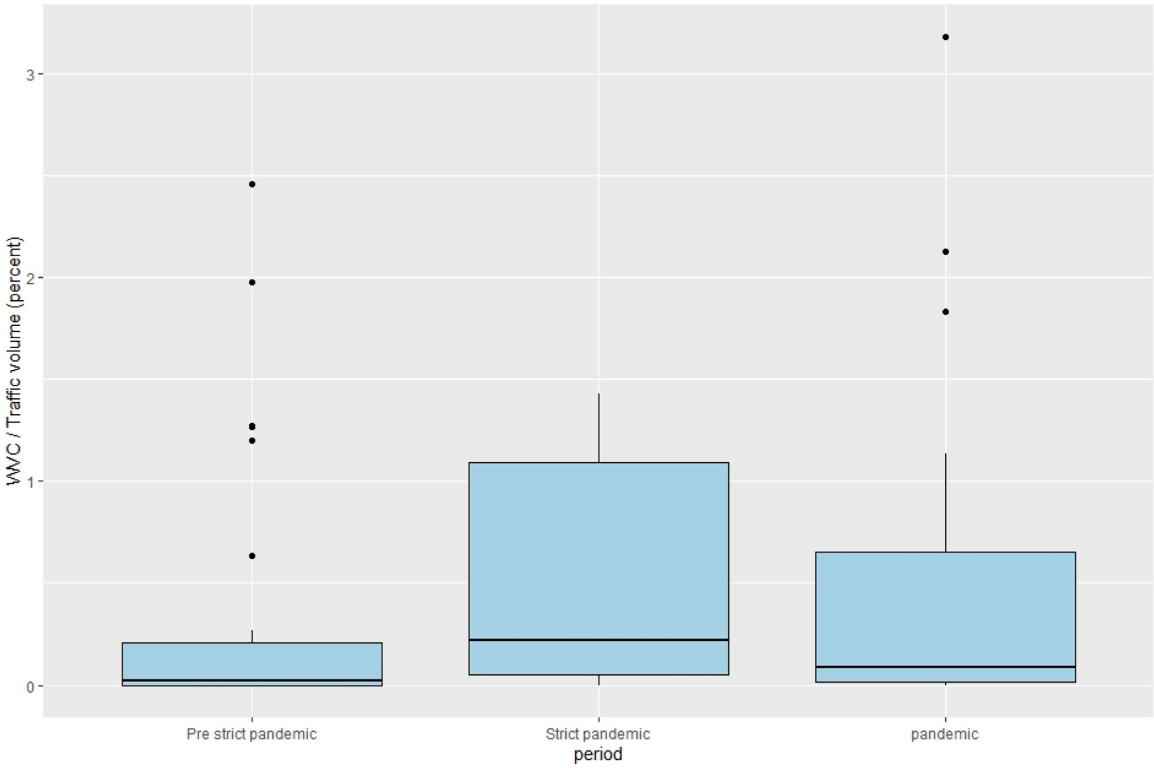

Fig. 6. Wildlife–vehicle collision (WVC) occurrence data per traffic volume by period for all study routes. (pandemic: April 2020 to December 2020, Pre-strict pandemic: February to March between 2015 and 2019, strict pandemic: February to March 2020).

Therefore, a paired t-test was employed to examine the statistical significance of the mean difference in WVC occurrence per traffic volume between periods. There was a statistically significant difference in the incidence of WVCs per traffic volume between the strict pandemic and the pandemic periods (t=–4.2939, df=5, $p = 0.008$). There is a positive correlation between the strict and pandemic periods and a negative correlation between the pre-strict pandemic and the strict pandemic (Table 4).

During the COVID-19 pandemic, social distancing measures and associated restrictions considerably decreased human activities worldwide. Several researchers predicted that the reduced traffic volume would lead to fewer WVCs (Primack et al., 2021; Coelho et al., 2008; D'Amico et al., 2015; Lin, 2016). A study on traffic volume and WVCs on the Anuran highway in Ontario, Canada, found a negative relationship between the two variables. Saeki and Macdonald (2004) also discovered collisions in Japan and traffic volume whereby WVCs occurred more frequently when traffic volume decreased.

