Summary

Developing a model for predicting fires, crashes, and breakdowns in road tunnels

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Negative binomial regression models were developed in order to calculate predicted numbers of vehicle fires, crashes, and breakdowns as a function of traffic volume and several tunnel-related variables, such as vertical grade, speed limit, and twin- vs. single-tube tunnel. The models are meant for use in planning processes for new tunnels as well as risk analysis of existing tunnels. The model results indicate that the number of vehicle fires in tunnels increase with increasing vertical grade, especially at grades at or above 7%, and with increasing length of steep grades. The number of vehicle breakdowns is also higher in tunnels with steep grades (7% or more), than in other tunnels. Steep slopes upstream of the tunnels may contribute to fires in tunnels. However, this has not been possible to investigate in the current study. Other variables are mostly unrelated to numbers of fires and breakdowns. The number of accidents is independent of vertical grade. It is higher in twin-tube tunnels than in single-tube tunnels, higher at lower speed limits (below 80 km/t), higher in completely straight tunnels than in tunnels with slight curves, and lower in tunnels with a height of at least 4.5 meters than in other tunnels. Over time, from 2008 to 2017, the number of vehicle fires in tunnels has been about unchanged, the number of injury crashes is about halved, and for the number of serious crashes only a slight decrease has been observed.

Method and data

All models are negative binomial regression models with a variable overdispersion parameter. Models are calculated for the following dependent variables:

- ***Number of fires:*** The fire models are based on 296 fires in 1101 tunnels in 2008-2015.
- ***Number of injury accidents:*** The accident models for injury accidents are based on 1039 accidents in 1181 tunnels in 2008-2017.
- ***Number of accidents with killed or severely injured (KSI):*** KSI accident models are based on 169 accidents in 1181 tunnels in 2008-2017.
- ***Number of breakdowns:*** The breakdown models are based on 1322 breakdowns in 105 tunnels in 2016 and 2017. Models for different types of breakdowns with different types of vehicles (i.e. all/light/heavy) have been calculated as well.

Predictor variables in the models are (not all variables are included in all models):

- Length
- Traffic volume: AADT (natural logarithm)
- Proportion of long vehicles (numerical)
- Type of tunnel: Single-tube tunnel, twin-tube tunnel, ramp (dummy variables)
- Vertical grade: Different sets of variables: Length with steep grade (numerical); maximum vertical grade (numerical); maximum vertical grade (two dummy variables); maximum vertical grade (seven dummy variables)
- Speed limit (dummy variables)
- Minimum curve radius (dummy variables)

- Tunnel height (above vs. below 4.5 meters)
- Tunnel ramp (yes/no)
- Year: 2008-2017 (one dummy variable for each year)
- Camera Monitoring (ITV) and Automatic Incident Detection (AID) (two dummy variables; only in accident models).

For **fires** and **accidents** eight models were calculated (each). The modes differ with respect to the predictor variable for vertical grade (four different types). Each of these four models was calculated with and without predictors for horizontal curves and height (some tunnels lack information about curves and height). ITV/AID is not included in the accident and fire models.

The models for **breakdowns** contain all predictor variables, including ITV/AID, but not curves, height, ramp and year. Only one model has been calculated for each type of breakdown.

Overview of models and Excel-tool

As an attachment to this report, a tool has been developed in MS Excel for calculating predicted numbers of fires, injury accidents, and KSI accidents as a function of the tunnel characteristics listed above. The calculation tool uses (optionally) one of two models:

- One model (model 1) includes steep gradient length as a predictor, as well as curves and height.
- The second model (model 7) includes two dummy variables for steep gradient; curves and height are omitted.

Other predictor variables are as described above (traffic volume, proportion of long vehicles, number of tubes, speed limit,…). The effects are tested for statistical significance ($p < .05$). The predictor variables in the models are chosen regardless of significance. Only the variables describing the type of tunnel were omitted from the models because they led to partly counterintuitive predictions.

Tables S.1 and S.2 shows an overview of the relative numbers of fires, injury accidents, KSI accidents, and breakdowns predicted by the two models. The results for breakdowns apply to all breakdowns, regardless of the type of vehicle (models for specific types of accidents involving light and heavy vehicles have also been developed). The results for the individual variables are described in the following paragraphs.

