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Safety effects of fixed speed cameras - An empirical Bayes evaluation

The safety effects of 223 fixed speed cameras that were installed between 2000 and 2010 in Norway were investigated in a before-after empirical Bayes study with control for regression to the mean (RTM). Effects of trend, volumes, and speed limit changes are controlled for as well. On road sections between 100 m upstream and 1 km downstream of the speed cameras a statistically significant reduction of the number of injury crashes by 22% was found. For killed and severely injured (KSI) and on longer road sections none of the results are statistically significant. However, speed cameras that were installed in 2004 or later were found to reduce injury crashes and the number of KSI on road sections from 100 m upstream to both 1 km and 3 km downstream of the speed cameras. Larger effects were found for KSI than for injury crashes and the effects decrease with increasing distance from the speed cameras. At the camera sites (100 m up- and downstream) crash reductions are smaller and non-significant, but highly uncertain and possibly underestimated.

1. Introduction

Speed cameras aim at reducing speed and thereby crashes, especially the most serious crashes. In Norway, the first fixed speed cameras were installed in 1988. All speed cameras are signposted at some distance upstream of the cameras, and the cameras are well visible. Speed cameras in Norway can take pictures of vehicles driving above the speed limit (or some other limit above the speed limit), and the drivers of vehicles that had too high speed may be prosecuted.

Until year 2000 all speed cameras were equipped with analogue cameras in which the film reels had to be changed manually, and the cameras were rotated between the camera housings. In the years 2001-2011 all analogue cameras were replaced by remote controlled digital cameras and remote controlled digital cameras were installed in all new speed cameras. The proportion of vehicles taken pictures of, and the proportion of drivers prosecuted (among those who had too high speed) has increased with the installation of digital cameras. At the same time as digital cameras were installed, the compliance with the official criteria for the installation for speed cameras, especially the focus on the criterion for high speed, increased.

The criteria for the installation of speed cameras referred until 2008 to the number of injury crashes at potential camera sites (above average and at least 0.5 per kilometer per year during a period of four years) and speed (mean speed above the speed limit). In 2009 the criterion for injury crashes was replaced by a criterion for crash costs (at least 30% above average crash costs on similar roads in Norway) and it is now possible to install speed cameras at sites that meet one of the criteria (speed or crash costs) with a good margin, but not the other, as long as the expected costs of installing speed cameras are lower than the expected reduction of crash costs.

Other studies of the crash effects of speed cameras that are summarized by Høye (2014A) by means of meta-analysis found a reduction of the number of injury crashes by 20% and a reduction of the number of killed or severely injured (KSI) by 51%. These results refer to unspecified stretches of road at speed cameras (up to several kilometers from the camera sites) and the result for KSI may be affected by regression to the mean (RTM) and thereby overestimated. Studies that have investigated effects at specified distances from the camera sites found a reduction of the number of injury crashes at the camera sites by 18%, and decreasing effects with increasing distance from the cameras. At distances above 1 km a non-significant reduction of injury crashes by 4% was found. Speed measurements from other studies that also are summarized by Høye (2014A) found the largest speed reductions at the camera sites (on average -11%), while speed was reduced by 1.4% on average two kilometers from the speed cameras.

The effects of speed cameras in Norway were investigated in an earlier study by Elvik (1997). The study is based on 64 road sections between 0.5 and 20 km of length (5.3 km on average) with an unspecified number of speed cameras and found a statistically significant reduction of the number of injury crashes by 20%. RTM is not controlled for.

The aim of the present study is to investigate the effects of speed cameras on injury crashes and on the number of killed or severely injured (KSI) on road sections of different lengths downstream of the camera sites. Since criteria for installing speed cameras include unfavorable crash records, RTM is likely to occur. In order to control for RTM the evaluation is conducted with the empirical Bayes (EB) method that compares observed to expected crash numbers in the after period.

Because of the changes of the criteria for installing speed cameras and the change of the technical equipment of the cameras, crash effects are compared between speed cameras with different years of installation.

2. Data

Speed cameras that were installed in Norway between 2000 and 2010 were included in the evaluation. Speed cameras that were taken down after less than three years and speed cameras for which relevant information about road characteristics or crashes was not available, were not included in the evaluation. Thus, 223 speed cameras (about 80% of all speed cameras that were installed in Norway during this time period) were available for the evaluation. Crash data was available until 2013 which is why speed cameras installed after 2010 were not included in the evaluation. The before and after periods were three whole years (January to December) for all sites. The year of installation was excluded from the study. Speed cameras from earlier years were not included because crash data and information about road characteristics from before 1997 are not easily available. The speed limit at the camera sites at the time of installation was as follows: 50 km/h (9%), 60 km/h (24%), 70 km/h (27%), 80 km/h (38%), 90 km/h (1%). The number of lanes is two at most sites and all sites are outside urban areas.