During the pandemic period, certain sections of the expressways exhibited a higher incidence of WVCs than in any other period. This can be attributed to wildlife behavioral characteristics, including breeding, foraging, dispersal patterns, and their preferred routes for crossing in search of better habitats (Dean et al., 2019; Saint-Andrieux et al., 2020). In this study, the behavioral characteristics of water deer are among the most critical factors influencing WVCs on the DYE, JAE, and JBE routes. These collisions mostly occurred in the spring, while winter and spring are the known breeding seasons for water deer. During this period, the water deer mainly used wetlands and farmland; however, they can also expand their home range (Park and Lee, 2013). Thus, the lockdown period coincided with the water deer's breeding season, thereby increasing the risk of a vehicle collision. Some wildlife restrains from roads when the traffic volume increases (van Langevelde and Jaarsma, 2005). According to Seiler (2005), as wildlife tends to intrude on less crowded roadways, WVCs would occur more frequently in sections where the traffic volume is moderate compared to high-traffic sections. For example, WVCs involving moose (*Alces alces*) occurred most frequently in areas with moderate traffic volumes. Similarly, Rendall (Rendall et al., 2021) discovered that the WVC rate was highest on roadways with moderate traffic volume.

WVC increased on sections with reduced traffic during strict COVID, and the reduction in WVC was maintained after strict COVID. Other studies also demonstrated similar results. In a study of an expressway in northwestern Spain, the WVC occurrence rate decreased in number after the lockdown (García-Martínez-de-Albéniz et al., 2022). The sharp decrease in traffic volume, similar to that during the strict pandemic, can temporarily increase the occurrence of WVCs. However, it can also have a lasting impact on reducing such incidences. A significant temporary reduction in traffic volume can help to reduce WVCs.

The causes for WVC are extensive and their interplay is complex. Previous studies have suggested that changes in traffic volume might impact the behavior of certain wildlife species, particularly large mammals, which might complicate the relationship between traffic volume and WVCs (Seiler and Helldin, 2006; Jaarsma and Willems, 2002; Alexander et al., 2005). The frequency of wildlife crossings is determined by the animal's behavioral patterns (Kämmerle et al., 2017), and the surrounding environment often influences behavioral patterns. The occurrence of WVCs follows a very specific spatiotemporal pattern (Park et al., 2021; García-Martínez-de-Albéniz et al., 2022), so the characteristics of the road and the distribution of traffic must also be considered (García-Martínez-de-Albéniz et al., 2022). Thus, it is essential to understand the ecological characteristics of wildlife to comprehend their relationship with human activities and, consequently, the causes of WVCs.

4. Conclusion

Newly constructed expressways increase the risk of WVCs, leading to significant socioeconomic consequences. Thus, the relationship between traffic volume and WVCs has been widely studied. Human interactions with nature were fundamentally changed by the COVID-19 lockdowns, introduced globally to mitigate the risks associated with the disease (Bates et al., 2021). During the pandemic, containment measures restricted human activities, thereby offering opportunities to quantitatively assess the human influence on WVCs.

During the strict COVID period, when movement restrictions were in place due to the COVID-19 outbreak, we found a negative correlation between traffic and WVC. After strict COVID, WVC maintained a downward trend. Therefore, this study is of great significance in quantitatively revealing the relationship between WVC and traffic volume on Korean expressways due to movement restrictions caused by the COVID-19 outbreak. It provides a basis for establishing alternatives to WVC occurrence on expressways.

It is important to note that this study primarily focused on the impact of traffic volume, among several factors contributing to wildlife–vehicle collisions, and only utilized data from the initial phase of the pandemic. Therefore, there may be certain limitations to the generalizability of the study's findings. Subsequently, further studies that examine the relationship between traffic restrictions and WVCs for a longer period of time, from the beginning to the end of the pandemic, are needed to provide ample information on WVC mitigation (García-Martínez-de-Albéniz et al., 2022). Additional research on various causes of WVCs, such as land cover, landscape structure, speed, and road characteristics, can also help to expand the understanding of the human influence on WVCs on expressways.

WVCs are the result of an interaction between humans and wild animals, and thus, it is essential to comprehend the relationship and

Table 4
Correlation of ratio (WVC/traffic volume) analysis results for each period using Pearson correlation (pandemic: April 2020 to December 2020; pre-strict pandemic: February to March between 2015 and 2019; strict pandemic: February to March 2020). **$P < .01$.

