Crash risk on entrance versus exit zones of road bridges in Norway

Abstract

Using data from the national register of police-reported crashes and from the bridge register of the Norwegian Public Roads Administration, we estimated rates of single-vehicle crashes on road sections adjacent to road bridges and on different sections of the bridges. Data included all single-vehicle personal injury crashes occurring on or close to road bridges in Norway between 2010 and 2016, a total of 219 crashes. All bridges on state and county roads were included. Crash rate was found to be highest in the approach zone of short bridges (last 50 m before bridge) and lowest in the middle of long bridges. On bridges shorter than about 100 m, crash rate was higher in the first than in the last bridge zone. Total crash rate on bridges was close to the figure for the total road network. However, for the approach to short bridges, crash rate was significantly higher than for the total road network, and for the middle part of long bridges it was significantly lower. A supplementary analysis of in-depth data from 31 fatal crashes including both single-vehicle and multiple-vehicle crashes supported the results from the main analysis. A higher proportion of fatal crashes occurred on approaching or entering a bridge than when leaving the bridge, as seen from the direction of travel of the at-fault vehicle. Concerning countermeasures against bridge accidents, particular attention should be payed to the approach zone and to the design of barriers.

Keywords: Road bridge; Crash rate; Bridge zones

1 Introduction

Road bridges may differ from adjacent road sections in several respects possibly related to crash risk, such as road width, presence of barriers, etc. Pavement type and quality may be different, possibly influencing friction conditions. There may be humps or bumps related to joints between bridge elements. In addition, some bridges have sharp curves at one or both ends, e.g. where the road crosses a narrow valley. Consequently, a relevant question is whether crash risk is higher on and close to road bridges than on the road network in general. If so, there may be a need of improved measures to alleviate the consequences of bridge-related risk factors. A related question is whether crash risk is higher on entering a bridge than on exiting from the bridge. It may be hypothesised that approaching and entering a bridge is associated with a higher likelihood of an expectancy violation (Alexander and Lunenfeld, 1986), and consequently an increased risk of losing control, compared to exiting from the bridge.

The purpose of the present study is two-fold. First, we wanted to investigate whether crash risk differs between vehicles approaching and leaving a bridge. Preliminary analyses (Sagberg and Langeland, 2017) showed crash risk to be higher at the end zones of bridges (including 50 m before and after the bridge) compared to the middle zone. In the present analyses, we differentiate between vehicles entering and leaving the bridge.

Second, we compare crash risk on the various bridge zones with risk on the remainder road network. The risk of personal injury crashes on the total Norwegian road network has been estimated at 0.11 crashes per million vehicle kilometres for the years 2010-2015 (Elvik, 2017). It is consequently interesting to see whether crash risk on each bridge zone deviates significantly from this value.

We have not found any previous studies comparing crash risk of bridges to that of roads in general. However, there are some studies of specific risk factors related to bridges.

A previous analysis of Norwegian road bridges (Elvik, Sagberg, and Langeland, 2019) using binomial regression models, found crash risk to be lower on long than on short bridges, and lower on recently built compared to older bridges. Furthermore, annual average daily traffic was shown to be the strongest predictor of crash number.

Several studies point out potential safety problems related to pavement quality, such as humps and irregularities related to joints between bridge elements and between bridge and firm ground (e.g., Mahlo and Martin, 2015; Akl et al., 2017). Cracks resulting from traffic load, vibration or other sources of wear and tear are also pointed out as possible risk factors (Kamaitis, 2006; 2012; Li et al., 2014; 2016; Liu et al., 2017). Di Mascio et al. (2017) have analyzed how humps related to expansion joints on bridges in curves influence heavy vehicles. They find that the humps may cause reduced contact between the wheels and the road surface and result in loss of control due to lateral acceleration.

Side winds may also be a possible safety problem on bridges, as pointed out in some studies (Zhou and Chen, 2015; Kozmar et al., 2015; Alonso-Estebanez et al., 2016; Ma et al., 2016), particularly on bridges with long spans, where the road surface is high above the ground or water level.