The evaluation was conducted on road sections of different lengths:

- Long sections: From 100 m upstream to 3 km downstream of the camera sites
- Medium sections: From 100 m upstream to 1 km downstream of the camera sites
- Short sections: From 100 m upstream to 100 m downstream of the camera sites

For each speed camera all three types of sections, long, medium, and short, were defined. In many cases the road sections overlap for two or more speed cameras (e.g. when there are two speed cameras in opposite directions at the same location). Overlapping sections are combined in order to avoid double counting of crashes. All road sections included in the analysis are for the sake of the model calculations (see next section) split up into sections that are homogeneous with respect to traffic volume, speed limit, number of lanes, presence of median and median barrier (road characteristics change within almost all sections). The general road category (e.g. country road, national road) does not change within any of the sections and none of the sections extends over two counties.

Table 1 summarizes information about the number, total and average length of road sections of different lengths included in the analysis (where overlapping sections are combined and, for example, a long section with two speed cameras in opposite directions at the same location is 6 km long while the medium section for the same two speed cameras is 2 km long), the average number of speed cameras per section, average volumes and million vehicle kilometers travelled in the before and after period, as well as the number and average length of the homogenous sections that are the unit of analysis in the statistical analyses of the evaluation (the homogeneous sections are shorter than the whole sections on average because almost all sections had to be split up into homogeneous sections). Traffic volumes have increased from the before to the after period by about 9 % on average.

Table 1: Combined road sections included in the evaluation (overlapping sections for two or more speed cameras are combined).

	N of (combined) sections	Total length (km)	Average length (km)	Speed cameras per section	AADT (mean) before	AADT (mean) after	Mill. veh.-km before	Mill. veh.-km after	N of homo-geneous sections	Average length of homogeneous sections (m)
Long	103	471.1	4.6	2.2	8,186	8,940	4,211	4,576	940	501
Medium	130	200.3	1.5	1.7	8,419	9,213	1,835	2,001	477	420
Short	174	38.1	0.2	1.3	8,740	9,410	363	388	238	160

3. Method

The effect of speed cameras on injury crashes and on the number of KSI was investigated in a before-after evaluation. In order to control for RTM the EB method was applied (Hauer, 1997; Elvik, 2008). Effects of speed cameras were also calculated with a similar design but without control for RTM.

3.1 EB before-after evaluation

According to the EB procedure, the observed number of crashes on roads with speed cameras in the after period (**O_a**) is compared to the expected number of crashes on the same roads in the after period (**E_a**), i.e. the xnumber of crashes that would have occurred without speed cameras. Formula 1 shows an unbiased estimate of the effect of speed cameras according to Hauer (1997). A simple comparison of O_a and E_a is a biased estimate of the average effect on a number of road sections because of the aggregation of fractions (Hauer, 1997). The term in the denominator adjusts for this bias.

$$Effect = \frac{\frac{O_a}{E_a}}{1 + \frac{Var(E_a)}{E_a^2}} \tag{1}$$

The estimated percentage change of the number of crashes from the before- to the after period is (Effect – 1) * 100. $\mathbf{E_a}$ is for each site estimated as a function of the expected number of crashes in the before period ($\mathbf{E_b}$) and changes over time. $\mathbf{E_b}$ is a function of the observed number of crashes in the before period ($\mathbf{O_b}$), the predicted number of crashes in the before period ($\mathbf{P_b}$), and a statistical weight (**w**) (formula 2).

$$E_b = w * P_b + (1 - w) * O_b \tag{2}$$

$\mathbf{P_b}$ is the number of crashes that would have been expected in the before period on road sections with the same AADT and other characteristics as the ones with speed cameras. The safety performance function (SPF) that is used to estimate P_b is described by Høye (2014B). It is based on crash prediction models for the major part of the Norwegian road network (except private and municipal roads and tunnels). The models are based on 73,710 homogeneous sections of up to 1.1 km length. The models are negative binomial models with a variable overdispersion parameter. The coefficients for all predictor variables that are relevant for the road sections included in the evaluation are shown in table 2 for injury crashes and for the number of KSI. Section length and the number of data years were included as exposure variables, i.e. the coefficients for the natural logarithms of these variables were set to one. Coefficients for the overdispersion parameter are shown in the last three rows of table 2. Predictor variables that are not relevant are not shown (e.g. none of the sites has a speed limit of 100 km/h). Omitted predictor variables are dummy variables for speed limits 30, 40, and 100 km/h, five or more lanes, and motorway. Coefficients for 19 county dummy variables that are included in the model, are also omitted from table 2. About 10% of the total road length is in tunnels. For these, modified models for tunnels, including predictors for tunnel, two-tube tunnels and undersea tunnels described by Høye, 2015 are applied. The coefficients in these models are very similar to those in table 2

Table 2: Generalized negative binomial crash prediction model parameter estimates, standard deviations in parentheses (Høye, 2014B).