	Pre-strict pandemic	Strict pandemic	Pandemic
Pre-strict pandemic	1.000	-	-
Strict pandemic	-0.543	1.000	-
Pandemic	0.246	0.740**	1.000

relevance of the interactions between humans and wildlife. In this sense, it is noteworthy that this study drew a quantitative conclusion on the interaction between humans and animals. Moreover, it can serve as a reference to establish feasible strategies for WVC prevention.

CRediT authorship contribution statement

Hyomin Park: Methodology, Data curation. **Sangdon Lee:** Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

We confirm that there is no conflict among authors.

Data availability

Data will be made available on request.

Acknowledgements

The financial support was from KRF-2021R1A2C1011213, MOE-2020002990006 and 2021003360002.

Appendix 1

Wildlife–vehicle collision (WVC) occurrence on the expressways in Korea between 2015 and 2019: the three routes with the highest WVC occurrence were selected as study sites.

Route no.	Route	km	WVC
30	Dangjin–Yeongdeok Expressway	278.6	1665
55	Jungang Expressway	288.8	1560
35	Jungbu Expressway	332.5	1364
1	Gyeongbu Expressway	416.05	911
50	Yeongdong Expressway	234.4	739
15	Seohaean Expressway	340.8	713
45	Jungbunaeryuk Expressway	301.7	404
151	Seocheon–Gongju Expressway	61.4	370
25	Honam Expressway	194.2	317
65	Donghae/Ulsan–Pohang Expressway	175.86	244
20	Ikan–Pohang Expressway	130.3	233
251	Honam Branch Expressway	54	226
27	Suncheon Wanju Expressway	117.8	209
12	Muan–Gwangju /Gwangju Daegu Expressway	223.2	188
10	Namhae Expressway	273.1	160
40	Pyeongtaek Jecheon Expressway	109.4	130
37	Second Jungbu Expressway	31.1	119
100	Capital Region First Ring Expressway	91.7	88
102	Namhae 1st Branch Expressway	17.9	57
300	Daejeon Southern Belt Expressway	13.3	39
60	Seoul–Yangyang Expressway	88.8	36
253	Gochang-Damyang Expressway	42.5	29
104	Namhae 2nd Branch Expressway	20.6	19
451	Jungbunaeryuk Expressway	30	18
16	Ulsan Expressway	14.3	15
600	Busan Ring Expressway	48.8	6
110	Second Gyeongin Expressway	26.7	5
551	Jungang Branch Expressway	8.2	2

Appendix 2

Average monthly traffic volume from 2015 to 2020 by study route (vehicles/day). The gray blocks represent the period when strict restrictions began in Korea during the COVID-19 pandemic (February–March 2020).

	DYE						JAE						JBE					
	2015	2016	2017	2018	2019	2020	2015	2016	2017	2018	2019	2020	2015	2016	2017	2018	2019	2020
Jan	131.74	148.84	158.90	125.10	133.55	213.29	1065.68	1082.32	1126.58	1050.97	1047.10	1017.42	4259.29	4426.77	4379.35	5296.06	6049.35	6047.03
Feb	151.36	157.10	166.43	171.07	157.93	140.21	1159.57	1175.59	1139.21	1120.71	1051.07	930.41	4327.36	4521.24	4729.43	5578.50	5923.86	5538.00
Mar	152.06	162.84	158.32	157.94	151.55	144.84	1218.32	1234.65	1267.68	1229.48	1145.81	885.23	4601.87	4986.26	5152.90	5802.84	6159.61	5704.39
Apr	172.20	184.07	181.07	167.13	184.53	163.67	1302.20	1309.60	1387.60	1308.27	1239.47	1048.67	4848.00	5356.53	5374.80	6246.20	6277.07	6330.00
May	167.94	190.32	168.32	170.58	173.81	188.77	1366.00	1424.90	1433.29	1331.29	1318.39	1112.58	5123.03	5215.55	5526.45	6318.84	6528.13	6385.10
Jun	158.27	185.00	178.60	173.67	172.20	187.80	1312.00	1426.60	1435.47	1350.73	1274.73	1277.33	4883.60	5054.33	5484.27	6235.33	6099.27	6533.53
Jul	169.29	168.71	156.65	164.97	126.84	176.19	1362.58	1413.10	1403.35	1374.26	1253.35	1249.55	5008.32	5038.06	5358.32	6006.39	6099.61	6304.13
Aug	178.97	171.74	153.10	155.55	123.42	178.32	1458.84	1569.35	1430.26	1365.81	1300.32	1106.06	5182.32	5383.23	5618.71	6032.71	6356.32	6018.90
Sep	207.60	199.00	184.73	241.47	163.20	193.67	1439.93	1495.80	1460.67	1322.33	1251.07	1123.47	5565.80	5519.73	6318.93	6804.20	6449.87	6818.60
Oct	196.39	178.65	233.94	178.45	182.90	225.03	1460.90	1587.10	1433.03	1366.84	1344.90	1195.35	5547.42	5313.23	6551.42	6726.52	6415.61	6837.42
Nov	174.53	176.40	169.73	164.47	215.93	186.60	1348.07	1450.93	1344.80	1334.20	1295.53	1169.80	5091.40	5915.60	6797.33	6688.67	6438.07	6731.60
Dec	164.26	151.94	135.94	129.48	174.77	148.84	1259.81	1285.03	1204.00	1142.84	1165.61	1011.61	4826.26	4632.52	6160.77	6011.29	6059.29	6281.94

