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Automated section speed control on motorways: An evaluation of the effect on driving speed

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ABSTRACT

Automated section speed control is a fairly new traffic safety measure that is increasingly applied to enforce speed limits. The advantage of this enforcement system is the registration of the average speed at an entire section, which would lead to high speed limit compliances and subsequently to a reduction in the vehicle speed variability, increased headway, more homogenised traffic flow and increased traffic capacity. However, the number of studies that analysed these effects are limited. The present study evaluates the speed effect of two section speed control systems in Flanders, Belgium. Both sections are located in the opposite direction of a three-lane motorway with a posted speed limit of 120 km/h. Speed data were collected at different points: from 6 km before the entrance of the section to 6 km downstream from the section. The effect was analysed through a before- and after comparison of travel speeds. General time trends and fluctuations were controlled through the analysis of speeds at comparison locations. On the enforced sections considerable decreases were found of about 5.84 km/h in the average speed, 74% in the odds of drivers exceeding the speed limit and 86% in the odds of drivers exceeding the speed limit by more than 10%. At the locations up- and downstream from the section also favourable effects were found for the three outcomes. Furthermore a decrease in the speed variability could be observed at all these data points.

1. Introduction

Excessive speed is a major traffic safety problem at all road types. Driving at a higher speed than the posted speed limits increases the chance to be involved in a crash and increases the severity of the crash (Elvik et al., 2004; Mountain et al., 2004). The SARTRE 3 survey, which provides information on self-reported speeding behaviour of drivers in Europe, showed that most self-reported speed limit violations occur on motorways. Twenty-four percent of the car drivers reported to violate the speed limit often, very often or always on motorways (SARTRE consortium, 2004). A more recent SARTRE study, which analysed drivers' perceptions of other drivers, indicated that on average 52% of the drivers believe that other car drivers speed on motorways (SARTRE consortium, 2012). Many countermeasures have been developed in order to tackle this problem at motorways from which average speed control is one of the most innovative measures that is gaining popularity. Automated section speed control (ASSC), also called average speed enforcement, time over distance cameras, trajectory control, and point-to-point speed enforcement, measures the average speed over a road section. The vehicle is identified when entering the enforcement section through the registration of the license plate, and again when leaving it. The system calculates the speed of the vehicle based on the time the vehicle needs to cover the distance of the section. Drivers that violate the speed limit are ticketed. The threshold for ticketing drivers may vary between countries. At Flemish motorways the fine includes €50 up to a speeding level of 10 km/h and €5 is added for every km/h above the initial level of 10 km/h. At a speeding level from 40 km/h or more drivers are brought to court, they get a fine between €55 and €2750 and a driving ban for 8 days to 5 years. A technical margin of 6 km/h is applied for speeds lower than 100 km/h; for higher speeds this margin is 6% of the measured speed (www.wegcode.be).

The main reason for the installation of ASSC is the compliance of speed limits. Section control is however also intended to homogenise traffic flows, reduce traffic congestion and environmental and noise pollution (Soole et al., 2013). In addition, the police uses this system for the identification of unlicensed or uninsured drivers and tracking of stolen vehicles.

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The focus in the present study is on the use of ASSC to improve speed limit compliance. It describes the results of a study that analysed the effects of ASSC on the driving speed. The remainder of this paper is organised as follows. The next section gives an overview of previous research that studied the speed effects of ASSC. This is followed by a description of the method. In a fourth section the results are described, and in a last section these results are discussed.

2. Background

Several European countries already have ASSC systems for a longer period, such as the Netherlands, the United Kingdom, Italy and Austria (Soole et al., 2013). However, others installed ASSC more recently, from which Belgium is one example. Since this is still a relatively new measure, there is only a limited number of studies present that analysed the impacts of this approach. Recently, Soole et al. (2013) applied a review of both published and grey literature that examined the effect of ASSC on crash rates, speeding offence rates, vehicle speed profiles, traffic flow and congestion. In general they found several studies which showed that section control is associated with very high rates of compliance with posted speed limits, with offence rates that were less than 1%. Studies reported reductions up to 90% in the proportion of vehicles exceeding the speed limit. Furthermore speed variability reduced, which resulted in more homogenised traffic flows, improved traffic density and reduced journey travel times. The authors concluded that ASSC is a greater network-wide approach to managing speeds that can reduce the impact of time and distance halo effects associated with other speed enforcement measures. Nevertheless these results should be taken into account with caution, since the authors reported that there were methodological flaws in many of the studies they found.

