



Effects of road fencing systems on wildlife-vehicle collisions

- Analysis of wildlife-vehicle collisions before and after fencing measures in Sweden, 2013–2024

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Effects of road fencing systems on wildlife-vehicle collisions. Analysis of wildlife-vehicle collisions before and after fencing measures in Sweden, 2013–2024

*Effekt av viltstängselsystem på viltolyckor. En analys av viltolyckor före och efter
stängslingsåtgärder i Sverige, 2013–2024*

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Abstract

Wildlife-vehicle collisions are a prominent issue becoming more apparent with increasing traffic volumes and wildlife populations. This thesis looks at the effect of road fencing on the frequency of wildlife-vehicle collisions (WVC) on 2+1 roads, mainly involving ungulates. By studying WVC on road sections before and after fencing with surrounding road network as controls and controlling for average annual daily traffic, differences in fence efficacies could be attributed to fence characteristics such as fence openings, intersections, cattle grids or jump outs. The results showed a mean accident reduction of 62 % with a range of -1 % to 89 %. The single fence attribute that most strongly correlated with the differences in efficacy was the frequency of connecting secondary roads. Standard procedure to secure connections by extending fences along the connecting roads does not serve its purpose as an effective mitigation measure and must be improved.

Keywords: Wildlife-vehicle collisions, wildlife fencing, open connections, ungulates, fencing attributes, 2+1 road

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Abbreviations

WVC	Wildlife-vehicle collision
UVC	Ungulate-vehicle collision
ADT	Annual average daily traffic

1. Introduction

Road networks cut through landscapes enhancing accessibility for motorists while imposing lethal barriers to wildlife as well as fellow road users. Each year, more than 60,000 incidents with wildlife are reported by the Swedish police, most of which are ungulate-vehicle collisions (UVC), and through the years numbers are continuing to rise (Gabrielsson, Östman, Lundin & Sjölund 2022). Both in Sweden and other European countries, UVC are on the rise while roads are expanding, traffic increases and wildlife populations recover and increase in numbers (Seiler, Willebrand, Olsson & Wahlman 2019; Hothorn, Müller, Held, Möst & Mysterud 2015; Beckmann, Clevenger, Huijser & Hilty 2010; Langbein et al. 2010).

1.1 Swedish road fencing systems

Internationally, fencing in combination with safe passages for wildlife has proven to be most effective in reducing the number of collisions with wildlife (Rosell et al. 2023; Beckmann et al. 2010). To prevent wildlife-vehicle collisions (WVC), over 8000 km of roads have been fenced in Sweden. Motorways and many national highways have been prioritized due to their high speed and high traffic volume. According to the fencing directives, roads with more than 4000 annual average daily traffic (ADT) and 80 km/h or above should be considered for fencing (Trafikverket 2020; Trafikverket 2014). The Swedish Transport Administration assumes a standard collision reduction of 80 % involving moose (*Alces alces*) and 55 % involving roe deer (*Capreolus capreolus*) (Seiler, Olsson, Rosell & Van Der Grift 2016; Trafikverket 2012). Seiler (2005) argued that lowering speed was a more effective method in reducing the risk for collisions with ungulates than fences. Lower speed means more reaction time as well as shorter breaking distance (Älgskadefondsöreningen 2022).

This study will focus on 2+1 i.e., roads that are separated for oncoming traffic with wire railing as a protective measure for motorists. For wildlife, however, these railings pose an additional obstacle which risks prolonging time spent on the road (Trafikverket 2014). Upgraded 2+1 roads usually have many connecting local and private roads and provide many openings in the fence where wildlife may find access to the road.

The use of wildlife fencing induces other types of problems, mostly related to barrier effects and WVC-patterns across the landscape. However, fencing can be intended to both keep animals in or out. In these cases, fencing can have a positive effect by keeping for example livestock or invasive species from entering an

ecosystem (McInturff, Xu, Wilkinson, Dejid & Brashares 2020). Wildlife fencing can be constructed with extenders on top to prevent animals from climbing over or have the base buried to stop animals digging under. To increase the efficiency of fences and safety for motorists, fences are now updated with escape gates, ramps, animal-detection systems, cattle grids, wildlife passages, etc. When installed and maintained correctly, fencing combined with safe passage solution can reduce WVC by 80-95 % (Clevenger, Chruszcz & Gunson 2001; Rytwinski et al. 2016). When these fences are not maintained properly or faulty in planning/placing the effectiveness is reduced. It should also be noted that the decrease of WVC is apparent only for the fenced section. WVC at adjacent roads are not mitigated as much as accidents are moved to other locations, usually to the fence-ends, road crossings or other openings in the fence (Cserkés, Ottlecz, Cserkés-Nagy & Farkas 2013; Clevenger, Chruszcz & Gunson 2001). Also, the cumulative effects of fencing at a larger scale are often difficult to predict and study. This study focuses on the wild ungulate species in Sweden, which are moose, red deer, fallow deer (*Dama dama*), roe deer (*Capreolus capreolus*) and wild boar (*Sus scrofa*). Semi-domesticated reindeer (*Rangifer tarandus*) although common in the mountainous and northern regions of Sweden will not be a part of this study since they are legally livestock with an owner, and their accident reports are not handled in the same way as WVC.

Even though it is required by law to report all UVC as well as collisions with some other species, this is not always done or done incorrectly. Therefore, hidden statistics from non-reported, wrongly reported or collisions given another category are not uncommon. These factors vary between species, county and year. The estimated rate of underreported WVC is thought to be approximately 9 % to 19 %, depending on the species (Seiler & Jägerbrand 2016). When a WVC has occurred, it is the driver's responsibility to call the Swedish emergency number, 112 and report the collision, what species was involved and if possible, mark the spot. The police then contact the contracted hunter for the area to locate and handle the injured or dead game. The hunter reports back to the National Council for Wildlife Accidents to receive reimbursement (Nationella Viltolycksrådet 2024; Nationella Viltolycksrådet n.d.). It is from these hunter reports we obtained the most accurate location of the accidents.