References

Abraham, J.O., Mumma, M.A., 2021. Elevated wildlife-vehicle collision rates during the COVID-19 pandemic. Sci. Rep. 11 (1), 20391 https://doi.org/10.1038/s41598-021-99233-9.

Alexander, S.M., Waters, N.M., Paquet, P.C., 2005. Traffic volume and highway permeability for a mammalian community in the Canadian Rocky Mountains. Can. Geogr. 49 (4), 321–331. https://doi.org/10.1111/j.0008-3658.2005.00099.x.

Bates, A.E., Primack, R.B., Biggar, B.S., et al., 2021. Global COVID-19 lockdown highlights humans as both threats and custodians of the environment. Biol. Conserv. 263, 109175 https://doi.org/10.1016/j.biocon.2021.109175.

Bencin, H.L., Prange, S., Rose, C., Popescu, V.D., 2019. Roadkill and space use data predict vehicle-strike hotspots and mortality rates in a recovering bobcat (*Lynx rufus*) population. Sci. Rep. 9 (1), 15391 https://doi.org/10.1038/s41598-019-50931-5.

Bíl, M., Andrášik, R., Svoboda, T., Sedoník, J., 2016. The KDE+ software: a tool for effective identification and ranking of animal–vehicle collision hotspots along networks. Land. Ecol. 31 (2), 231–237. https://doi.org/10.1007/s10980-015-0265-6.

Bíl, M., Andrášik, R., Cícha, V., Arnon, A., Kruuse, M., Langbein, J., Náhlik, A., Niemi, M., Pokorny, B., Colino-Rabanal, V.J., Rolandsen, C.M., Seiler, A., 2021. COVID-19 related travel restrictions prevented numerous wildlife deaths on roads: a comparative analysis of results from 11 countries. Biol. Conserv. 256, 109076 https://doi.org/10.1016/j.biocon.2021.109076.

Coelho, I.P., Kindel, A., Coelho, A.V.P., 2008. Roadkills of vertebrate species on two highways through the Atlantic Forest Biosphere Reserve, southern Brazil. Eur. J. Wildl. Res. 54, 689–699. https://doi.org/10.1007/s10344-008-0197-4.

D'Amico, M., Román, J., De los Reyes, L., Revilla, E., 2015. Vertebrate road-kill patterns in Mediterranean habitats: who, when and where. Biol. Conserv. 191, 234–242. https://doi.org/10.1016/j.biocon.2015.06.010.

Da Silva, A.C.F.B., De Menezes, J.F.S., Santos, L., G.R.O, 2022. Roadkill risk for capybaras in an urban environment. Landsc. Urban Plan 222, 104398. https://doi.org/10.1016/j.landurbplan.2022.104398.

Dean, W.R.J., Seymour, C.L., Joseph, G.S., Foord, S.H., 2019. A review of the impacts of roads on wildlife in semi-arid regions. Diversity 11 (5), 81. https://doi.org/10.3390/d11050081.