	Original models			
	Injury crashes		KSI	
Ln(AADT)	1.230	(0.066)	1.937	(0.167)
Ln(AADT)^2	-0.016	(0.004)	-0.074	(0.011)
Speed limit: 80 km/h (dummy[a])	(reference)		(reference)	
Speed limit: 90 km/h (dummy[a])	-0.248	(0.070)		
Speed limit: 90 or 100 km/h (dummy[a])			-0.343	(0.159)
N of lanes: 2 (dummy[a])	(reference)		(reference)	
N of lanes: 3 (dummy[a])	0.110	(0.062)	0.160	(0.157)
N of lanes: 4 (dummy[a])	0.325	(0.056)	0.156	(0.168)
T-junctions (number[b])	0.138	(0.016)	0.111	(0.043)
X-junctions (number[b])	0.314	(0.041)	0.176	(0.121)
Off-ramps (number[b])	-0.433	(0.078)	-0.214	(0.215)
On-ramps (number[b])	-0.216	(0.080)	-0.229	(0.222)
Curves (50 km/h) (number[b])	-0.192	(0.030)	-0.192	(0.084)
Curves (60 km/h) (number[b])	0.037	(0.026)	0.138	(0.068)
Curves (70 km/h) (number[b])	0.005	(0.043)	-0.043	(0.103)
Curves (80 km/h) (number[b])	0.218	(0.019)	0.120	(0.044)
Curves (90 or 100 km/h) (number[b])	0.183	(0.251)	0.034	(0.568)
Vertical grades (50 km/h) (number[b])	-0.191	(0.057)		
Vertical grades (60 km/h) (number[b])	0.037	(0.050)		
Vertical grades (70 km/h) (number[b])	0.221	(0.081)		
Vertical grades (80 km/h) (number[b])	-0.005	(0.033)		
Vertical grades (90 or 100 km/h) (number[b])	0.496	(0.232)		
Vertical grades (number[b])			-0.117	(0.059)
Median and median barrier (dummy[a])	-0.140	(0.135)	-1.635	(0.606)
Median (no barrier) (dummy[a])	0.100	(0.045)	0.131	(0.122)
Median barrier (no median) (dummy[a])	-0.096	(0.307)	-0.127	(0.671)
Median rumble strips (dummy[a])	-0.348	(0.168)	-0.162	(0.332)
Road category: 2-/3 lane with median barrier (dummy[a])	-0.499	(0.070)	-0.123	(0.163)
Road category: Trans European Network road (dummy[a])	-0.101	(0.027)	0.259	(0.063)
Road category: Other national road (dummy[a])	-0.024	(0.023)	0.220	(0.057)
Road category: District road (dummy[a])	(reference)		(reference)	
County (one dummy for each of 19 counties)				
Constant	-17.62	(0.254)	-21.05	(0.628)
Ln (km * years)	1.000		1.000	
Overdispersion parameter (φ)				
Ln (km * years)	-0.778	(0.028)	-0.787	(0.062)
AADT	-0.371	(0.035)	-0.730	(0.047)
Constant	8.53	(0.439)	13.70	(0.734)

[a] Dummy variables: 1 if yes, 0 otherwise
[b] Number of junctions, curves etc.: Ln(number of X + 1), for curves separate variables are defined for each speed limit, for vertical grades separate variables are defined for each speed limit in the models for injury crashes.

The statistical weight (**w**) in formula 2 is a function of the overdispersion parameter **φ** that is estimated along with P_b with the SPF and P_b (Hauer et al., 2002, formula 3).

$$w = \frac{1}{1 + \frac{P_b}{\varphi}} \tag{3}$$

The overdispersion parameter and the statistical weights become smaller with increasing predicted crash numbers, and the expected crash numbers are therefore closer to the observed crash numbers, the higher the predicted crash numbers.

Speed limit changes in the evaluation period were taken into account by adjusting the expected crash numbers for the assumed effect of the speed limit changes on crashes. It was assumed that speed is reduced by 3.6 km/h for each 10 km/h speed limit reduction according to a meta-analysis by Elvik (2012). The effects on injury crashes and KSI of a speed reduction by 3.6 km/h were estimated with the help of the power model by Elvik (2009).

Changes over time are taken into account by applying a trend factor. Without adjustment for trend, the model predictions refer to the year 2008. In order to take into account general changes of traffic volumes and crash numbers in Norway over time a trend factor has been developed along with the crash models by Høye (2014B) that allows the conversion of model predictions to any year between 1997 and 2020. The relative numbers of injury crashes and KSI in the years 1997-2013 according to the trend factor are shown in figure 1. For example, from 2008 to 2013 the number of KSI per million vehicle kilometers has decreased by 33% (1 – 0.67) and the predicted number of KSI in 2013 is therefore calculated as 0.67 times the predicted number of KSI in 2008. According to the trend factor, the general decrease of crash and injury risk over time would have contributed to a decrease of the annual numbers of injury crashes by about 15% from the before- to the after period and to a decrease of the number of KSI by about 23% from the before- to the after period if all else had remained unchanged.