The Swedish Transport Administration annually invests in smaller, efficient measures – each up to 100 million SEK – for traffic safety and environmental measures (Trafikverket 2021). Amid environmental measures are a tool the Swedish Transport Administration uses to address or correct deficiencies in existing infrastructure. For the period of 2022 to 2033 an amount of 11.5 billion SEK is planned to go towards different environmental measures (Trafikverket 2025). Through these financial means, new fencing, fauna passages and other

measures will be built. Studies on the effect of these mitigation measures are still in a relatively early stage, except evaluations within single projects (e.g. ecoduct Sandsjöbacka, at-grade fauna passage road 108; Olsson et al. 2023; Trafikverket 2019). A study of the mitigation measures conducted on road 108 shows that the level passage, equipped with heat sensing cameras and radars, were most frequently used at dawn and dusk. The number of WVC showed to have decreased by overall 66 % along road 108 after mitigation measures, including fencing and wildlife crossing opportunities (Bhardwaj et al. 2022).

1.2 Previous studies on fencing systems and WVC

Previous studies of road fencing systems in relation to UVC occurrence and hot-spots from different countries have found similar results. A nationwide study in Lithuania showed that fencing can reduce UVC on high intensity and speed roads, but simultaneously redirecting animals to nearby lower intensity and speed roads without mitigation, where UVC then increase (Kučas A & Balčiauskas 2021). A study conducted in Alberta, Canada shows similar results, where UVC decreased notably along the fenced section while it increased on road sections close by (MacDougall, Bíl, Andrášik, Sedoník & Stuart 2024).

A study on large mammal-vehicle collision combining literature reviews and field studies focused on North America show that shorter fencing sections had an average reduction of 53 %, while longer fencing sections of 5 kilometres or more, had an average reduction effect of 84 %. The sections shorter than 5 kilometres also suggested a reduces effectiveness based on a stronger fence-end effect (Clevenger, Chruszcz & Gunson 2001; Huijser et al. 2016). Another study points out the importance of fence end placement, not only fence length, when planning fencing measures, for example placing fence ends in suitable environments (Huijser & Begley 2022). Examination of underpasses revealed that fencing presence or length had no effect on use of underpasses by large mammals, rather the usage is likely dependent on factors such as location of the underpass (Huijser et al. 2016).

A study by Bíl, Kubeček and Andrášik (2020) of UVC in relation to ADT shows that road with lower traffic volumes, less than 750 cars/hour, were at a higher risk of UVC. The study suggests that using ADT in UVC calculations would not may lead to inaccurate calculations, since ADT represents the average daily traffic volume and therefore does not accurately reflect nighttime traffic levels, which is when most UVC occur (Bíl, Kubeček & Andrášik 2020). Even though a higher ADT on main roads does not show an effect on UVC numbers, it may influence their distribution by shifting UVC towards lower category roads. This also applied to fencing, where increased fence length resulted in reduced UVC on main roads,

whereas for lower category roads it seemed to increase instead of decrease UVC. These findings indicate that fencing might be less effective for lower category roads (Kučas & Balčiauskas 2021). Another study found that moose vehicle collisions increase non-linearly with traffic, showing a hump-backed curve with maximum at around 5000 ADT (Seiler 2005).

These previous studies are relevant for understanding, evaluating and interpreting the results of this study in a broader research context.

1.3 Aim and objectives

The aim of this study is to obtain a comprehensive understanding of the effects of wildlife fencing effects on frequency of WVC through a broader analysis across Sweden.

This will be achieved by answering the following questions:

1. How strong mitigating effect does fencing have on wildlife-vehicle collisions? I.e., does fencing reduce wildlife-vehicle collisions by 80 % as assumed by The Swedish Transport Administration (Trafikverket 2012)?
2. What fencing attributes affect the reduction of wildlife accidents at fenced road sections?

2. Material and method

2.1 Study design

The effectiveness of wildlife fencing in reducing wildlife–vehicle collisions were evaluated using a Before–After–Control–Impact (BACI) approach. Thirty fenced road sections across Sweden were identified and analyzed within a 100m buffer zone together with unaltered control roads within a 6 km buffer zone for each test road during the period from 2013 to 2024. The BACI method isolates the fencing effect by comparing changes in collision rates on the fenced roads before and after fence installation, in relation to trends on unfenced control roads within a 6 km range.

2.2 Data sources

2.2.1 Roads and fence

Road, fence attributes and traffic data used in this study is from the Swedish National Road Database (Nationell vägdata n.d.) combined with remote analysis and mapping through orthophotos in ArcGIS Pro version 3.5 and QGIS version 3.40.6. Fence attributes and year of installation were confirmed by the Transport Administration and verified using remote sensing and field visits. All fence attributes relevant to the study are described in table 1. All attributes, i.e. frequency for attributes, are expressed as frequencies per kilometer per year to allow comparability for the roads.

Table 1. Description for all fence attributes used in the study.

Fenceend.open	Whether the fence has open ends
Conn.open	Connecting road openings and unprotected, fence arms extended for some length from one or both sides
Conn.gate	Connecting road secured by gates (some made of wood)
Conn.grid	Connecting road secured by a cattlegrid
Door.ped	Door for pedestrians in fence (often in relation with gates or cattle grids. Some made of wood)
Jump-out	Jump-outs
Isolator	Short net section made of plastic (sometimes wood) instead of metal, often placed by powerlines
Passage	Over- or underpass for fauna, people, water, road, etc (can be used by wildlife)
Brige (road)	Over- or underpass for road traffic only (unlikely used by wildlife)
Interchange	Connecting or intersecting major road, often with a roundabout, at-grade or two-level, unsuitable for wildlife

In order to produce WVC data for at least three years before and after fence installation had to be occurred between 2016 and 2021, with WVC records being between 2013 and 2024. A minimum length of 1km for test roads was applied. 32 road sections were identified that were upgraded with fences, 2 of these were later removed due to lack of WVC data leaving 30 sections. In 11 of the 30 identified

road sections, a new road had been built parallel to the original road. Due to the lack of accuracy in WVC locations, it was not always possible to separate accidents between ‘old’ test road and ‘new’ test road since they were so close to each other. Both roads were therefore treated as one in the analysis, like the upgraded roads (Figure 1, Table 2). These new sections assumed most of the traffic load from the old roads, which remained open but are mostly used for local traffic. All upgraded and newly constructed roads (hereafter referred to as test roads) are national roads (riksvägar) and share many characteristics such as wildlife exclusion fences, wire-median barrier and speed limits of 100 to 110km/h (local reductions to 80–90 km/h). However, they differed in length, traffic volume, fence attribute and number of years pre- and post-mitigation measures. To provide a comparison, public roads within a 6 km radius of each test road that were not upgraded with fencing during the study period (2013 to 2024) were selected as control roads.