The relationship between crash risk and bridge characteristics was investigated in a database study of bridges in Alabama, USA (Mehta et al., 2014). They estimated "safety performance functions" for both crashes in general and single-vehicle crashes on long bridges. They found that the three most important variables for predicting both categories of crashes are average annual daily traffic, bridge length, and share of heavy vehicles.

Guardrails is an important issue concerning crashes on bridges and in the approach zone before a bridge. Tomasch et al. (2011) analyzed a German database and investigated fatal crashes where a vehicle ran off the road before a bridge and ended outside the roadside guardrail. On the basis of the crash analyses they developed guidelines for guardrail length before bridges.

The importance of guardrails was also shown in a US study of fatality risk among crash-involved motorcyclists (Nunn, 2011). Crashes against guardrail, bridge or median was associated with a 12% fatality rate.

In the present study, we focus on single-vehicle crashes involving a motorized vehicle. We selected single-vehicle crashes in order to estimate rate of crashes occurring on various zones of the bridge with reference to direction of travel; i.e., differentiating between start and end of the bridge. For crashes between two vehicles at one end of the bridge, the site would have been the first zone of the bridge for one vehicle and the last zone for the other, and therefore start and end zones cannot be differentiated for multi-vehicle crashes. Analysing single-vehicle crashes enables us to investigate whether entering a bridge is associated with a different risk from leaving the bridge. The purpose of the study is to see whether crash risk differs between the transition zone onto the bridge, various distance zones on the bridge, and the zone of transition from the bridge to firm ground. A further purpose is to compare crash rates for the various bridge zones to comparable data for the remainder of the road network.

2 Method

2.1 Data sources

We selected data on single-vehicle crashes from the national register of police-reported road crashes, administered by the Norwegian Public Roads Administration (NPRA), for the years 2010-2016. The register contains all personal injury crashes on roads in Norway. The data file contained information on exact location of the crash, with reference to road number, road section number, and distance in metres along the section. Coordinates recorded in the data file are based on police reports containing both map coordinates and distance in metres from fixed objects. However, since crash location is defined by point of contact with other road user or object, or by departure from roadway, the location of any initiating event leading to a crash may not be known exactly. Despite this limitation, we consider location of the crash itself as sufficient for comparing risks across bridge zones.

From the database we selected all single-vehicle crashes that had occurred on a bridge or within 50 metres before or after a bridge. This amounted to 373 crashes for the years 2010-2016. Direction of travel was specified for 219 out of the 373 crashes. Our analyses consequently included the 219 crashes with available data on direction of travel.

For fatal crashes we also had access to reports from in-depth crash investigations by the NPRA, which were used for supplementary analyses.

2.2 Matching crashes to bridge zones

Start and end coordinates for all road bridges with length above 10 metres were extracted from the NPRA bridge register. This register also contained data on annual average daily traffic (AADT) for each bridge.

Bridge crashes were identified by matching coordinates for crashes and for the start and end of the bridges. The following zones were defined (see Figure 1):

1. Last 50 m before start of bridge

2. First part of bridge (50 m for bridges above 100 m, and half the bridge length for shorter bridges).

3. From 50 m to 150 m onto the bridge (less for bridges shorter than 300 m)

4. From 150 m onto the bridge to 150 m before the end (for bridges above 300 m)

5. From 150 m (less for bridges shorter than 300 m) to 50 m before end of bridge

6. Last part of bridge (50 m for bridges above 100, and half the bridge length for shorter bridges).

7. First 50 m after end of bridge.

This definition of bridge zones was adopted from an older study of crash risk on Norwegian road bridges (Ranes, 1999).