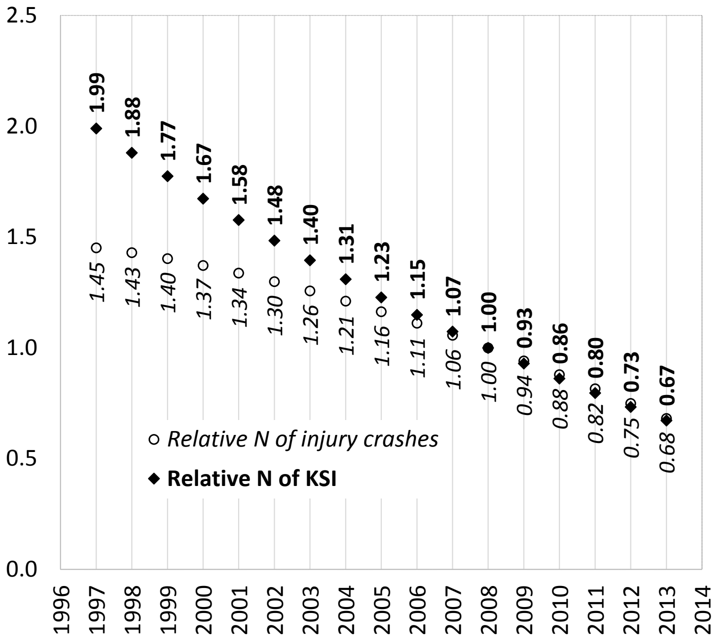

Figure 1: Relative numbers of injury crashes and KSI in 2006-2013 according to the trend factor.

Changes of traffic volumes from the before- to the after period and the (nonlinear) relationship between traffic volumes and crash numbers, as described by the SPF (see above), are taken into account as well.

In order to calculate aggregated effects for a number of sites, the numbers of $\mathbf{O}_a$ and $\mathbf{E}_a$ are summed up over all sites and the summary effect is calculated with the formula described above. Standard deviations and confidence intervals for aggregated effects were calculated as described by Hauer (1997) and Persaud et al. (2005).

3.2 Before-after studies without control for RTM

In order to estimate the effects of speed cameras without control for RTM, the effect of speed cameras on crashes is estimated as an odds ratio (formula 4).

$$Effect = \frac{O_a}{O_b} \Big/ \frac{P_a}{P_b} \tag{4}$$

where O_a, O_b, P_a, and P_b are defined as described above. Thereby, the same factors are controlled for as in the EB evaluation, except RTM. The estimated effect of speed cameras with control for traffic volumes only is calculated according to formula 5.

$$Effect = \frac{O_a}{O_b} \Big/ \frac{Mill.\,vehicle\;km_a}{Mill.\,vehicle\;km_b} \tag{5}$$

4. Results

4.1 Results for all speed cameras

The results of the EB-evaluation are summarized in table 3 for all road sections included in the evaluation with 95% confidence intervals (CI). Table 3 shows additionally the results from a before-after study without control for RTM (as described in section 3.2, formula 4) and from a simple comparison of crash rates (section 3.2, formula 5). Observed (O_b and O_a), predicted (P_b and P_a), and expected crash numbers (E_b and E_a) are shown as well. The ratios of the observed and predicted crash numbers in the before period indicate that speed cameras have been installed at sites with above average crash numbers, and that RTM therefore is likely to occur, especially for KSI and more on shorter than on longer sections. Accordingly, larger crash reductions were found in the before-after study without control for RTM. Still larger crash reductions were found in the simple comparison of crash rates.

Table 3: Estimated effects of speed cameras on injury crashes and KSI (results from EB-evaluation and without control for RTM).