Ragnøy (2011) studied three road stretches with ASSC in Norway. The sections had a length of 5 km to 9.5 km, all with a speed limit of 80 km/h. A before- and after study of the speeds showed a decrease for all three treated locations, with higher effects for roads with a higher driving speed during the before period. From an initial average speed of 76.7 km/h, 88.5 km/h and 89.4 km/h the speed decreased by 2.7 km/h, 10.2 km/h and 8.8 km/h respectively. Furthermore higher speed decreases were found at the entrance and the exit of the section, compared to the middle of the section. An analysis of the speeds downstream after the exit of the section, showed that the speed was influenced for at least 1000 m after the exit.

It should be noted that despite the favourable results that were found by Soole et al. (2013) effects can strongly differ. An evaluation of the driving speed after the installation of ASSC at the A3 motorway in Italy showed a high noncompliance of the speed limits. This noncompliance was 50.5% directly after the installation of ASSC and 57.4% one year after the installation (Montella et al., 2012b). Another study that analysed the effect of ASSC on motorway A56, which is located in the same geographic area, showed more favourable results. The noncompliance of the speed limits in the after period was on average 17% (Cascetta et al., 2010). The authors stated that differences in traffic conditions and the function in the territory could partly justify these differences. Nevertheless they indicated that also the enforcement strategy is an important difference and that higher compliance to the speed limits could be achieved by a better strategy of communication and information to the road users and an increased level of enforcement in the follow-up of offences.

These studies already give an indication of the effects of ASSC. Nevertheless Soole et al. (2013) stated that future research is necessary to improve the scientific rigour of conducted evaluations. At this moment there is only a limited number of peer reviewed journal articles that examined the traffic safety effects of ASSC. The present study analyses the effect of ASSC on speed on a methodologically sound basis, in order to examine whether or not similar results can be found with the limited number of previous studies. Furthermore the present study not only analyses the effects on the section, but also takes the effects at the locations upstream and downstream from the enforced section into account.

3. Method

3.1. Design

In order to analyse the speed effect of ASSC, a before- and after study was implemented. The recorded speeds during the before period were compared with the speeds during the after period. Other elements that could have had an effect on the driving speed during both periods were controlled through the inclusion of comparison locations. These locations were similar with the treated locations on traffic volume and types of vehicles but differed in that there was no ASSC.

3.2. Study and comparison locations

At the Flemish motorways, four locations are currently equipped with ASSC. Two locations at the E17 nearby Ghent, which were however not eligible for a before- and after study since there were problems with the homologation of the system for several years and thus it was not possible to apply an accurate before- and after research. Motorways are defined here as roads for motorized vehicles only with a median barrier and no at-grade junctions (Elvik et al., 2009). The minimum speed limit at Flemish motorways is 70 km/h and the entrance is forbidden for pedestrians, cyclists, moped riders and all vehicles that cannot drive faster than 70 km/h. The two systems which were included in the present study are located at the E40, which runs from the north–west of the country to the south–east and connects different main cities. The enforced sections are located between Ghent and Brussels, more specifically between the exits/entries of Wetteren and Erpe-Mere which covers a length of 7.4 km. The maximum speed limit at this road is 120 km/h, which means that it should take at least 222 s to travel this distance. The section has three lanes in each direction and an emergency lane. Each traffic lane has a width of 3.75 m, the emergency lane is 2.90 m wide. It is a straight road, with no curves below $R = 4000$ m. No formal information on the vertical curvature is available, but in general this environment is flat-surfaced. In 2011 the average daily traffic volume was 52,361 vehicles in the direction of Brussels and 52,662 vehicles in the direction of Ghent. At both directions 11.4% of the traffic were heavy vehicles (vehicles longer than 6.8 m).

Data on speeds were gathered through double inductive loops embedded in the pavement. These loops are present at several locations on the Flemish motorways, however are mainly present at exits/entries and at interchanges. The loops are managed by a government agency, and the data gathered by these loops are frequently controlled. The installations collect speed information on the vehicle level, together with information on date and time, lane number and length of the vehicle.

The selection of the locations to measure speed was based on the presence of inductive loops in the pavement. In total nine locations were selected: five locations in the direction of Brussels and four in the direction of Ghent.

1) E40 in the direction of Brussels:

- Location 1: 2.4 km upstream from the entrance of the section.
- Location 2: 1.7 km upstream from the entrance of the section.

- Location 3: on the section (4 km after the entrance).
- Location 4: 0.6 km downstream from the exit of the section.
- Location 5: 6.4 km downstream from the exit of the section.

2) E40 in the direction of Ghent:

- Location 1: 6.4 km upstream from the entrance of the section.
- Location 2: 0.6 km upstream from the entrance of the section.
- Location 3: on the section (3.4 km after the entrance).
- Location 4: 2.3 km downstream from the exit of the section.

In order to control for trend effects, two comparison locations were selected.