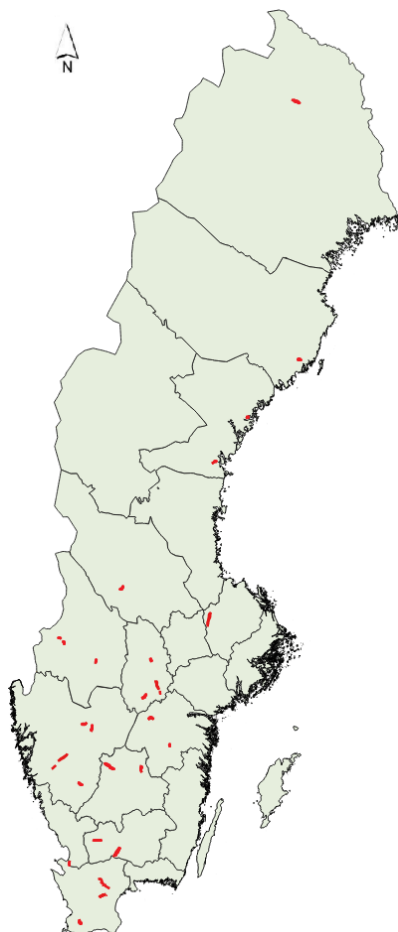


Figure 1. Overview map of Sweden with county borders in black and the locations of all 30 test road sections in red. Map created in SWEREF99 TM. Source: GSD-Översiktskartan, vektor (2021) © Lantmäteriet.

Table 2. Test road basic characteristics including study ID, locality, length, year and intervention type

Road_ID	Locality	Length (km)		No. of years		Intervention
		before	after	before	after	
1	E4 Docksta	2,1	2,1	6	5	upgrade
2	E6 Hallandsås	3,7	3,7	8	3	upgrade
3	RV10 Svappavara	12,6	12,6	3	8	upgrade
4	E12 Umeå	1,5	1,5	7	4	upgrade
5	E14 Sundsvall	5,4	10,8	6	6	newroad
6	E20 Skara	7,9	7,9	8	3	upgrade
7	RV21 Hässleholm	23,8	23,8	6	5	upgrade
8	RV23 Älmhult	15,9	15,9	6	5	upgrade
9	RV25 V Ljungby	11,9	11,9	8	3	upgrade
10	RV47 Mullsjö	17,1	33,9	4	8	newroad
11	RV50 Askersud	8,7	8,7	5	6	upgrade
12	RV56 N Heby	20,2	42,0	3	9	newroad
13	RV61 Arvika	4,0	4,0	8	3	upgrade
14	RV63 Karlstad	4,7	4,7	4	7	upgrade
15	RV108/65 Svedala	6,9	6,9	6	5	upgrade
18	RV50 N Örebro	3,4	3,4	5	6	upgrade
19	RV61 Ämotfors	2,1	2,1	3	8	upgrade
20	E20 Allingsås	15,1	30,0	7	5	newroad
21	RV 34 Motala	6,4	13,1	7	5	newroad
22	E20 S Allingsås	1,8	1,8	3	8	upgrade
23	RV44 Lidköping	6,0	13,1	5	7	newroad
24	RV51 Palsboda	12,1	25,2	6	6	newroad
25	E18 Svennevad	2,2	2,2	4	7	upgrade
26	E16 Vansbro	7,2	12,5	6	6	newroad
27	RV22 Tollarp	3,1	6,4	8	4	newroad
28	E20 Lerum	5,6	5,6	8	3	upgrade
29	RV27 S Borås	5,7	5,7	6	5	upgrade
30	RV32 Aneby	8,4	17,1	4	8	newroad
31	RV22 Linderöd	5,6	11,5	4	8	newroad
32	RV34 Hamra	1,7	1,7	5	6	upgrade

2.2.2 Wildlife–vehicle collisions

WVC data were obtained from hunter reports compiled by the National Council for Wildlife Accidents (Nationella viltolycksrådet n.d.). Since 2013, hunter reports have accounted for approximately 80 % of all police-reported wildlife collisions (Seiler et al. 2019). Each record includes a GPS coordinate, though accuracy varies and no road segment is specified. To ensure spatial precision, only accidents with GPS coordinates located within 250m of the nearest main road were included in the analysis, corresponding to about 90 % of all records. Consequently, our dataset represents approximately 72 % of all police-reported WVCs. However, it is estimated that an additional 10–20 % of collisions remain unreported due to underreporting, missing police records or misclassification of

wildlife accidents (Seiler & Jägerbrand 2017). Overall, the compiled dataset thus covers approximately 60 % of all WVC occurring during the study period.

The WVC dataset comprised primarily collisions with ungulates including roe deer, moose, fallow deer, red deer and wild boar. Occasional records also involve other large mammals such as wolf (*Canis lupus*), Eurasian lynx (*Lynx lynx*) and brown bear (*Ursus arctos*). Species unlikely influenced by fencing such as otters (*Lutra lutra*) or birds of prey, were excluded from the analysis.

To account for the fact that wildlife collisions cannot be separated between the old and parallelly built new road for category *newroad* the length after intervention is doubled to account for both road stretches (Table 1). The year of construction and WVC for that period for each road section has been removed from the analysis to avoid skewed data during the construction period.