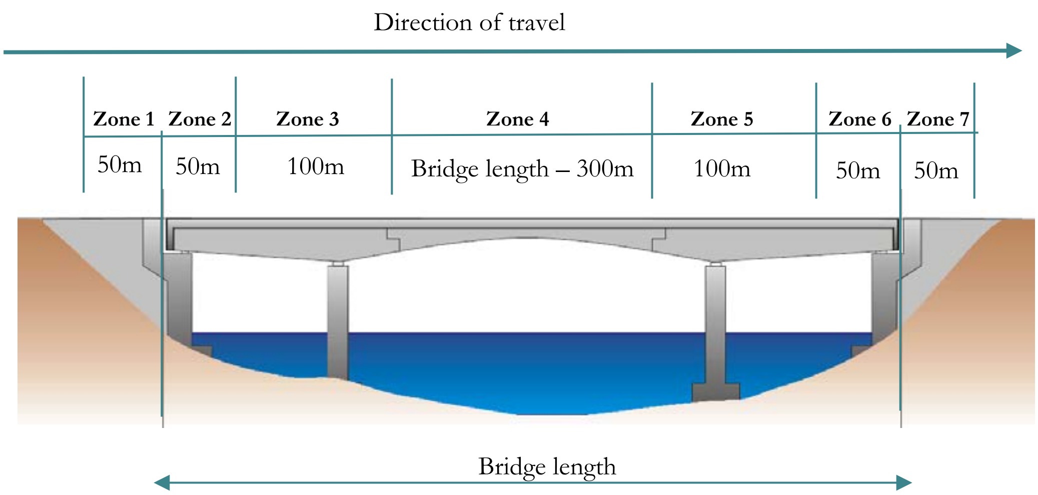

Figure 1. Bridge zones. Example shows zones for bridges longer than 300 m. (Adapted from Ranes, 1999).

Based on number of crashes, AADT, and zone lengths for each bridge, we computed crash rate for each zone and for the total length of the bridge (including 50 m before and after).

3 Results

3.1 Rate of personal injury crashes

Table 1 shows crash rates for each bridge zone, including 50 metres before and after the bridge. We see that crash rates are higher at the approach and exit zones of the bridges compared to the middle zones, and they tend to be higher at the entrance than at the exit zones. Furthermore, the zones just before and after the bridge (Zones 1 and 7) have higher crash rates than the end zones on the bridge (Zones 2 and 6). Concerning bridge length, crash rate is highest for the shortest bridges; this is apparent both for the approach (Zones 1 and 2) and exit zones (Zones 6 and 7). For bridges shorter than 50 metres, the total crash rate of 0,033 crashes per million km is two to three times higher than for longer bridges.

A table of vehicle kilometres by bridge length and bridge zone, which was used for computing crash rates in Table 1, is shown in Appendix 2.

We made pairwise comparisons between the crash rates in Table 1 to see if there were significant associations between crash risk and bridge length or bridge zone. For assessing statistical significance, we used a chi-square formula recommended by Brühning and Völker (1982). We refer to Appendix 1 for a description of the test of significance and an example.

For all bridges combined, the crash rate for Zone 1 (0.033) was significantly higher than for Zone 2 ($p=0.001$), Zone 3 ($p=0.02$), Zone 4 ($p<0.001$), Zone 5 ($p=0.003$), and Zone 6 ($p<0.001$). The crash rate for Zone 7 was significantly higher than for Zone 2 ($p=0.03$), Zone 4 ($p<0.001$), Zone 5 ($p=0.02$), and Zone 6 ($p<0.001$).

Table 1. Single-vehicle crashes on Norwegian road bridges 2010-2016, by bridge zone and bridge length. Crashes per million vehicle kilometres. (Number of crashes in parenthesis.) For explanation of bridge zones see Figure 1.

		Bridge length (no. of bridges)				All bridges (6673)
		10 – 50 m (4943)	51 – 100 m (915)	101 – 300 m (639)	> 300 m (176)	
Bridge zone	1	0.041 (62)	0.023 (14)	0.021 (10)	0.034 (5)	0.033 (91)
	2	0.025 (10)	0.017 (7)	0.006 (3)	0.020 (3)	0.015 (23)
	3	n/a	n/a	0.019 (6)	0.010 (3)	0.015 (9)
	4	n/a	n/a	n/a	0.004 (4)	0.004 (4)
	5	n/a	n/a	0.013 (4)	0.007 (2)	0.010 (6)
	6	0.018 (7)	0.007 (3)	0.008 (4)	0.000 (0)	0.009 (14)
	7	0.032 (48)	0.013 (8)	0.025 (12)	0.027 (4)	0.026 (72)
All zones		0.033 (127)	0.015 (32)	0.015 (39)	0.010 (21)	0.021 (219)

For a more powerful comparison between risks for approaching and entering a bridge vs. leaving the bridge, we computed crash rates for zones 1 through 3 combined and for zones 5 through 7 combined. The crash rates are 0.025 for the first three zones and 0.019 for the last three zones. The difference between the two rates is statistically significant ($p=0.03$).