Driessen, M.M., 2021. COVID-19 restrictions provide a brief respite from the wildlife roadkill toll. Biol. Conserv. 256, 109012 https://doi.org/10.1016/j.biocon.2021.109012.

Fahrig, L., Rytwinski, T., 2009. Effects of roads on animal abundance: an empirical review and synthesis. Ecol. Soc. 14, 21.

Forman, R.T., Sperling, D., Bissonette, J.A., Clevenger, A.P., Cutshall, C.D., Dale, V.H., Fahrig, L., France, R., Goldman, C.R., Heanue, K., Jones, J.A., Swanson, F.J., Turrentine, T., Winter, T.C., 2003. Road ecology. Science and solutions. Island Press, Washington.

García-Martínez-de-Albéniz, Í., Ruiz-de-Villa, J.A., Rodriguez-Hernandez, J., 2022. Impact of COVID-19 lockdown on wildlife-vehicle collisions in NW of Spain. Sustainability 14 (8), 4849. https://doi.org/10.3390/su14084849.

Garrah, E., Danby, R.K., Eberhardt, E., Cunnington, G.M., Mitchell, S., 2015. Hot spots and hot times: wildlife road mortality in a regional conservation corridor. Environ. Manag 56 (4), 874–889. https://doi.org/10.1007/s00267-015-0566-1.

Huijser, M.P., Duffield, J.W., Clevenger, A.P., Ament, R.J., McGowen, P.T., 2009. Cost-benefit analyses of mitigation measures aimed at reducing collisions with large ungulates in the United States and Canada: a decision support tool. Ecol. Soc. 14 (2), 15.

Jaarsma, C.F., Willems, G.P., 2002. A Reducing habitat fragmentation by minor rural roads through traffic calming. Landsc. Urban Plan. 58, 125–135. https://doi.org/10.1016/S0169-2046(01)00215-8.

Kämmerle, J.L., Brieger, F., Kröschel, M., Hagen, R., Storch, I., Suchant, R., 2017. Temporal patterns in road crossing behaviour in roe deer (*Capreolus capreolus*) at sites with wildlife warning reflectors. PLoS One 12 (9), e0184761. https://doi.org/10.1371/journal.pone.0184761.

Laube, P., Ratnaweera, N., Wróbel, A., Kaelin, I., Stephani, A., Reifler-Baechtiger, M., Graf, R.F., Suter, S., 2023. Analysing and predicting wildlife–vehicle collision hotspots for the Swiss road network. Land. Ecol. 38, 1765–1783. https://doi.org/10.1007/s10980-023-01655-5.

Laurance, W.F., Goosem, M., Laurance, S., 2009. Impacts of roads and linear clearings on tropical forests. Trends Ecol. Evol. 24, 659–669. https://doi.org/10.1016/j.tree.2009.06.009.

Lee, G., Tak, J., Pak, S., 2014. Spatial and temporal patterns on wildlife road-kills on highway in Korea. J. Vet. Clin. 31, 282–287.

Lester, D., 2015. Effective wildlife roadkill mitigation. J. Traffic Transp. Eng. 3, 42–51. https://doi.org/10.17265/2328-2142/2015.01.005.

Lin, S.C., 2016. Landscape and traffic factors affecting animal road mortality. J. Environ. Eng. Landsc. 24, 10–20. https://doi.org/10.3846/16486897.2015.1098652.

Litvaitis, J., Tash, J., 2008. An approach toward understanding wildlife-vehicle collisions. Environ. Manag. 42, 688–697. https://doi.org/10.1007/s00267-008-9108-4.

Main, M.B., Allen, G.M., 2002. Landscape and seasonal influences on roadkill of wildlife in southwest Florida. Fla Sci. 65, 149–158.

Manenti, R., Mori, E., Di Canio, V., Mercurio, S., Picone, M., Caffi, M., Brambilla, M., Ficetola, G.F., Rubolini, D., 2020. The good, the bad and the ugly of COVID-19 lockdown effects on wildlife conservation: insights from the first European locked down country. Biol. Conserv. 249, 108728 https://doi.org/10.1016/j.biocon.2020.108728.

Pagany, R., 2020. Wildlife-vehicle collisions - influencing factors, data collection and research methods. Biol. Conserv. 251, 108758 https://doi.org/10.1016/j.biocon.2020.108758.