2.2.3 WVC rates

WVC rates (r) are expressed as collision frequencies per million vehicle-kilometers per year to control for differences in section length and traffic volume:

$$r = \frac{\text{number of WVC}}{\text{ADT} \times 365 \times \text{length (km)} / 10^6}$$

where ADT is the average daily traffic count provided by the NVDB, and r was calculated separately for test and control roads, and for the pre- and post-fencing periods.

The change in WVC rate attributable to fencing was calculated for each road as a log response ratio (LRR; (Hedges, Gurevitch & Curtis 1999):

$$\text{LRR} = \ln \left(\frac{r^T \text{after} / r^T \text{before}}{r^C \text{after} / r^C \text{before}} \right)$$

where T = test (fenced) and C = control (unfenced) road.

Negative LRR values indicate that collision rates decrease.

Relative change WVC rates can be expressed as:

$$\% \Delta = 100 \times (1 - \exp(\text{LRR})),$$

representing the percentage reduction in WVC compared with the background trend.

Each road's LRR was accompanied by a sampling variance

$$\text{Var}(\text{LRR}) = \frac{1}{WVC^T_{\text{after}}} + \frac{1}{WVC^T_{\text{before}}} + \frac{1}{WVC^C_{\text{after}}} + \frac{1}{WVC^C_{\text{before}}}$$

The inverse of this variance was used as an analysis weight

$$w_i = 1/\text{Var}(\text{LRR}_i),$$

so that roads with more observations contributed proportionally more to the regression. This compensated for the differences in the number of years with data before and after mitigation and the total number of accidents reported across the 30 road sections.

2.2.4 Fencing attribute effectiveness

Fence attribute effectiveness was calculated as effectiveness per kilometre to account for differences of number of attributes and length for each section.

For each model:

$$E(x) = e^{-\beta_{\text{open}}x}$$

where $E(x)$ is the *remaining fence effectiveness* (fraction of functional length per km) given an opening density (x).

The “effective length loss” per km of fence is then calculated as:

$$L_{\text{loss}} = (1 - E(1)) \times 1000$$

2.2.5 Statistical analysis

Analyses were performed in JMP Pro 18; JMP Student Edition 18 (SAS Institute Inc.), first a mean log response ratio (LRR) test across all roads differed from zero, indicating no deviation from the general trend in WVC rates, using a weighted fixed-effect meta-analytic test (inverse-variance weighting). A Wilcoxon signed-rank test to verify robustness against deviations from normality was applied. A significantly negative mean LRR result indicates an overall reduction in WVC frequencies not related to background temporal trends.

Prior to model fitting, all predictor variables were examined for multicollinearity following Zuur, Ieno and Elphick (2010) and Dormann et al. (2013). Variance inflation factors (VIFs) were computed, and variables with VIF values exceeding 5 were excluded, reflecting acceptable collinearity thresholds. In cases where predictors were correlated, only the variable with the strongest correlation with the response variable (LRR) was used to ensure model stability. A One way analysis of variance (ANOVA) was used to compare and determine the relation between test road types (*new road* and *upgrade*).

To identify the most parsimonious combination of variables explaining LRR variation, a normal error distribution was assumed. An information-theoretic approach for model selection was used in a weighted ordinary least squares (OLS) framework using the Akaike Information Criterion corrected for small sample size (AICc; Burnham & Anderson 2002). Because the precision of LRR estimates varied among sites due to differences in WVC frequencies and monitoring duration, models were weighted by the inverse of the variance of each LRR value (*Preci.weight*), giving greater influence to road sections with higher precision. Predictor variables included mitigation type (*upgrade* or *new road*) and all fencing attributes. Due to limited sample size ($n = 30$ road sections), at most three predictors were entered simultaneously to reduce the risk of overfitting. The final model was obtained when the addition or removal of further predictors no longer improved AICc. The resulting coefficients and standard errors were used for all interpretations.

3. Result

3.1 Fencing analysis

A total of 29 783 WVC were analysed along all test roads ($n = 30$) over the period of 2013 to 2024 (Figure 2, Appendix A), For test roads 2 582 WVC were recorded before fencing or reconstruction and 1 920 WVC were recorded after and on the corresponding control roads 10 542 WVC occurred before and 14 739 WVC after fencing or new road upgrade. The majority of collisions ($>99\%$) along test roads involving ungulates were dominated by roe deer ($>65\%$).

For test and control road sections the results show that collision frequencies on the test roads generally decreased after fencing while for the surrounding control roads collision generally increased. All test roads ($n = 30$) were included in the analysis and the frequency of WVC per kilometre driven is presented within a range of 0 to 3.5. A one-way ANOVA indicated a significant difference among road section categories ($F = 4.36$, $DF = 116$, $p = 0.006$; Figure 2). A pairwise comparison using a Student's t-test showed a significant difference between test-after and control-after ($t = 1.98$, $p = 0.0005$) and between test-before and test-after sections ($t = 1.98$, $p = 0.022$). No statistically significant difference was observed between test-before and control-before ($t = 1.98$, $p = 0.852$).

A pooled two-sample t-test showed no difference between test and control sections prior to fencing ($t = 0.15$, $df = 58$, $p = 0.879$). In contrast, after fencing was implemented, test sections differed significantly from control sections ($t = 5.00$, $df = 58$, $p = <0.005$)