- Location 1: E40 in the direction of Brussels, 35.4 km upstream from the entrance of the section.
- Location 2: E40 in the direction of Ghent, 35.4 km downstream from the exit of the section.

The ASSC systems were installed in March 2013. Speed data was gathered for one week in March 2012 and for one week in April 2013. These periods appeared to be the best moments since there were no holidays, and no road works, nor crashes on the study locations during these periods. The data of the before period was selected more than one year before the installation, in order to exclude possible influences of the media, who broadly discussed this subject and to select a period that was similar to the after period regarding season and length of daytime.

3.3. Data analysis

The present study analysed the effect of ASSC on driving speed. Three outcomes were measured:

- Effect on average speed.
- Effect on odds of drivers exceeding the speed limit.
- Effect on odds of drivers exceeding the speed limit by more than 10%.

The odds of drivers exceeding the speed limit can be defined as the ratio of the probability drivers exceed the speed limit and the probability drivers do not exceed the speed limit.

The effect was compared according to the time of the day and the time of the week

- Day (defined as 6.00 a.m. until 10.00 p.m.) vs. night.
- Peak hours (defined as 7.00–8.59 a.m. and 4.00–5.59 p.m.) vs. off-peak hours.
- Week (defined as Monday 6.00 a.m. until Friday 10.00 p.m.) vs. weekend.

To estimate the rates at which mean speeds changed at the treated locations and to take the general trend effect into account, two regression models were applied. The effect on the average speed was analysed through a linear regression model (using SPSS GENLIN procedure) with normal distribution and identity link function. For each data collection point a model was calculated, which can be expressed as next:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_2 x_1 x_2 \qquad (1)$$

with y = average speed; x_1 = location (dummy variable: treated vs. comparison location); x_2 = period (dummy variable: before vs. after period) and β_1 = difference in the average speed between the treated location and the comparison location; β_2 = difference in the average speed between the before and the after period; β_3 = interaction-effect, which indicates the difference in the average speed between the before and the after period in the treated group, with control for other factors that had an influence on the driving speed through the use of the data of the comparison locations.

The effect on the odds of drivers exceeding the speed limit and the effect on the odds of drivers exceeding the speed limit by more than 10% was analysed through a logistic regression model (SPSS GENLIN) with binomial distribution and logit link function. For these analyses the same independent variables were used.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 \qquad (2)$$

with $y = \frac{P(A)}{1-P(A)}$ = ratio of the probability drivers exceed the speed limit and the probability drivers do not exceed the speed limit; x_1 = location (dummy variable: treated vs. comparison location); x_2 = period (dummy variable: before vs. after period) and β_1 = relative difference in the odds of speed violations between the treated and comparison group; β_2 = the relative difference in the odds of speed violations between the before and the after period; β_3 = the relative difference in the odds of speed violations between the before and after period in the treated group, with control for other factors that had an influence on the driving speed through the use of the data of the comparison locations.

Furthermore separate effects were analysed according to the time of the week (week/weekend) and the time of the day (day/night and peak/off-peak). In order to analyse the effect for each time period separately, the above mentioned formulas were applied. However, in order to analyse the difference between the two time periods (for example week and weekend) this was included as third independent variables, which can be expressed through next formula:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1 x_2 + \beta_5 x_2 x_3 + \beta_6 x_1 x_3 + \beta_7 x_1 x_2 x_3 \qquad (3)$$

with x_1 = location (dummy variable: treated vs. comparison location); x_2 = period (dummy variable: before vs. after period); x_3 = time (dummy variable: week/weekend or day/night or peak/off-peak)

In this analysis β_7 is the most important value, as it shows the difference between the two time variables (for example week and weekend) and indicates whether this difference is significant. A number close to one indicates that the effect on the drivers exceeding the speed limit are similar for both periods.

3.4. Selection of three traffic conditions

An accurate evaluation of the effect of ASSC through a before- and after comparison can only be applied if the moments are included at which drivers were free to choose their speed. For this reason only the moments with free-flow to conditioned flow were included (further referred to as traffic condition A). This was based on the combination of the flow rate and the average speed. Only the minutes during which the flow rate was less than 21 vehicles per minute per lane and the average speed was higher than 80 km/h were included.

Table 1
Average number of vehicles per measurement point, included in this study.

		Before	After
Direction of Brussels	Traffic condition A	213,113	209,329
	Traffic condition B	62,007	65,448
Direction of Ghent	Traffic condition A	223,388	216,677
	Traffic condition B	71,813	77,725
Comparison locations	Traffic condition A	202,228	203,860
	Traffic condition B	19,021	25,179

However, in order to get a full view on the effects during the different traffic flow states, also a separate analysis of the moments with conditioned flow to congested flow was applied, which included all minutes during which the flow rate was higher than 21 vehicles per minute per lane or the average speed was lower than 80 km/h (further referred to as traffic condition B). Thirdly an analysis of all the vehicles, irrespective of the traffic flow, was applied.