Table S.1: Relative number of fires, injury and KSI accidents in the tool, calculated with Model 1 (with length of gradient curves and height among the predictor variables) and Model 7 (with maximum gradient, and without curves/height among the predictor variables); **statistically significant** *effects (p<.05) are marked in bold font.*

		Model 1			Model 7		
	Effect given as relative number…	**Fires**	**Inj. acc.**	**KSI acc.**	**Fires**	**Inj. acc.**	**KSI acc.**
AADT	**When AADT increase with 10%**	**1.060**	**1.068**	**1.054**	**1.058**	**1.067**	**1.054**
Proportion of long vehicles	**When the proportion of long vehicles increases with 5 percentage points**	0.932	**0.771**	0.866	0.916	**0.786**	0.855
Speed limit	**Speed limit 30-50 km/h**	1.004	**2.755**	1.768	0.693	**2.483**	1.617
	Speed limit 60 km/h	1.322	**1.824**	1.153	1.087	**1.909**	1.254
	Speed limit 70 km/h	1.207	**2.018**	**1.572**	1.085	**2.290**	**1.538**
	Speed limit 90-110 km/h	1.409	**1.832**	1.397	1.431	**1.499**	1.007
	(Rel. number = 1 at 80 km/h)	1 (ref.)	1 (ref.)	1 (ref.)	1 (ref.)	1 (ref.)	1 (ref.)
Length of vertical gradient	**When length with gradient 5+% increases with 500 m**	**1.122**	1.001	0.998	-	-	-
	When length with gradient 7+% increases with 500 m	1.060	1.001	0.998	-	-	-
	Max. gradient 5+ %	-	-	-	**1.644**	**1.312**	1.063
	Max. gradient 7+ %	-	-	-	**2.683**	**1.312**	1.063
	(Rel. number = 1 with max gradient below 5%)	-	-	-	1 (ref.)	1 (ref.)	1 (ref.)
Kurve	**Min. curve radius 0-149 m**	0.882	1.311	1.234	-	-	-
	Min. curve radius 150-299 m	1.155	1.230	1.160	-	-	-
	Min. curve radius 300-599 m	0.981	1.182	1.231	-	-	-
	Completely straight tunnel	1.070	**1.694**	0.356	-	-	-
	(Rel. number with min. curve gradient 600+ m)	1 (ref.)	1 (ref.)	1 (ref.)	-	-	-
Height	**Tunnel over 4.5 m height** (vs. lower)	**0.652**	**0.701**	0.784	-	-	-
Year	**2008**	0.969	**1.698**	1.020	0.964	**1.849**	1.037
	2009	0.839	**1.942**	0.709	0.879	**2.100**	0.693
	2010	0.895	**1.709**	1.139	0.859	**1.817**	1.109
	2011	1.461	**1.617**	0.993	1.376	**1.732**	0.974
	2012	1.279	**1.464**	0.579	1.165	**1.511**	0.606
	2013	1.465	1.299	0.814	1.282	1.292	0.712
	2014	1.233	1.399	0.615	1.161	1.388	0.589
	2015	1 (ref.)	1.171	0.737	1 (ref.)	1.195	0.703
	2016	-	1.150	**0.378**	-	1.152	**0.396**
	(Rel. number = 1 in 2017)	-	1 (ref.)	1 (ref.)	-	1 (ref.)	1 (ref.)

Table S.2: Relative numbers of light and heavy vehicle breakdowns in the tool, calculated with Model 7 (with maximum gradient, and without curves/height among the predictor variables); **statistically significant** *effects (p<.05) are marked in bold font.*

	Effect given as relative number…	**Light vehicle breakdowns**	**Heavy vehicle breakdowns**
AADT	**When AADT increase with 10%**	**1.113**	1.031
Proportion of long vehicles	**When the proportion of long vehicles increases with 5 percentage points**	1.006	1.120
Speed limit	**Speed limit 30-50 km/h**	1.630	4.792
	Speed limit 60 km/h	1.549	1.406
	Speed limit 70 km/h	0.830	0.824
	Speed limit 90-110 km/h	1.134	0.386
	(Rel. number = 1 at 80 km/h)	1 (ref.)	1 (ref.)
Vertical grade	**Max. gradient 5+ %**	**1.155**	1.333
	Max. gradient 7+ %	2.966	1.422
	(Rel. number = 1 with max gradient below 5%)	-	-

Traffic volume and heavy vehicle volumes

Increasing **traffic volume** is related to increasing numbers of fires, accidents and breakdowns. However, the numbers of fires, accidents and breakdowns increase much less than proportionally to volume. An increase in traffic volume of 10% is related to an average increase in the number of fires and accidents of about 5% and an average increase in the number of breakdowns of about 7%.