For the longest bridges (over 300 m), the middle zone (Zone 4) had significantly lower crash rate than both the approach ($p<0.001$) and exit ($p=0.002$) zones. The lower crash rate in the middle zone of long bridges explains why total crash rate decreases with bridge length, from 0.033 for bridges shorter than 50 m to 0.010 for bridges longer than 300 m.

3.1.1 Crash circumstances by bridge zone

We investigated whether crash characteristics varied across bridge zones, to see if there were systematic differences between crashes occurring in the approach and starting zones on one hand and crashes in the middle or end and exit zones on the other hand. Results of these analyses are summarized in Table 2. Due to few crashes in Zones 3, 4, and 5 (as shown in Table 1) we have collapsed data across those three zones.

*Table 2. Crash circumstances by bridge zone. Percent of crashes. *Significant difference between bridge zones (p<.01).*

Crash circumstance	Category	Bridge zone					
		1	2	3, 4, 5	6	7	All
Vehicle type	Moped or motorcycle	12	22	11	14	17	15
	Other vehicle	88	78	89	86	83	85
Trip purpose*	Leisure or work-related trip	26	30	26	29	53	23
	Other purpose	74	70	74	71	47	77
Crash type	Hitting barrier (guardrail, kerb)	47	39	79	50	46	49
	Other crash type	53	61	21	50	54	51
Crash severity	Killed or severely injured	11	30	11	21	18	16
	Slightly injured	89	70	89	79	82	84
Median barrier*	Yes	13	22	11	29	31	21
	No	87	78	89	71	69	79
Road covered by snow or ice	Yes	19	22	37	21	24	22
	No	81	78	63	79	76	78
Precipitation	Yes	21	26	37	43	21	24
	No	79	74	63	57	79	76
Light condition	Darkness, dusk or dawn	39	39	58	43	44	42
	Daylight	61	61	42	57	56	58
Number of crashes		91	23	19	14	72	219

For each crash condition we applied Fisher's exact probability test to see whether proportions differed significantly between bridge zones. For the presence of a median barrier we found a significant linear-by-linear association (chi square=7.86; df=1; p=0.005), implying that bridges with a median barrier had a relatively lower crash frequency in the approach zones (Zones 6 and 7), compared to bridges without a median barrier. A significant difference in the same direction was found also for leisure or work-related trips compared to other trip purposes (chi square=11.3; df=1; p<0.001).

For the other conditions listed in Table 2, there are no statistically significant overall association with bridge zone. There is however a tendency for crashes involving hitting a side barrier to be more frequent in the middle zones (chi square=8.19; p=0.083), with 79% of crashes, compared to the overall proportion of 49%.

A further comparison between approach and exit bridge zones was done by estimating the odds of a crash occurring in zones 1, 2, or 3 vs. zones 5, 6, or 7, as a function of the following variables in addition to those listed in Table 2: bridge length category, bridge width, year of construction, and speed limit. The four crashes occurring in zone 4 were omitted from this analysis. The strongest predictor variables were entered into a logistic regression model, which yielded significant odds ratios for trip purpose (OR=0.353; p<0.001) and bridge width in metres (OR=0.926; p=0.011). This model implies that crashes during leisure or work-related trips as well as crashes on wide bridges are relatively less likely to happen in the approach zones as compared to the exit zones. The model including these two variables had a Nagelkerke R^2 of 0.11. An alternative model where bridge width was substituted by presence of a median yielded very similar results, due to a substantial correlation between bridge width and presence of a median. Entering both bridge width and median did not improve the model substantially.