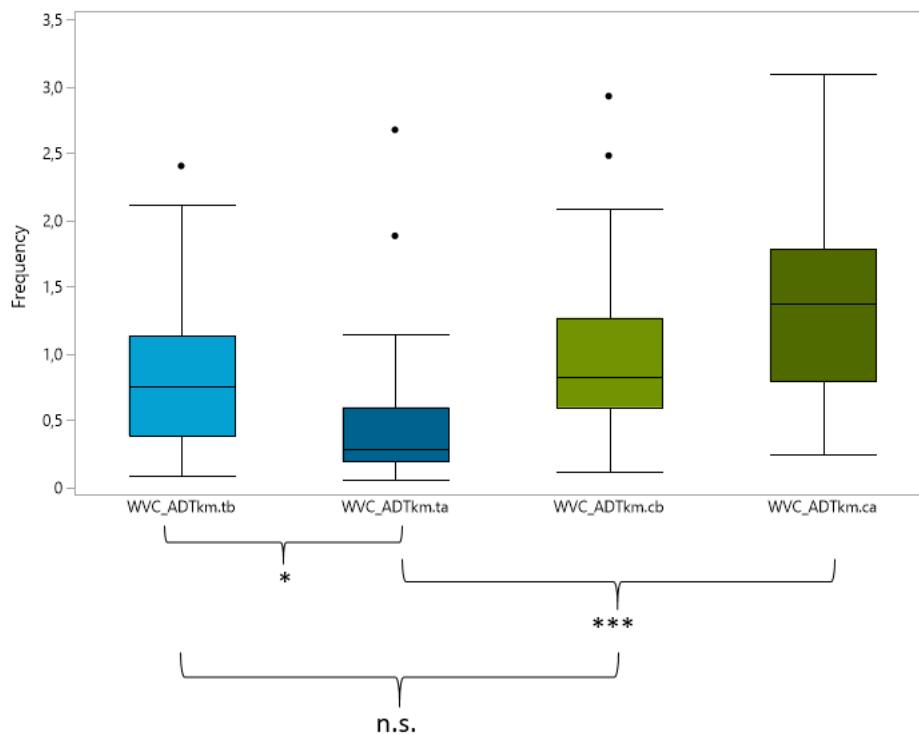


Figure 2. Data chart with the frequency of WVC per vehicle per kilometre on the Y-axis and frequency of WVC per kilometre driven for the different test roads and periods on the X-axis visualised by boxplots with line representing medians and outliers as black dots. The category sections are defined as following: test before (tb), test after (ta), control before (cb) and control after (ca). Data from 30 road sections in Sweden during 2013–2024. Stars indicate significance levels.

The efficiency% for the test roads is generally positive, meaning accident decrease on almost all roads except Road_ID 25 where the %efficiency is -1 % (Figure 3). Looking at the mean %effect for WVC on the test roads it is 62 %. The highest %efficiency is 89 %. Confidence interval based on the uncertainty of LRR sampling error, the WWV/ADT were calculated per million vehicle kilometres (Appendix B).

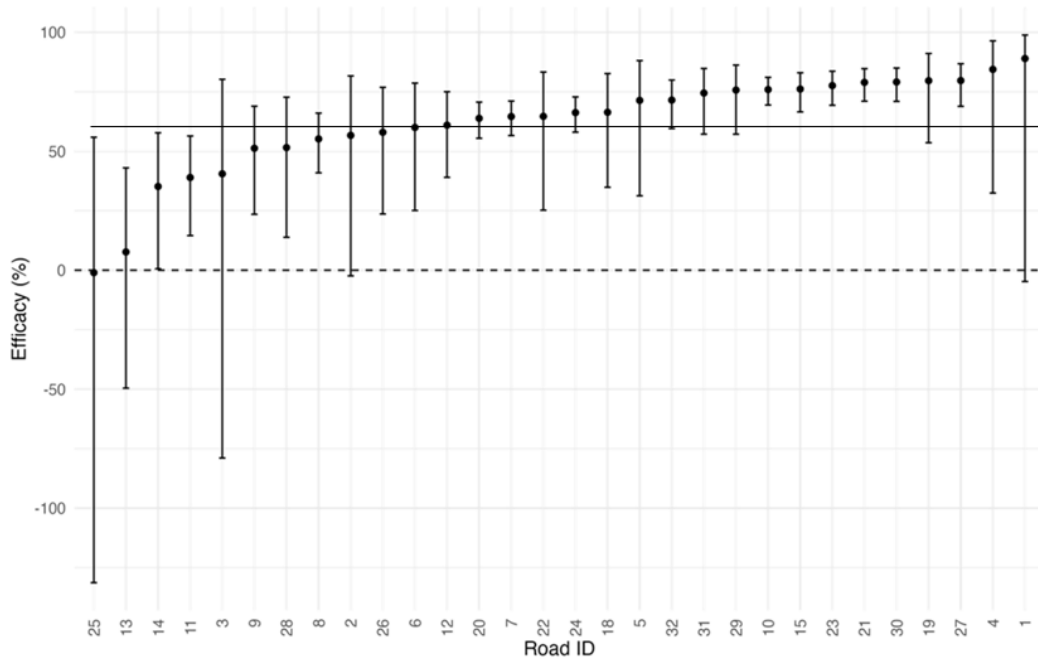


Figure 3. Reduction results of WVC in efficiency percentage ranked in increasing order, with confidence intervals for each section and a solid black line representing mean value (62 %). Data from 30 road sections in Sweden during 2013–2024.

Comparing *new roads* ($n = 11$) and *upgraded roads* ($n = 19$) the results primarily show negative trends which represents a decrease in WVC on test road sections. The difference between road categories was statistically significant ($F = 2.90$, $df = 29$, $p = 0.049$; Figure 4). These negative trends indicate the reduction in WVC is generally more pronounced for the *new road* sections, while the upgraded road sections show less effectiveness.

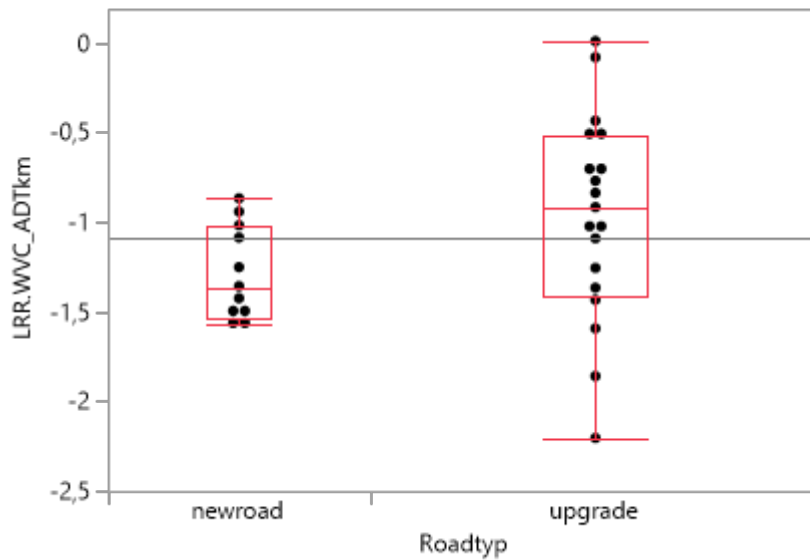


Figure 4. Log Response Ratio (LRR) of WVC of a weighted stepwise fit model ANOVA in relation to the different road categories, test roads are represented by the black dots, the overall mean for road type by the grey line and the confidence interval and group mean is represented by the red boxplots. Data from 30 road sections in Sweden during 2013–2024.