Table 1 shows the number of vehicles that were included in this study, for which an average per measurement point was calculated for the locations in the direction of Brussels, for the locations in the direction of Ghent and for the comparison locations. A distinction is made between traffic condition A and condition B.

3.5. Selection of passengers cars

The application of a linear regression model is only possible when the dependent variable (i.e. the speed) is distributed normally. However, when all vehicles are taken into account, a bimodal graph can be found: with a peak at around 90 km/h for the heavy vehicles and a peak around 120 km/h for the passenger cars. It was thus not possible to use this dataset in a linear regression model. For this reason, and because these vehicles are generally limited to a speed of 90 km/h, we excluded heavy vehicles (i.e. vehicles with a length above 6.8 m), and only motor riders, passengers cars and vans were included in the study. The speeds of this selection showed a normal distribution.

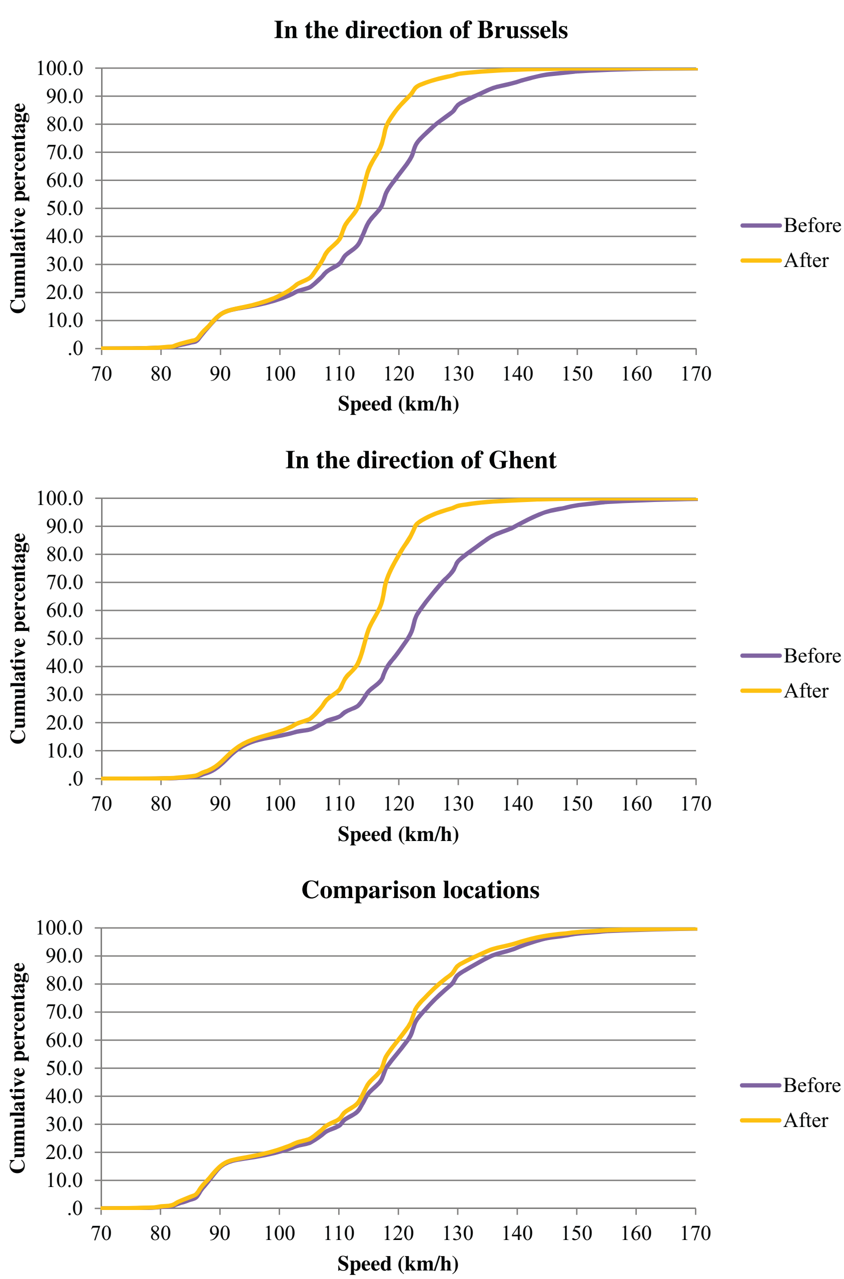

Fig. 1. Cumulative speed distribution on the ASSC during traffic condition A in the two directions and at the comparison locations.