		Observed		Predicted		Expected		Observed/ Predicted (before)	EB: Percentage change (95% CI)	BA[a] Percentage change (95% CI)	BA[b] Percentage change (95% CI)
		Before	After	Before	After	Before	After				
Injury crashes	**Long**	914	723	863.0	775.4	844.3	760.7	1.06	**-5 %** *(-12; +2)*	**-13 %** *(-21; -4)*	**-27 %** *(-34; -20)*
	Medium	457	292	393.9	354.6	418.3	374.7	1.16	**-22 %** *(-30; -14)*	**-29 %** *(-39; -17)*	**-41 %** *(-49; -32)*
	Short	98	69	68.0	60.1	75.0	66.1	1.44	**+1 %** *(-36; +37)*	**-19 %** *(-41; +11)*	**-34 %** *(-52; +11)*
KSI	**Long**	201	111	150.8	119.3	161.5	128.1	1.33	**-17 %** *(-47; +14)*	**-31 %** *(-46; -12)*	**-49 %** *(-60; -36)*
	Medium	101	42	54.6	43.4	60.7	48.6	1.85	**-24 %** *(-72; +24)*	**-49 %** *(-65; -26)*	**-62 %** *(-73; -45)*
	Short	18	7	10.1	7.9	10.4	8.1	1.79	**-14 %**[c] *(-92; +65)*	**-49 %** *(-80; +26)*	**-64 %** *(-85; -13)*

[a] Before-after study without control for RTM (otherwise, the same factors are controlled for as in the EB-evaluation)

[b] Before-after study with control for vehicle kilometers travelled only (comparison of crash rates)

[c] The effect on KSI on the 200 m sections is calculated without adjustment for bias (see text).

For injury crashes, a statistically significant reduction by 22% was found in the EB-evaluation on the medium sections. No statistically significant effects were found for the long and short sections. The results indicate that the effects on KSI are somewhat more favorable than the effects on injury crashes, but none of the results KSI is statistically significant. The results indicate further that the effects of speed cameras decrease with increasing distance from the camera sites.

On the short road sections the number of injury crashes was about unchanged according to the EB evaluation. The results for KSI on the short sections are not easily interpreted. According to the before-after study without control for RTM the effect is about the same as on the medium sections and the ratio of observed to predicted numbers of KSI is similar as well. In the EB-evaluation the effect on KSI would be a reduction by 73% (-98; -48) according to formula 1. This result is however illogical. In the presence of a relatively large effect of RTM the crash reduction cannot be greater than without control for RTM (-49%). The result in table 3 is therefore calculated without the term in the denominator in formula 1. This result is more consistent with the other results, but biased according to Hauer (1997; see section 3.1). Another problem with the result for KSI on the short sections is a large outlier bias. There were only seven KSI on these sections in the after period and two of these were killed / injured in one crash on a very short road section (120 m) where the predicted number of KSI is 0.03. Had only one person been killed or seriously injured in this crash the number of KSI would have been reduced by 26% (-94; +41) when calculated in the same way as the result from the EB-evaluation in table 3. Omitting this section from the analysis increases the effect on the number of KSI to a reduction by 38% (-95; +18) which is still non-significant because of the small number of KSI.

4.2 Comparison of crash effects of speed cameras from different installation years

The effects of speed cameras are compared between different installation years because of changes of the criteria for installing speed cameras and the change of the technical equipment: Early (2000-2003), medium (2004-2006), and late (2007-2010). Each group contains about one third of all vehicle kilometers travelled on the road sections included in the analysis. Table 4 shows the effects on injury crashes and on KSI for each of these groups and for sections of the three different lengths. The effects of speed cameras with medium and late installation years are for the most part similar and consistently more favorable than those of the earliest speed cameras. Figure 2 compares therefore the effects of the early and medium/late speed cameras (from table 4), in addition to the combined effects of all speed cameras (from table 3).

While the earliest speed cameras had only relatively small and for the most part non-significant effects, larger and statistically significant reductions of both injury crashes and KSI were found for the medium / late speed cameras on the medium and long road sections.

On the short road sections no statistically significant effects were found of the speed cameras with medium or late installation years, although the effects are somewhat more favorable than the effects of the early speed cameras. The results for KSI on the short sections with late and medium / late installation year are affected by the same type of outlier bias, due to the same crash, as the result for all speed cameras. Had only one person been killed or severely injured in the one crash with two KSI in the after period, a reduction of the number of KSI by 33% (-85; +19) would have been found in the EB-evaluation of the medium / late speed cameras on the short road sections. Omitting this section improves the effect further, KSI would be statistically significantly reduced by 55% (-90; -21). These results and the large confidence intervals make it difficult to draw any conclusions about the effects of medium / late speed cameras on KSI on short road sections.