3.2 Fence attributes

Fence attributes were calculated per million vehicle kilometres.

Already when studying univariate correlations, only the density of open connections (Conn.open) was statistically significant ($P < 0.0001$) (Table 3).

Table 3. Univariate regression specifics for the different fence attributes.

Predictor variable	Mean	Standard deviation	Max	Sum of squares	F Ratio	P-value
Fenceend.open	0,28	0,33	1,37	3,69	1,05	0,31
Conn.open	0,54	0,73	2,98	47,40	24,51	>0,0001
Conn.gate	0,86	1,05	4,45	8,75	2,64	0,11
Conn.grid	0,37	0,69	3,06	3,82	1,09	0,30
Door.ped	1,30	1,35	4,66	6,78	2,00	0,16
Jump.out	0,25	0,30	1,12	1,97	0,55	0,46
Isolator	0,36	0,48	1,69	5,77	1,68	0,20
Passages	0,29	0,33	1,27	0,00	0,00	0,97
Bridge (road)	0,33	0,30	1,16	0,09	0,02	0,87
Interchange	0,08	0,15	0,69	0,00	0,00	0,97
Predictor variable (categorical)						
Intervention	upgrade, N=19	newbuilt, N=11				

Stepwise AIC model selection kept three predictors Conn.open, Conn.gate and Conn.grid. The lowest AICc was obtained by model 1 containing only Conn.open and Conn.gate (Tabel 4), while adding Conn.grid did not improve the outcome substantially ($\Delta AICc < 3.4$).

Table 4. Tabel of the four best OLS fit models with estimate, SE, F, SS, P-value and AICc of attributes included, where model 1 is the best overall with AICc of 106.97.

Model 0	Estimate	SE	F	SS	P-value
AICc:110,16					
Intercept	- 1,28	0,06	0	0	<0,0001
conn.open	0,42	0,08	24,5	47,4	<0,0001
Model 1	Estimate	SE	F	SS	P-value
AICc: 106,97					
Intercept	- 1,24	0,06	0	0	<0,0001
Conn.open	0,66	0,13	32,99	51,03	<0,0001
Conn.gate	- 0,23	0,10	8	12.38	0,0242
Model 2	Estimate	SE	F	SS	P-value
AICc: 108,11					
Intercept	- 1,21	0,07	0	0	<0,0001
Conn.open	0,52	0,09	56,4	34,1	<0,0001
Conn.gategrid	- 0,10	0,05	5,7	9,43	0,041
Model 3	Estimate	SE	F	SS	P-value
AICc: 109,38					
Intercept	- 1,22	0,07	0	0	<0,0001
Conn.open	0,63	0,13	28,39	44,88	<0,0001
Conn.gate	- 0,21	0,10	5,96	9,42	0,0217
Conn.grid	- 0,05	0,07	0,42	0,66	0,5219

Upgraded road sections contained more open road connections on average than new road sections (ANOVA F-ratio = 6.12, DF = 28, P = 0.019) (Figure 5).

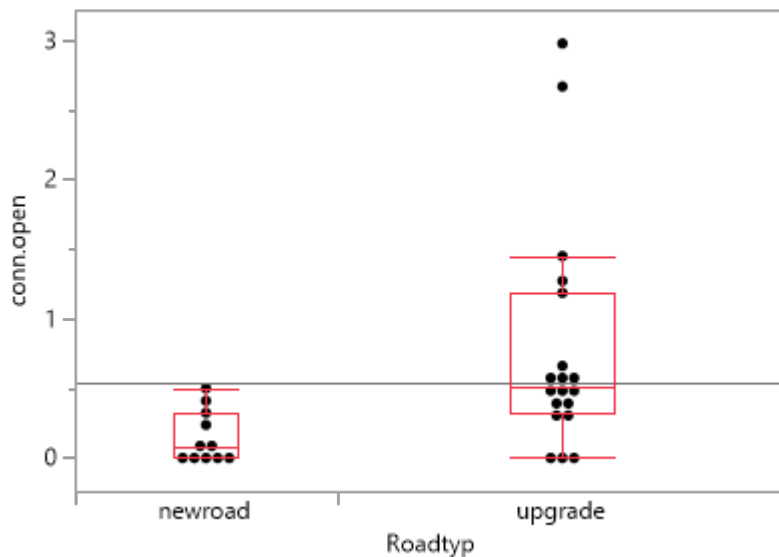


Figure 5. The frequency of open connections per kilometre in relation to the different road categories. Test roads are represented by black dots, the overall mean for road type by the grey line and the confidence interval and group mean is represented by the red boxplots. Results from a weighted stepwise fit model ANOVA. Data from 30 road sections in Sweden 2016–2021.

Using the coefficient for fence openings (β_0 , Table 5), the functional performance of a fenced road segment can be expressed as ‘effective fenced length’. Mitigation effect declines exponentially in relation to the density of openings: $E(x)=e^{(-\beta)}$. One open connection/km about halves the fence efficiency and two open connections/km reduce it to about one quarter. For the models that fit the data almost equally well, one opening per kilometre leaves between 0.52 to 0.66 km of so considered functional fence (Tabel 5).

Table 5. Tabel of efficiency loss from the coefficient for the four best OLS models, calculated as described in the main text (Section 3.2).