4. Results

4.1. General effects

4.1.1. Free-flow to conditioned flow (traffic condition A)

Fig. 1 displays the cumulative speed distribution on the ASSC in each of the two directions and at the comparison locations. For these graphs data are used from traffic condition A. In the first two graphs, which show the speeds on the section in each of the two directions, can be seen that the line shifts to the left, which clearly indicates speeds are lower during the after period. In the direction of Brussels the average speed limit was 119.43 km/h during the before period, whereas this was 113.50 km/h during the after period. The proportion of drivers exceeding the speed limit (i.e. the number of drivers exceeding the speed limit on the total number of drivers) decreased from 43% to 16%; the proportion of drivers exceeding the speed limit by more than 10% decreased from 12% during the before period to 2% during the after period. In the direction of Ghent the average speed was 124.57 km/h and 115.53 km/h during the before and after period respectively; 63% of the drivers exceeded the speed limit during the before period, whereas this was 23% during the after period; for the proportion of drivers exceeding the speed limit by more than 10% these numbers were 22% and 2%.

At the comparison locations (see third graph) also a small decrease in the speed from the before to the after period can be found. The average speed decreased from 122.13 km/h to 120.48 km/h; the proportion of drivers exceeding the speed limit decreased from 53% to 48% and the proportion of drivers exceeding the speed limit by more than 10% decreased from 17% to 13%. It is difficult to explain this decrease. However, the speed was measured during one week in the before period and one week in the after period. Possibly the weather