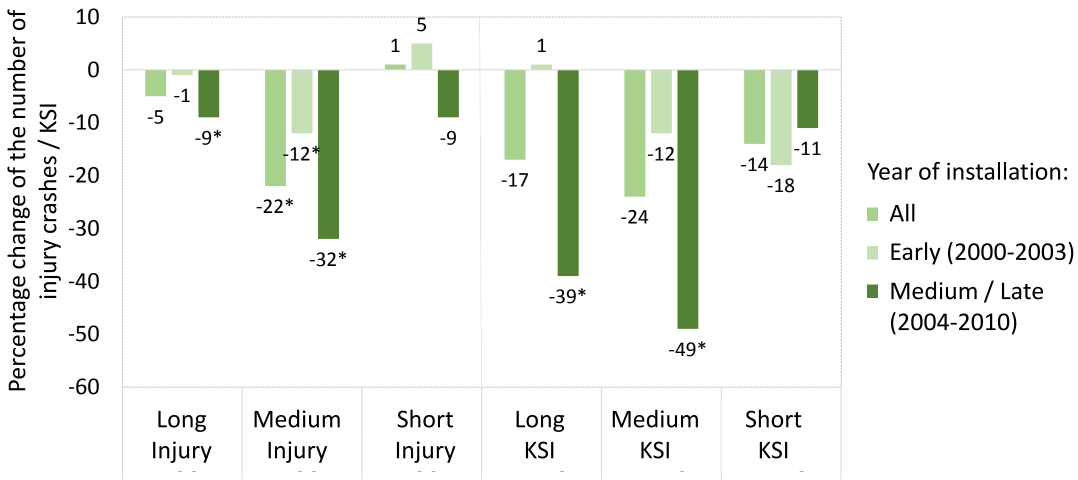

*Figure 2: Effects of speed cameras on injury crashes and KSI, based on the EB-evaluation. Statistically significant results are highlighted with a *.*

Table 4: Estimated effects of speed cameras with different installation years on injury crashes and KSI (results from EB-evaluation and without control for RTM).

			Observed		Predicted		Expected		Observed/ Predicted (before)	EB: Percentage change (95% CI)	BA[a] Percentage change (95% CI)	BA[b] Percentage change (95% CI)
			Before	After	Before	After	Before	After				
Early (2000-2003)	**Injury**	**3.1 km**	393	353	394.4	376.0	370.0	355.1	1.00	**-1 %** *(-11; +9)*	**-6 %** *(-19; +9)*	**-17 %** *(-28; -5)*
		1.1 km	198	155	171.3	161.7	182.8	174.8	1.16	**-12 %** *(-24; 0)*	**-18 %** *(-34; +1)*	**-28 %** *(-42; -11)*
		200 m	37	33	27.5	25.6	31.0	28.9	1.34	**+5 %** *(-49; +60)*	**-5 %** *(-41; +54)*	**-17 %** *(-48; +33)*
	KSI	**3.1 km**	99	69	76.4	61.8	79.7	64.8	1.30	**+1 %** *(-44; +45)*	**-14 %** *(-37; +19)*	**-36 %** *(-53; -13)*
		1.1 km	43	25	25.8	20.7	29.0	23.7	1.67	**-12 %** *(-76; +52)*	**-31 %** *(-59; +15)*	**-47 %** *(-67; -13)*
		200 m	9	3	4.4	3.5	4.6	3.6	2.03	**-18 %**[c] *(-81; +46)*	**-58 %** *(-89; +63)*	**-69 %** *(-92; +15)*
Medium (2004-2006)	**Injury**	**3.1 km**	278	221	268.0	240.4	264.0	235.8	1.04	**-7 %** *(-19; +6)*	**-12 %** *(-26; +6)*	**-27 %** *(-39; -13)*
		1.1 km	163	84	146.9	134.8	154.3	136.5	1.11	**-39 %** *(-51; -27)*	**-42 %** *(-55; -24)*	**-53 %** *(-64; -39)*
		200 m	39	23	27.3	24.4	29.5	26.1	1.43	**-19 %** *(-61; +24)*	**-32 %** *(-60; +16)*	**-45 %** *(-67; -8)*
	KSI	**3.1 km**	61	27	44.3	35.7	48.4	39.0	1.38	**-39 %** *(-78; 0)*	**-44 %** *(-65; -11)*	**-59 %** *(-74; -36)*
		1.1 km	32	10	18.8	15.5	20.4	16.9	1.70	**-61 %** *(-97; -25)*	**-62 %** *(-81; -20)*	**-71 %** *(-86; -42)*
		200 m	7	2	3.7	3.0	3.9	3.1	1.88	**-36 %**[c] *(-81; +10)*	**-65 %** *(-93; +75)*	**-73 %** *(-94; +28)*
Late (2007-2010)	**Injury**	**3.1 km**	243	149	200.6	158.9	210.3	169.8	1.21	**-13 %** *(-26; 0)*	**-26 %** *(-40; -9)*	**-44 %** *(-54; -31)*
		1.1 km	96	53	75.7	58.1	81.2	63.4	1.27	**-18 %** *(-37; +1)*	**-29 %** *(-50; 0)*	**-49 %** *(-64; -29)*
		200 m	22	13	13.2	10.1	14.5	11.2	1.66	**-8 %** *(-82; +65)*	**-25 %** *(-63; +54)*	**-45 %** *(-72; +10)*
	KSI	**3.1 km**	41	15	30.0	21.9	33.3	24.3	1.37	**-52 %** *(-92; -13)*	**-53 %** *(-75; -14)*	**-66 %** *(-81; -39)*
		1.1 km	26	7	10.0	7.2	11.3	8.0	2.61	**-55 %** *(-99; -11)*	**-65 %** *(-85; -17)*	**-75 %** *(-89; -43)*
		200 m	2	2	1.9	1.4	1.9	1.4	1.04	**+46 %**[c] *(-19; +110)*	**+92 %** *(-82; +1948)*	**-7 %** *(-87; +563)*
Medium / late (2004-2010)	**Injury**	**3.1 km**	521	370	468.6	399.3	474.3	405.6	1.11	**-9 %** *(-18; 0)*	**-18 %** *(-29; -6)*	**-35 %** *(-43; -25)*
		1.1 km	259	137	222.6	192.9	235.5	199.9	1.16	**-32 %** *(-42; -22)*	**-37 %** *(-50; -23)*	**-51 %** *(-61; -40)*
		200 m	61	36	40.5	34.5	44.0	37.2	1.51	**-9 %** *(-52; +33)*	**-29 %** *(-54; +8)*	**-45 %** *(-63; -17)*
	KSI	**3.1 km**	102	42	74.3	57.6	81.8	63.3	1.37	**-39 %** *(-73; -6)*	**-48 %** *(-64; -25)*	**-62 %** *(-74; -46)*
		1.1 km	58	17	28.8	22.6	31.7	24.9	2.01	**-49 %** *(-92; -5)*	**-63 %** *(-79; -36)*	**-73 %** *(-84; -54)*
		200 m	9	4	5.7	4.4	5.8	4.5	1.59	**-11 %**[c] *(-79; +58)*	**-41 %** *(-83; +104)*	**-58 %** *(-87; +35)*