Model	0	1	2	3
β (Conn.open)	0.42	0.66	0.52	0.63
95 % CI(β)	[0.23–0.60]	[0.41–0.91]	[0.34–0.70]	[0.37–0.89]
Effect retained (E(1))	$e^{-0.42} = 0.66$	$e^{-0.66} = 0.52$	$e^{-0.52} = 0.59$	$e^{-0.63} = 0.53$
Effect lost (%)	34%	48%	41%	47%
Effective length (m/km)	660 m	520 m	590 m	530 m
Effective loss (m/km)	210–450	330–600	290–500	310–590

4. Discussion

This thesis addressed two research questions. 1) How strong is the mitigating effect of fencing systems on wildlife-vehicle collisions? 2) Which fencing attributes affect the reduction of wildlife accidents at fenced road sections? The results show that WVC in relation to fencing on average decrease with a mean of 62 %. However, reduction in collisions varied from -1 % to 89 % and uncertainty intervals are large (Figure 3). Differences in efficacy were strongly related to the occurrence of open road connections ($P < 0.0001$).

The percentage of WVC decrease of course varies between sections, two have a decrease more than 80% while one section even shows an increase in collisions. An explanation for this could be landscape factors in combination with damaged or faulty fencing construction. Factors such as where the fence and crossing structures are placed in the landscape impacts whether wildlife is likely to continue trying to cross the road section. For example, a fence or crossing connecting where landscape features create an obstacle or offer no protection, such as forest cover, are less appealing (Huijser & Begley 2022; Huijser M P et al. 2016).

However, considering that the main species in the study is roe deer which have an assumed accident reduction of 55 % (Seiler et al. 2016; Trafikverket 2012) the Swedish Transport Administration's assumed reduction for roe deer could be reached if a study where to look at all species individually. Still, getting reduction rates up to 80 % or more would be better and possible for all WVC with properly designed fencing structures (Clevenger, Chruszcz & Gunson 2001; Rytwinski et al. 2016). Like this study has shown, open connections are the main shortcoming (Tabel 3). Improving the design of connecting roads by adding other features beyond fence extensions along the secondary road should improve this issue.

Another factor could be fencing length, as studies have showed that shorter fence sections (<5km) generally have a lower reduction rate, around 53%, than longer fenced sections (>5km), around 84%. The lower reduction of shorter fence sections can sometimes be attributed to a stronger fence-end effect (Clevenger, Chruszcz & Gunson 2001; Huijser et al. 2016). Figure 2 illustrates that WVC decreased along the test section following implementation of fencing measures while collisions increased in the control sections, i.e., the surrounding road networks and landscape. Since the difference in WVC frequencies in the control roads before and after fencing of the test roads was not statistically significant, the results indicate that the observed increase in WVC in this study is more likely related to increases in traffic or wildlife populations (Seiler et al. 2019; Hothorn et

al. 2015; Beckmann et al. 2010; Langbein et al. 2010), rather than collisions having been shifted from the fenced test roads to surrounding control roads (MacDougall et al. 2024; Kučas & Balčiauskas 2021). WVC frequencies before fencing did not differ significantly between the control roads and the rest roads, however they deviated significantly after fencing (Figure 2).

Out of the examined attributes the only attribute showing a statistical significance in relation to the occurrence of WVC were open connecting roads ($p < 0.0001$). Also gated connections have some effect in relation to connecting roads. Having unprotected openings makes it easy for wildlife to enter the road. The finding that secured gates are important further supports the conclusion that properly closed and protected fence openings are essential for making fencing effective in reducing WVC.

Having more than 2 open connections per kilometre fence would in theory neutralise the protective effect of the wildlife fence. Coefficient for open connections ranged between 0.42 (univariate model) and 0.66 (full model with gates and grids), corresponding to a decrease in fence efficiency between 66 % to 52 % per open connection/km. Another aspect to the loss of fence effects could be holes, gaps and other openings caused by damaged fence sections. Since these damages are not permanent feature and can be hard to detect, therefore could not be included in this study. However, further studies using different methods to analyse road sections would give an idea about other problem areas of fencing as well as additional explanatory power and patterns for both open connections and other openings, such as in a recent study by Sedoník, Andrášik and Bíl (2023) where the STKDE+ tool was used to locate fence gaps.

Considering the continuing increase of both traffic volumes and wildlife populations (Seiler et al. 2019; Hothorn et al. 2015; Beckmann et al. 2010; Langbein et al. 2010) road administrations will continue to require securing and maintaining fencing and crossing structures. For future projects it is important to continue studying both fence components as well as general fence placement in order to continue evaluating and gain new knowledge of wildlife fencing.

4.1 Conclusion

This study demonstrates that open connections in wildlife fencing are the main reason for a loss in fence effectiveness. To improve the protective fencing efficiency, one important measure is to secure open connections from wildlife. A reduction in WVC of almost 62 % is substantial. However, open connections remain a significant weakness and should be examined further to determine how they can be secure to further reduce collisions. Applying these findings in the

Transport Administrations work could improve wildlife fencing infrastructure, contributing to reduced WVC rates and benefit wildlife management.

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Map material

GSD-Översiktskartan (2021). Vektor. Lantmäteriet.

Populärvetenskaplig sammanfattning

Bilister, yrkeschaufförer, och pendlare - många reser dagligen utmed vägnätet på Sveriges större riksvägar. Trots åtgärder som viltstängsel kanske du ändå någon gång haft otur att ha hamnat i en viltolycka längs dessa vägar? Syftet med denna masteruppsats är att utreda hur effektivt de viltstängsel som sitter längs våra större 2+1 vägar är samt vilka stängselattribut som påverkar ett viltstängsels effektivitet att förhindra viltolyckor.

Det togs ut 30 lämpliga vägsträckor runt om i Sverige, för att studera effekten av stängsel. Jag använde en Före-Efter-Kontroll-Påverkan (BACI) metod där *"uppgraderade-vägar"* utgör 19 av dessa 30 sträckor. Dessa har blivit uppgraderade från ostängslade vägar till 2+1 vägar med viltstängsel. Medan resterande 11 sträckor består av *"nya-vägar"* vilket syftar till vägar där en ny 2+1 väg med viltstängsel byggts parallellt till den gamla och tar över trafikflödet från den ursprungliga vägen. Kringliggande vägnät inom en 6 km buffert användes som kontroll mot teststräckorna. Jag jämförde olyckor för alla studiesträckorna sinsemellan och mot kringliggande vägnät för att kunna följa viltolyckornas utveckling. För att utröna ifall någon av stängseldetaljerna hade någon inverkan på en ökning eller minskning av viltolyckor utfördes även fjärranalyser och fältbesök för att kartlägga stängseldetaljerna.