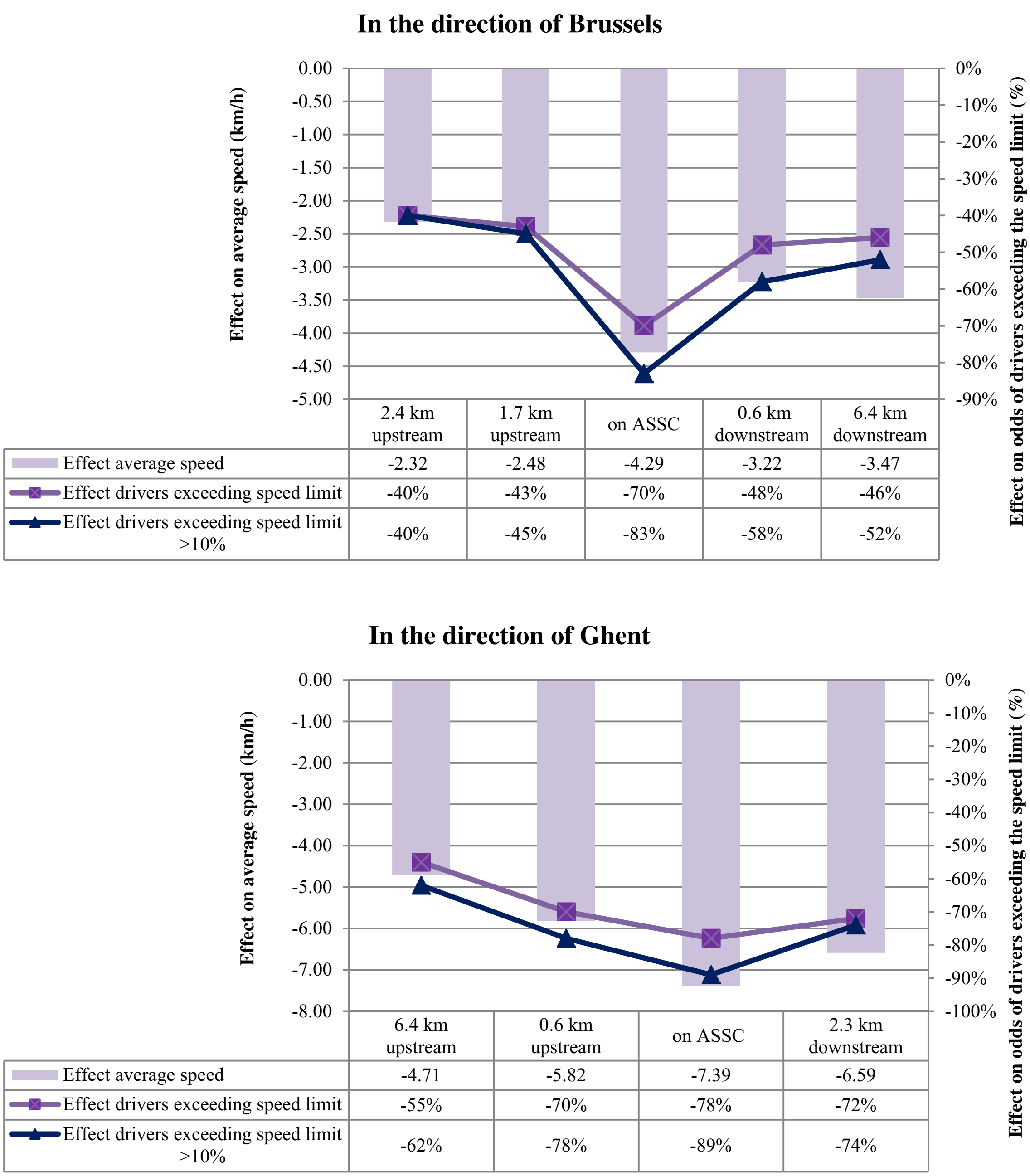

Fig. 2. Graphical display of the speed effects during traffic condition A at the different measurement points as a result of the installation of ASSC.

Table 2
Detailed results of the speed effects during traffic condition A at the different measurement points as a result of the installation of ASSC.

	Effect on average speed[a] [95% CI][b]	Effect on odds of drivers exceeding the speed limit[c] [95% CI][d]	Effect on odds of drivers exceeding the speed limit > 10%[c] [95% CI]
	In the direction of Brussels		
2.4 km upstream	−2.32	0.60	0.60
	[−2.42; −2.23]*	[0.59; 0.61]*	[0.58; 0.61]*
1.7 km upstream	−2.48	0.57	0.55
	[−2.57; −2.38]*	[0.57; 0.58]*	[0.54; 0.57]*
On ASSC	−4.29	0.30	0.17
	[−4.38; −4.19]*	[0.30; 0.31]*	[0.17; 0.18]*
0.6 km downstream	−3.22	0.52	0.42
	[−3.33; −3.11]*	[0.51; 0.53]*	[0.41; 0.43]*
6.4 km downstream	−3.47	0.54	0.48
	[−3.56; −3.37]*	[0.53; 0.54]*	[0.47; 0.49]*
	In the direction of Ghent		
6.4 km upstream	−4.71	0.45	0.38
	[−4.80; −4.62]*	[0.44; 0.46]*	[0.37; 0.39]*
0.6 km upstream	−5.82	0.30	0.22
	[−5.91; −5.73]*	[0.29; 0.30]*	[0.22; 0.23]*
On ASSC	−7.39	0.22	0.11
	[−7.49; −7.29]*	[0.22; 0.22]*	[0.11; 0.12]*
2.3 km downstream	−6.59	0.28	0.26
	[−6.69; −6.50]*	[0.28; 0.29]*	[0.25; 0.27]*

*Significant at the 5% level.
[a] Calculated through the interaction effect of Eq. [1], using SPSS GENLIN models.
[b] Calculated through the Wald confidence intervals (SPSS GENLIN models) with next formula: $\beta^j \pm z_{1-\alpha/2}\sigma^{\beta_j}$ where z_p is the 100pth percentile of the standard normal distribution (IBM, 2011).
[c] Calculated through the interaction effect of Eq. [2], using SPSS GENLIN models. The relative effect can be calculated as: 100(effect − 1)%
[d] Calculated through the Wald confidence intervals (SPSS GENLIN models) with next formula: $\exp(\beta^j \pm z_{1-\alpha/2}\sigma^{\beta_j})$ (IBM, 2011).

circumstances had an effect on the driving speed since there was no rain during the before period, but there were some rainy periods during the after period.

Fig. 2 shows the effects (i.e. the difference from the before to the after period, taking general trend effects into account) of the installation of ASSC at the different measurement points in the two directions. At first sight the effects on the section are clearly visible. Nevertheless, also at the locations upstream and downstream from the ASSC high decreases could be observed, which are all significant (see Table 2).

On the enforced section in the direction of Brussels the average speed decreased by 4.92 km/h. At 0.6 km and 6.4 km downstream from the exit of the section also decreases were found of 3.22 km/h and 3.47 km/h respectively. The decreases upstream from the entrance of the section were somewhat more limited: −2.32 km/h at 2.4 km upstream and −2.48 km/h at 1.7 km upstream. The odds of drivers exceeding the speed limit decreased by 70% from before to after the installation of the ASSC system. The effects at the locations up- and downstream from the section were close to each other: from minimum −40% to maximum −48%. The effects on the odds of drivers exceeding the speed limit by more than 10% were even higher, with a decrease of 83% on the section. At 0.6 km and 6.4 km downstream, the odds of speed limit violations decreased by 58% and 52% respectively, while 2.4 km and 1.7 km upstream decreases of 40% and 45% were found.

On the section in the direction of Ghent the speed decreased by 7.39 km/h on average (see Table 2). At 2.3 km downstream from the exit the speed decreased by 6.59 km/h on average. Also upstream

Table 3
Detailed results of the speed effects during traffic condition B at the different measurement points as a result of the installation of ASSC.