Increasing **proportion of heavy vehicles** is related to decreasing numbers of fires and accidents, but the effect is non-significant in most models. The number of breakdowns is not related to the proportion of heavy vehicles.

Tunnel length

Tunnel length is included in all models, with a coefficient that is set equal to one, i.e. it is assumed that the number of fires, breakdowns, and accidents increases proportionally with tunnel length. In a supplementary analysis, the numbers of accidents and fires per million vehicle kilometers are compared between tunnels of different lengths.

The results show no general relationship between tunnel length and fires per million vehicle kilometers. However, tunnels that are between four and ten kilometers long have on average about three times as many fires per million vehicle kilometers as tunnels less than 300 meters long. The explanation is probably that most subsea tunnels are in this category. These have long stretches with steep gradients and more fires than other tunnels.

The risk of **accidents** (injury accidents per million vehicle kilometers) is highest in short tunnels (100-500 meters) and decreases with increasing tunnel length. We see the same trend for FSIA, but the relationship is weaker than for PIA. Tunnels that are 100-200 meters long have an average risk of PIA that is 4.8 times higher and about 30% higher risk for FSIA than tunnels longer than 10 km.

Type of tunnel and ramps

Twin-tube tunnels have more **fires** than single-tube tunnels, but the difference varies widely between models and is not statistically significant in all models. The relative number of fires in twin-tube tunnels (compared to single-tube tunnels) is from 1.4 to 2.6 in the different models.

Ramps are not included in the fire models because none of the fires occurred on a ramp. Tunnels with ramps have more fires than tunnels without ramps, but without the difference is not statistically significant.

The number of **accidents** is also higher in twin-tube tunnels than in single-tube tunnels. The difference is statistically significant in all models for injury accidents but not in any of the models for KSI accidents. The number of injury accidents is about three times as high in twin-tube tunnels as in single-tube tunnels in all models. The difference between twin and single tube tunnels can mainly be explained by large numbers of injury accidents in urban twin-tube tunnels.

Ramps are not related to the number of accidents. There are no statistically significant differences in the number of accidents between tunnels with and without ramps.

The number of **breakdowns** is higher in twin-tube tunnels than in single-tube tunnels, but without the difference being statistically significant. There are large differences between some types of breakdowns, but the only statistically significant effect on a specific type of breakdown is the effect on punctures (more in twin-tube tunnels). The explanation is unknown; the effect is probably due to random variation (some results can be expected to be statistically significant even though there is no connection). Ramps are not included in the analyzes for breakdowns.

Speed limit

The number of **fires** is not related to the speed limit. The number of **accidents** is higher in tunnels with lower speed limits than in tunnels with a speed limit of 80 km/h or higher. Compared to the speed limit of 80 km/h, the number of injury accidents is about twice as high in tunnels with speed limits of 60 or 70 km/h and about three times as high in tunnels with speed limits of 30-50 km/h (all effects are statistically significant). For KSI accidents, the models show the same trend, but the differences are far smaller and not statistically significant.

The number of **breakdowns** is not related to the speed limit.

The model predictor speed limit cannot be used to predict expected effects of changing the speed limit in a tunnel. The predictor describes the relationship between speed limit and fires, accidents, and breakdowns in existing tunnels at their current speed limit. Expected effects of speed limit changes on accidents can be estimated based on the relationship between speed limit, speed, and accidents.

Vertical grades

Vertical grade is the most important predictor of the number of **fires**, besides traffic volume and tunnel length. The length of steep gradients, i.e. the number of meters in the tunnel with a gradient of more than 7% (or more than 5%) contributes most to fires in tunnels. The fire models show that tunnels with a gradient of 7% or more for at least 5 km have 6.7 times as many fires as tunnels where the maximum gradient is below 5%.

The fire models also show that the number of fires increases with increasing gradient, especially from a gradient of 7%. On average, tunnels with a maximum gradient of 7% or more have 4.3 times as many fires as tunnels with a maximum gradient below 5%. Tunnels with a maximum gradient between 5% and 6.9% have 1.5 times as many fires as tunnels with a maximum gradient below 5%.