Resultatet från studien visade att generellt minskar viltolyckorna längs stängslade vägsträckor med i genomsnitt nästan 62 %. Olycksminskningen på nya-vägar visar sig vara mer effektiv än för många uppgraderade-vägar. Den enda stängseldetalj som signifikant ökade viltolycksfrekvensen var s.k. *"öppna anslutningar"*, en öppning i stängslet till sekundära vägar där stängseltrattar löper en bit längs den anslutande vägbanan, men där i övrigt hinder saknas hinder som förhindrar från att ta sig ut på vägbanan. Denna stängseldetalj visade att stängslets effektivitet minskade med hälften så att en sträcka med ett 1 km långt stängsel med en *öppen anslutning* skyddar ungefär lika lite som 500 meter stängsel utan någon *öppen anslutning*. Antalet *öppna anslutningar* per kilometer var generellt färre för nya-vägar än för uppgraderade-vägar. Detta resultat pekar på att osäkrade stängselanslutningar är den största faktorn för att effektivisera många viltstängsel och minska antalet viltolyckor, en viktig faktor att beakta vid om- eller nybyggnation av vägar som ska utrustas med viltstängsel.

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Appendix

Table A. Numbers of WVC described by WVC.Ntb - Sum of WVC on test roads before, WVC.Nta - Sum of WVC on test roads after, WVC.Ncb - Sum of WVC on control roads before, WVC.Nca - Sum of WVC on control roads after.

Road_ID	years.before	years.after	WVC.Ntb	WVC.Nta	WVC.Ncb	WVC.Nca
1	6	5	4	1	21	47
2	8	3	29	7	179	105
3	3	8	6	23	11	68
4	7	4	21	2	219	129
5	6	6	10	11	168	346
6	8	3	72	12	561	296
7	6	5	347	160	1114	1313
8	6	5	171	96	518	586
9	8	3	168	36	163	77
10	4	8	139	197	529	1279
11	5	6	78	99	226	463
12	3	9	27	181	126	776
13	8	3	55	27	502	296
14	4	7	40	56	306	661
15	6	5	176	45	1034	1071
18	5	6	24	16	152	311
19	3	8	10	18	51	462
20	7	5	250	191	979	942
21	7	5	155	64	476	425
22	3	8	11	20	230	1012
23	5	7	86	101	338	764
24	6	6	210	214	632	765
25	4	7	8	27	79	252
26	6	6	22	26	198	263
27	8	4	69	38	440	330
28	8	3	74	15	568	240
29	6	5	69	17	189	189
30	4	8	86	106	189	515
31	4	8	25	58	100	415
32	5	6	140	56	244	341
mean	5,63	5,73	86,07	64	351,4	491,3
stdev	1,69	1,80	84,28	64,33	293,40	355,14
MAX	8	9	347	214	1114	1313
SUM	169	172	2582	1920	10542	14739
median			69	37	228	380,5
Total WVC test						
			all	4 502		
			roe deer	2 947		

Table B. WVC rates in relation to kilometre, ADT, period and relevant attributes for each road calculated in length, log response ration, %effect and precision weight.

Road_ID	WVC /ADT*km (test)		WVC /ADT*km (control)		LRR.WVC	%effct	Preci. weight	
	before	after	before	after				
1	0,199	0,055	0,113	0,284	-	2,204	88,969	0,758
2	0,121	0,070	0,273	0,363	-	0,836	56,673	5,196
3	0,179	0,233	0,306	0,670	-	0,520	40,519	3,167
4	0,438	0,070	0,233	0,239	-	1,859	84,414	1,786
5	0,088	0,054	0,212	0,458	-	1,251	71,377	5,006
6	0,403	0,216	0,671	0,899	-	0,916	59,994	9,767
7	0,719	0,349	1,215	1,666	-	1,038	64,584	92,669
8	1,080	0,661	1,563	2,136	-	0,803	55,197	50,247
9	1,221	0,727	0,787	0,962	-	0,718	51,251	18,921
10	0,844	0,230	1,243	1,409	-	1,424	75,932	66,923
11	0,607	0,571	1,195	1,841	-	0,494	38,968	33,891
12	0,443	0,346	0,799	1,599	-	0,941	60,968	19,310
13	0,818	1,148	1,162	1,767	-	0,080	7,668	16,505
14	0,800	0,580	0,403	0,451	-	0,434	35,202	20,992
15	1,448	0,387	1,096	1,227	-	1,433	76,140	33,552
18	0,363	0,200	0,558	0,914	-	1,090	66,381	8,775
19	1,073	0,782	0,751	2,690	-	1,593	79,660	5,639
20	0,609	0,289	1,226	1,609	-	1,017	63,835	88,350
21	1,667	0,412	1,365	1,602	-	1,558	78,950	37,693
22	0,400	0,228	0,842	1,360	-	1,040	64,668	6,838
23	0,854	0,288	0,681	1,026	-	1,496	77,602	38,765
24	2,406	1,009	2,082	2,586	-	1,086	66,235	81,141
25	1,107	1,883	1,838	3,094		0,010	- 1,032	5,597
26	0,420	0,224	1,128	1,432	-	0,867	57,964	10,779
27	1,606	0,164	2,928	1,394	-	1,541	78,584	21,687
28	0,238	0,130	0,722	0,810	-	0,724	51,522	11,613
29	1,014	0,281	0,649	0,739	-	1,415	75,718	11,919
30	2,117	0,582	1,413	1,860	-	1,566	79,113	35,342
31	0,316	0,148	0,618	1,135	-	1,365	74,469	14,357
32	8,321	2,677	2,483	2,803	-	1,255	71,506	31,220
							%effct	
Upgrade							Min	- 1,032
Newroad							Max	88,969
							Mean	61,768

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