	Effect on average speed [95% CI]	Effect on odds of drivers exceeding the speed limit [95% CI]	Effect on odds of drivers exceeding the speed limit > 10% [95% CI]
	In the direction of Brussels		
2.4 km upstream	1.04	0.55	0.58
	[0.68; 1.39]*	[0.53; 0.57]*	[0.54; 0.64]*
1.7 km upstream	0.27	0.55	0.55
	[−0.10; 0.64]	[0.53; 0.57]*	[0.51; 0.59]*
On ASSC	1.69	0.26	0.14
	[1.36; 2.03]*	[0.25; 0.27]*	[0.13; 0.16]*
0.6 km downstream	4.19	0.50	0.45
	[3.70; 4.69]*	[0.48; 0.52]*	[0.42; 0.49]*
6.4 km downstream	−17.24	0.27	0.23
	[−17.91; −16.57]*	[0.26; 0.29]*	[0.20; 0.26]*
	In the direction of Ghent		
6.4 km upstream	0.40	0.43	0.44
	[−0.17; 0.95]	[0.41; 0.45]*	[0.40; 0.49]*
0.6 km upstream	0.43	0.28	0.22
	[0.05; 0.82]*	[0.27; 0.29]*	[0.20; 0.24]*
On ASSC	0.30	0.21	0.08
	[−0.05; 0.64]	[0.20; 0.22]*	[0.07;0.09]*
2.3 km downstream	2.62	0.89	1.00
	[2.14; 3.10]*	[0.86; 0.92]*	[0.94; 1.06]

*Significant at the 5% level.

Table 4
Detailed results of the speed effects at the different measurement points as a result of the installation of ASSC, including all vehicles.

	Effect on average speed [95% CI]	Effect on odds of drivers exceeding the speed limit [95% CI]	Effect on odds of drivers exceeding the speed limit > 10% [95% CI]
	In the direction of Brussels		
2.4 km upstream	−1.77 [−1.87; −1.67]*	0.60 [0.59; 0.61]*	0.60 [0.58; 0.61]*
1.7 km upstream	−2.02 [−2.12; −1.91]*	0.58 [0.57; 0.59]*	0.55 [0.54; 0.57]*
On ASSC	−2.87 [−2.97; −2.77]*	0.30 [0.30; 0.31]*	0.17 [0.16; 0.18]*
0.6 km downstream	−1.54 [−1.67; −1.42]*	0.53 [0.52; 0.53]*	0.43 [0.42; 0.44]*
6.4 km downstream	−5.41 [−5.54;−5.28]*	0.53 [0.52; 0.53]*	0.48 [0.46; 0.49]*
	In the direction of Ghent		
6.4 km upstream	−3.69 [−3.80; −3.59]*	0.45 [0.45;0.46] *	0.40 [0.39;0.41]*
0.6 km upstream	−4.73 [−4.83;−4.63]*	0.30 [0.29;0.30]*	0.22 [0.21;0.23]*
On ASSC	−5.40 [−5.50; −5.29]*	0.23 [0.22;0.23]*	0.10 [0.10;0.11]*
2.3 km downstream	−5.65 [−5.77;−5.53]*	0.42 [0.42; 0.43]*	0.39 [0.38; 0.40]*

*Significant at the 5% level.

high decreases were found: −4.71 km/h at 6.4 km and −5.82 km/h at 0.6 km before the entrance. The odds of drivers that exceeded the speed limit on the enforced section decreased by 78%. At 6.4 km and 0.6 km upstream decreases of 55% and 70% respectively were found. Downstream the number of violations also clearly decreased (−72%). A decrease of 89% was found in the odds of speed limit violations above 10% of the posted speed limit. For both types of violations also high decreases were found at the locations upstream (−62% and −78%) and downstream (−74%) from the enforced section.

For the section in the direction of Ghent clearly higher decreases were found compared to the section in the direction of Brussels (e.g. average speed decreased by 7.39 km/h and 4.29 km/h respectively). However, as can be seen from Fig. 1 the initial speed during the before period was higher in the direction of Ghent, compared to the direction of Brussels. In the direction of Brussels the average speed was 119.43 km/h, whereas in the direction of Ghent this was 124.57 km/h.