Unlike fires and breakdowns, the number of **accidents** is not related to vertical grade. This is despite the fact that other studies have shown that tunnel fires often occur as a result of accidents.

The number of **breakdowns** is higher in tunnels with a maximum gradient of 7% or more than in tunnels without a steep gradient. This applies in particular to engine breakdowns and other technical breakdowns, but not punctures and accidents of the "other/unknown" type.

Horizontal curves

The number of **fires** *in*creases in all models with increasing curve radius, indicating that sharper curves are related to *fewer* fires. Tunnels with a minimum curve radius below 150 meters have 60-70% fewer fires than tunnels with slight curves (600+ meter radius) or completely straight tunnels. In model 1 (which is used in the Excel calculation tool), the effects of minimum curve radius are smaller than in the other models and not statistically significant.

For the number of **accidents**, the relationship with the smallest curve radius is reversed. According to the model results the number of accidents *de*creases with increasing curve radius, i.e. sharper curves are related to *more* accidents.

However, completely straight tunnels have more injury accidents than curved tunnels. Completely straight tunnels have about 2.3 times as many injury accidents as tunnels with slight curves. The number of KSI accidents is smaller in completely straight tunnels than in other tunnels, but without the effect being statistically significant.

Curves are not included in the models for **breakdowns**.

Tunnel height og width

Free-height tunnels (signage indicating over 4.5 meters in height) have approximately 30% fewer fires than low tunnels (statistically significant).

The number of **accidents** is also lower in tunnels with free height than in lower tunnels. Both the number of injury accidents and the number of KSI accidents are approximately 20% lower in free-height tunnels (statistically significant only for injury accidents).

Height is not included in the models for breakdowns.

The variable tunnel height (above vs. below 4,5 meters) is related to a number of other variables because most of the "lower" tunnels are of generally lower standard. Thus, the results for tunnel height cannot be interpreted as effects of height alone.

Land and shoulder width are not included in the models because of missing data. Both variables are strongly related to tunnel height. Thus, their effects are assumed to be covered to a large degree by the height predictor.

ITV og AID

Camera surveillance tunnels (ITV) or tunnels with automatic incident detection (AID) tend to have more **breakdowns** than other tunnels. However, most effects were not statistically significant. It is also unclear how ITV and AID can affect the number of breakdowns, except that a larger proportion of the breakdowns can be identified with such technology. It is also possible that ITV and AID are more often installed in tunnels that have more breakdowns than other tunnels, precisely because the tunnels have many vehicle breakdowns.

ITV and AID are not included in the models for **fires** and **accidents.**

Changes over time

Year is not statistically significantly related to the number of **fires** in any of the models, i.e. the models do not indicate that the number of fires in tunnels has changed over time (when controlling for changes in traffic volume).

The number of injury accidents is approximately halved since 2008 (with statistical control for traffic volume). For the number of KSI accidents, there was only a slight decrease over time, which was not statistically significant.

Changes over time were not investigated for **breakdowns**; Only accidents from two years (2016 and 2017) were included in the analyzes.

Crashes in tunnel zones

In order to investigate whether the accident risk varies within tunnels, all tunnels were divided into entrance zones (the first and last 100 meters of the tunnel) and mid zones (between the entrance zones). In short tunnels, where the middle zone is shorter than 100 meters, the entire tunnel is classified as an entrance zone. Ramps are not included in the analyses for entrance and middle zones.

The results show that for injury accidents, the accident risk is about twice as high in entrance zones as in mid-zones. In short tunnels where the entire tunnel is considered as "entrance zone" in our analyzes, the risk of injury accidents is about twice as high as mid zones in longer tunnels. In twin tube-tunnels, the difference between the entrance and the middle zone is somewhat smaller; here the accident risk is 60% higher in the entrance zone.

For KSI accidents, the risk differences were smaller. Compared to the middle zone, the risk in the entrance zone is 80% higher in single-tube tunnels and 33% higher in twin-tube tunnels.

Up- and downstream sections

The roads immediately up- and downstream of tunnels may affect incidents in tunnels, especially fires. For example, the last two fires in the Gudvanga-tunnel started on a steep slope before the tunnel. However, it was not possible in this project to include factors related to the road outside the tunnels as predictor variable in the regression models.