[a] Before-after study without control for RTM (otherwise, the same factors are controlled for as in the EB-evaluation)
[b] Before-after study with control for vehicle kilometers travelled only (comparison of crash rates)
[c] The effect on KSI on the 200 m sections is calculated without adjustment for bias (see text).

4.3 Sensitivity analysis

In order to assess the effects of several methodological aspects of the study the contribution of the assumed effects of speed limit changes on some of the road sections and possible outlier biases were investigated.

Contribution of assumed effects of speed limit changes: Speed limits were changed on several road sections during the evaluation period (both increases and decreases of the speed limits occurred) and these changes were taken into account by adjusting the predicted crash numbers according to the assumed relationships between speed limit changes and speed, and between speed and crashes. These adjustments are somewhat imprecise because they are based on general relationships between speed limits, speed, and crashes. Speed measurements on the road sections included in the study are not available. However, the estimated effects of the speed limit changes are only small. If all else had remained unchanged, the speed limit changes would have reduced injury crashes by up to 0.2% and the number of KSI by up to 0.4% from the before to the after period. The effects are only small partly because the proportion of the whole road length included in the study where speed limits were changed is not large and partly because speed limits were reduced on some roads and increased on other roads. Thus, more precise information about actual speed changes or different assumptions about the relationship between speed and crashes are not likely to change the results considerably.

Outlier analysis: The effects of one crash with two KSI in the after period on the results for the short road sections has been discussed in the previous sections. Otherwise, none of the road sections has a disproportionate influence on the overall results, such that the overall result would change noticeably if the section were omitted from the analysis or if the observed number of crashes or KSI were equal to the predicted number.

5. Discussion of the results

The results from the EB-evaluation of section control indicate that speed cameras that were installed in 2004 or later reduced the numbers of injury crashes and the number of KSI, and that the effects are larger on KSI than on injury crashes and larger on road sections of medium length than on longer road sections. For earlier speed cameras, as well as for all speed cameras combined, significant effects were only found for injury crashes on the medium road sections. These results are discussed in more detail in the following. It is also discussed how methodological aspects of the study may have affected the results and the results are compared to results from other speed camera evaluations.

5.1 Methodological aspects of the study

Sensitivity analyses in which methodological aspects of the study were investigated showed that the assumed effects of speed limit changes on some of the road sections only have a negligible influence on the overall results. Possible outlier biases were investigated and one section was found that has a disproportionate influence on the results for KSI on the short road sections. The effects of this crash are discussed below. Otherwise, none of the road sections can be regarded as an outlier. The effects that were found of RTM are in accordance with the fact that high crash numbers are one of the criteria for installing speed cameras. The results of a before-after study without control for RTM are therefore assumed to be overestimated.

5.2 Larger effects on more serious crashes

The finding that speed cameras have larger effects on more serious crashes is consistent for all speed cameras and all road sections. This finding is also consistent with results from studies of the relationship between speed and crash severity. Speed was consistently found to have the strongest effect on fatalities and weaker effects on less serious injuries (Elvik, 2009).