3.2 Fatal crashes

For fatal crashes, in-depth analyses had been carried out by crash investigation teams of the Norwegian Public Roads Administration, and we used their crash reports to identify at which bridge zone each crash had occurred. Both single-vehicle and multiple-vehicle crashes were included in this analysis, with bridge zones referring to the direction of travel of the traffic unit considered to be at fault of the crash.

We analysed reports from a total of 31 fatal crashes occurring on or close to bridges in the period 2010-2016. There were 18 single-vehicle crashes and 13 collisions between a motor vehicle and some other road user.

Apart from single-vehicle crashes, head-on collisions was the most frequent type of fatal bridge crash. Out of the 31 bridge-related fatal crashes, there were 26 off-road or head-on crashes; i.e., almost nine out of ten. For a comparison, a separate analysis of data from the national register of police-reported injury crashes showed that these crash types amounted to 38 % of bridge-related crashes when including all severities.

In 17 out of the 31 crashes, the vehicle at fault was in the approach zone to the bridge (Zone 1), compared to five crashes in the exit zone (Zone 7). The remaining nine crashes occurred after entering and before leaving the bridge. Although there are few crashes in this data set, a statistical test comparing two Poisson-distributed variables shows the difference between 17 crashes in Zone 1 and five crashes in Zone 7 to be statistically significant (p=0.008).

Additional analyses of the fatal bridge crashes have been published elsewhere (Elvik et al., 2019).

3.3 Bridges compared to remainder road network

As mentioned in the introduction, the risk of personal injury crashes on the total Norwegian road network has been estimated at 0.114 crashes per million vehicle kilometres for the years 2010-2015 (Elvik, 2017). The share of single-vehicle crashes was 29.4%, which means a risk of 0.033 crashes per million vehicle kilometres. The crash rate of 0.021 for all bridges combined (Table 1) is significantly lower than for the total network ($p<0.001$). However, the crash rate of the approach zone for all bridges combined is exactly the same as for the total network, whereas it is slightly higher for the shortest bridges.

It should be noted, though, that the share of road sections (and traffic volume) with high speed limits is higher for bridges than for the remainder road network. For example, on bridges, 29% of vehicle kilometres take place on roads with speed limit above 80 km/h, compared to 13% for the total road network. Crash risk is inversely proportional to speed limit (Elvik, 2017), which is explainable by low crash risk being one of the criteria for setting high speed limits. Consequently, the total expected crash rate for bridges, assuming the same risk as for other roads with similar speed limits, could be estimated at 0.028 crashes per million vehicle kilometres instead of the actual 0.033. This means that the difference between our crash rate estimates for bridges and for the total network is somewhat smaller than indicated above. However, the difference between the observed crash rate of 0.021 and the expected rate of 0.028 is still statistically significant ($p<0.001$).

Comparing crash rate for each bridge zone with the speed limit adjusted expected rate, we find that the crash rate of 0.041 for Zone 1 of the shortest bridges is significantly higher than the expected value ($p<0.001$). For the other combinations of bridge length and zone, crash rates are either lower or not significantly different from the expected value based on crash rate for the total road network.

4 Discussion and conclusions

This study shows clearly that the risk of bridge-related single-vehicle crashes is higher in the approach and exit zones of bridges (i.e., the 50 metres adjacent to the bridge) than on the bridge itself. It is also clear that the risk is higher in the approach zone than in the exit zone. Furthermore, on the bridge itself, crash risk is higher in the first part of the bridge than in the middle and end zones.

Since it was necessary to restrict the main analysis (including all injury severities) to single-vehicle crashes in order to differentiate between crashes at the start and end zones of the bridge, it is not obvious that the results can be generalised to at-fault vehicles in multiple-vehicle crashes. However, the separate analysis of reports from fatal crashes, although comprising relatively few crashes, supported the results from the main analysis in showing an over-representation of crashes in the approach zone also for at-fault drivers in multiple-vehicle crashes. We therefore conclude that the likelihood of being involved as at-fault party in a crash is higher when approaching or entering a bridge than when leaving the bridge.