Park, H., Lee, S., 2013. Habitat use pattern of Korean waterdeer based on the land coverage map. J. Wetl. Res. 15 (4), 567–572. https://doi.org/10.17663/JWR.2013.15.4.567.

Park, H., Kim, M., Lee, S., 2021. Spatial characteristics of wildlife-vehicle collisions of water deer in Korea Expressway. Sustainability 13 (24), 13523. https://doi.org/10.3390/su132413523.

Primack, R.B., Bates, A.E., Duarte, C.M., 2021. The conservation and ecological impacts of the COVID-19 pandemic. Biol. Conserv. 260, 109204 https://doi.org/10.1016/j.biocon.2021.109204.

Rendall, A.R., Webb, V., Sutherland, D.R., White, J.G., Renwick, L., Cooke, R., 2021. Where wildlife and traffic collide: roadkill rates change through time in a wildlife-tourism hotspot. Glob. Ecol. Conserv. 27, e01530 https://doi.org/10.1016/j.gecco.2021.e01530.

Rilett, L.R., Tufuor, E., Murphy, S., 2021. Arterial roadway travel time reliability and the COVID-19 pandemic. J. Transp. Eng. A Syst. 147 (7), 04021034 https://doi.org/10.1061/JTEPBS.0000559.

Rutz, C., Loretto, M.C., Bates, A.E., Davidson, S.C., Duarte, C.M., Jetz, W., Johnson, M., Kato, A., Kays, R., Mueller, T., Primack, R.B., Ropert-Coudert, Y., Tucker, M.A., Wikelski, M., Cagnacci, F., 2020. COVID-19 lockdown allows researchers to quantify the effects of human activity on wildlife. Nat. Ecol. Evol. 4, 1156–1159. https://doi.org/10.1038/s41559-020-1237-z.

Saeki, M., Macdonald, D.W., 2004. The effects of traffic on the raccoon dog (*Nyctereutes procyonoides viverrinus*) and other mammals in Japan. Biol. Conserv. 118, 559–571. https://doi.org/10.1016/j.biocon.2003.10.004.

Saint-Andrieux, C., Calenge, C., Bonenfant, C., 2020. Comparison of environmental, biological and anthropogenic causes of wildlife–vehicle collisions among three large herbivore species. Popul. Ecol. 62, 64–79. https://doi.org/10.1002/1438-390X.12029.

Seiler, A., 2005. Predicting locations of moose-vehicle collisions in Sweden. J. Appl. Ecol. 42, 371–382. https://doi.org/10.1111/j.1365-2664.2005.01013.x.

Seiler, A., Helldin, J.O., 2006. Mortality in wildlife due to transportation. The ecology of transportation: Managing mobility for the environment. Springer Netherlands, Dordrecht.

Seiler, A., Olsson, M., Rosell, C., Van Der Grift, E.A., 2016. SAFEROAD safe roads for wildlife and people: cost-benefit analyses for wildlife and traffic safety. SAFEROAD Tech. Rep. 4, 40.

Shilling, F., Nguyen, T., Saleh, M., Khant Kyaw, M., Tapia, K., Trujillo, G., Bejarano, M., Waetjen, D., Peterson, J., Kalisz, G., Sejour, R., Croston, S., Ham, E., 2021. A reprieve from US wildlife mortality on roads during the COVID-19 pandemic. Biol. Conserv. 256, 109013 https://doi.org/10.1016/j.biocon.2021.109013.

Taylor, B.D., Goldingay, R.L., 2010. Roads and wildlife: impacts, mitigation and implications for wildlife management in Australia. Wildl. Res. 37 (4), 320–331. https://doi.org/10.1071/WR09171.

Van der Ree, R., Smith, D.J., Grilo, C., 2015. The ecological effects of linear infrastructure and traffic: challenges and opportunities of rapid global growth. Handb. Road. Ecol. 1–9.
van Langevelde, F., Jaarsma, C.F., 2005. Using traffic flow theory to model traffic mortality in mammals. Land. Ecol. 19, 895–907. https://doi.org/10.1007/s10980-005-0464-7.
Visintin, C., Van Der Ree, R., McCarthy, M.A., 2017. Consistent patterns of vehicle collision risk for six mammal species. J. Environ. Manag. 201, 397–406. https://doi.org/10.1016/j.jenvman.2017.05.071.