5.3 Decreasing effects with increasing distance from the speed cameras

For the medium and long road sections the results show that the effects of speed cameras decrease with increasing distance from the camera sites. This is consistent with the results from studies of the effects of speed cameras on speed (e.g. Ali m.fl., 1997; Vägverket, 2009). When speed reductions decrease with increasing distance from the speed camera, one would also expect the crash effects to decrease.

5.4 Biased results on short sections or increased numbers of rear end collisions at camera sites?

On the short road sections no or only small effects were found on injury crashes (a non-significant reduction by 9% for speed cameras installed in 2004 or later). There are no specific findings that indicate that the reduction of injury crashes may be underestimated.

For KSI the results for the short road sections are highly uncertain and may be underestimated. The effects on KSI on the short sections are calculated with a simplified formula and these results are possibly biased. The more correct (unbiased) formula yields illogical results. With this formula larger reductions of KSI are found in the EB-evaluation with control for RTM than without control for RTM, although a large effect of RTM is present. Moreover, the results for KSI on the short road sections are based on only few KSI in the after period and they are highly sensitive for the injury outcome of one of these crashes. Omitting this crash improves the effect of speed cameras on short road sections to a (still non-significant) reduction by 38% for all speed cameras and to a statistically significant reduction by 55% for speed cameras installed in 2004 or later.

Small or lacking effects on the short road sections are in contrast to results from other crash evaluations of speed cameras. Other studies that are summarized by Høye (2014A) found a (non-significant) decrease of the number of injury crashes by 18% up to 250 m from the camera sites. The small or lacking effects are also in contrast to studies of the effects of speed cameras on speed that found large speed reductions at the camera locations (Ali m.fl., 1997; Andersson & Larsson, 2005; ARRB, 2005; Mountain et al., 2004; Retting et al., 2008; Shin et al., 2009; Vägverket, 2009). These studies found on average a speed reduction by 11% at the camera sites, which according to the power model of speed would be expected to reduce injury crashes by 18% and the number of fatalities by 43%. On the other hand, Keenan (2002) measured longitudinal speed changes at cameras sites and found that considerable proportions of drivers braked and accelerated immediately (ca. 50 m) before and after the speed cameras. Thus, the small or lacking effects on the short road sections may be due to an increase of rear end collisions due to braking and accelerating that partly or wholly offsets the favorable effects of speed reductions. This interpretation would still be consistent with more favorable effects on KSI because rear-end collisions are on average less serious than most other crashes.

5.5 Improved effects over time

For speed cameras that were installed in 2004 or later larger crash reductions were found than for earlier speed cameras. On the medium and long road sections, the effects are statistically significant for injury crashes and KSI, with the effects being larger for KSI than for injury crashes and larger for the medium than for the long road sections. For the earlier speed cameras the effects are smaller and statistically significant only for injury crashes on the medium road sections. On the short road sections, the results also indicate more favorable effects than for the early speed cameras, but none of the results are statistically significant.

Improved effects of later speed cameras may be due to improved compliance with the criteria, especially to improved compliance with the criterion for high speed. A comparison of observed and predicted crash numbers between early, medium and late speed cameras (table 4) indicates that speed cameras were more often installed at high-crash locations after 2003, but the change has not been dramatic, nor consistent for all road lengths and degrees of severity. The installation of digital cameras in all camera housings (instead of analogue cameras that were rotated between the camera housings) may have contributed as well because the proportion of speeding drivers who were prosecuted increased, although such an effect is more uncertain because many drivers may not have been aware of the change.

The effects of the earlier speed cameras on injury crashes that were found on the medium and long road sections (-12 % and -1 %, respectively) are smaller than the effect that was found in the earlier evaluation of speed cameras in Norway (Elvik, 1997), although the road sections in the study by Elvik (1997) were on average longer than in the present study. On the other hand, Elvik (1997) has not controlled for RTM and the results are therefore not directly comparable.

6. Conclusions

Speed cameras were found to reduce injury crashes by 22% on average on the medium road sections. The effects on KSI are larger but not statistically significant. On the long and short road sections the effects are smaller than on the medium sections and not statistically significant. RTM is likely to be present (speed cameras are for the most part installed at high-crash locations) and statistically controlled for by use of the EB-methodology. Speed cameras that were installed in 2004 or later had more favorable effects than speed cameras from earlier years. They were found to reduce injury crashes and the number of KSI by 9 % and 39 % respectively on the long road sections and by 32 % and 49 % respectively on the medium road sections. The improvement is probably due to changes of the criteria for installing speed cameras and changed camera technology. Results for the short sections are difficult to interpret. Injury crashes are most likely unchanged, KSI may be unchanged or reduced. Lacking effects may be due to an increase of rear end collisions at the camera sites, or due to an underestimation of the effects.

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