Since the approach zone and the first part of a bridge seem to be associated with the highest crash risk, efforts to prevent bridge-related crashes should focus on those zones. The reports from fatal crashes indicate that improved side barriers could have prevented a substantial share of the crashes. Design of side barriers in the transition zone between firm land and bridge seems to be crucial. It is essential that the barriers start at a sufficiently long distance before a bridge to reduce consequences of running off the road before reaching the section with barriers, and also that the end of the barrier is constructed in a way to minimize the effects of crashing into the guardrail end.

Norwegian road bridges are probably designed, constructed and maintained according to similar principles as in other countries. Consequently, we believe the results are relevant also to non-Norwegian bridges.

The finding of a rather large difference in number of fatal crashes between approach and exit zones may indicate that the risk of serious crashes is particularly high in the approach zone. More detailed studies are needed in order to get more knowledge about the relationships between bridge characteristics and crash severity.

It is interesting that the presence of a median barrier (and/or a wide bridge) is associated with a lower share of crashes among approaching vehicles (Zones 1-3) than exiting vehicles (Zones 5-7). There is a possibility that the presence of a median has a larger preventive effect on crashes occurring upon entering a bridge compared to leaving the bridge. Another possible explanation could be road characteristics that are correlated with bridge width and median barrier, which were not included in our analyses, e.g., road curvature. Further research may throw more light on this possible explanation.

Previous results indicating that aggregated crash risk on road bridges is slightly lower than for the whole road network may lead to the erroneous conclusion that road safety on bridges is a minor issue. The present results showing that crash risk in the approach zone to bridges – particularly on the shortest bridges – is higher than for roads in general therefore makes an important contribution to a more nuanced view of road bridge safety.

A limitation of this study is that only single-vehicle crashes were included. To include multiple-vehicle crashes one would have to examine police reports from each crash in order to determine direction of travel for the at-fault vehicle, since such data were not available in the database. A related limitation is the low number of crashes, which reduces statistical power both for comparing risks across bridge zones and for investigating associations with crash types, road user categories, and other crash circumstances.

It is also a limitation that data on driver-related factors were not included in the analyses. An indication that driver-related factors could be a relevant explanation is the finding that trip purpose was related to distribution of crash risk across bridge zones. Driver-related factors in bridge crashes is another possible topic for future research.

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Appendix 1: Test of statistical significance of differences between crash rates

For pairwise comparisons of crash rates we used the following chi-square test recommended by Brühning and Völker (1982).

$\chi^2 = (U_1 \cdot B_2 - U_2 \cdot B_1)^2 / (B_1 B_2 (U_1 + U_2))$,

where

U_1 = number of crashes in dataset 1,

U_2 = number of crashes in dataset 2,

B_1 = exposure measure in dataset 1, and

B_2 = exposure measure in dataset 2.

An example: Comparing crash rates of Zones 1 and 2 for all bridges combined.

As shown in Table 1, there were 91 crashes in Zone 1 and 23 in Zone 2. Exposure (vehicle kilometres) was 4719 million in Zone 1 and 2487 million in Zone 2 (see Appendix 2). Entering these figures into the Brühning and Völker (1982) formula, we get

$\chi^2 = (91 \cdot 2487 - 23 \cdot 4719)^2 / (2487 \cdot 4719 (91 + 23)) = 10.4$.

The value of 10.4 on a chi-square distribution with one degree of freedom corresponds to a p value of 0.0013, which implies that the difference in crash rate between the two bridge zones is clearly significant.

Appendix 2. Traffic volume on Norwegian road bridges 2010-2016, by bridge length and bridge zone. Million vehicle km.

		Bridge length (no. of bridges)				All bridges (6673)
		10 – 50 m (4943)	51 – 100 m (915)	101 – 300 m (639)	> 300 m (176)	
Bridge zone	1	2539	1138	809	234	4719
	2	670	775	809	234	2487
	3	n/a	n/a	545	468	1013
	4	n/a	n/a	n/a	1504	1504
	5	n/a	n/a	545	468	1013
	6	670	775	809	234	2487
	7	2539	1138	809	234	4719
All zones		6416	3826	4325	3375	17943