4.1.2. Conditioned flow to congested flow (traffic condition B)

Table 3 shows the effects of the analyses with traffic condition B, i.e. all minutes during which the flow rate was higher than 21 vehicles per minute per lane or the average speed was lower than 80 km/h. When these results are compared with the results as displayed in Table 2, it can be seen that the effects are clearly lower during traffic condition B, and even speed increases were found from the before to the after period. These distinct effects can probably be ascribed to other factors that were different between the before and the after period, which will mainly be the occurrence of traffic jams. There are however some remarkable results. For example, in the direction of Brussels, at 0.6 km downstream, the average speed increased by 4.19 km/h during traffic condition B, whereas a speed decrease of 3.22 km/h was found during traffic condition A. On the other hand, the average speed decreased by 17.24 km/h at 6.4 km downstream during traffic condition B, whereas this was −3.47 km/h during traffic condition A. For the effects on the odds of drivers exceeding the

Table 5
Effect according to the time of the week (week/weekend) and the time of the day (day/night and off-peak/peak) (effect [95% confidence interval]), during traffic condition A.

	Direction of Brussels			Direction of Ghent		
	Week	Weekend	Week vs. weekend	Week	Weekend	Week vs. weekend
Average speed	−4.22 [−4.35; −4.11]*	−4.43 [−4.60; −4.27]*	−0.21 [−0.41; 0.003]*	−7.53 [−7.65; −7.41]*	−7.19 [−7.35; −7.03]*	−0.34 [−0.14; −0.54]*
Drivers exceeding speed limit	0.29 [0.28; 0.29]*	0.33 [0.32; 0.34]*	1.15 [1.11; 1.20]*	0.21 [0.21; 0.22]*	0.24 [0.23; 0.25]*	1.14 [1.10; 1.18]
Drivers exceeding speed limit >10%	0.15 [0.14; 0.16]*	0.21 [0.20; 0.22]*	1.38 [1.28; 1.49]*	0.10 [0.09; 0.10]*	0.14 [0.13; 0.15]*	1.44 [1.35; 1.55]*
	Day	Night	Day vs. night	Day	Night	Day vs. night
Average speed	−4.15 [−4.25; −4.05]*	−4.96 [−5.27; −4.65]*	−0.81 [−1.11; −0.52]*	−7.02 [−7.13; −6.91]*	−7.74 [−8.02; −7.46]*	-0.72 [-0.99; -0.44]*
Drivers exceeding speed limit	0.31 [0.31; 0.32]*	0.27 [0.26; 0.28]*	0.87 [0.82; 0.91]*	0.23 [0.22; 0.23]*	0.22 [0.20; 0.22]*	0.95 [0.90; 0.99]*
Drivers exceeding speed limit > 10%	0.17 [0.17; 0.18]*	0.17 [0.16; 0.19]*	0.99 [0.90; 1.10]	0.12 [0.11; 0.12]*	0.12 [0.11; 0.13]*	1.06 [0.96; 1.16]*
	Off-peak	Peak	Off-peak vs. peak	Off-peak	Peak	Off-peak vs. peak
Average speed	−4.14 [−4.25; −4.04]*	−5.52 [−5.81; −5.24]*	−1.38 [−1.69; −1.07]*	−7.28 [−7.38; −7.18]*	−8.43 [−8.75; −8.11]*	-1.15 [-1.49; -0.81]*
Drivers exceeding speed limit	0.32 [0.31; 0.32]*	0.19 [0.18; 0.20]*	0.61 [0.57; 0.64]*	0.23 [0.22; 0.23]*	0.15 [0.15; 0.16]*	0.68 [0.64; 0.72]*
Drivers exceeding speed limit >10%	0.18 [0.18; 0.19]*	0.07 [0.06; 0.08]*	0.36 [0.30; 0.44]*	0.12 [0.11; 0.12]*	0.07 [0.06; 0.08]*	0.57 [0.48; 0.66]*

*Significant at the 5% level.

Table 6
Standard deviation (in km/h) at the different measurement locations, during traffic condition A.

	Before	After
Direction of Brussels		
2.4 km upstream	12.61	11.84
1.7 km upstream	12.94	11.74
On ASSC	12.89	9.35
0.6 km downstream	13.67	11.04
6.4 km downstream	13.60	11.91
Direction of Ghent		
6.4 km upstream	12.86	11.41
0.6 km upstream	12.86	10.86
On ASSC	13.27	9.05
2.3 km downstream	12.90	11.33
Comparison locations		
	13.57	13.15

speed limit, similar results were found for traffic condition B as for traffic condition A. Only at 6.4 km downstream in the direction of Brussels, higher effects were found during traffic condition B. However, it should be noted that the number of drivers that exceeded the speed limit are clearly lower at this measurement point compared to other measurement points. For example, the number of drivers that exceeded the speed limit during the after period was 13,797 at 1.7 km upstream, 8790 on the ASSC, 8542 at 0.6 km downstream and 1922 6.4 km downstream. These lower absolute rates can subsequently lead to higher relative differences.

4.1.3. All moments

Next to the analysis of the free-flow to conditioned flow and the conditioned to congested flow, a separate analysis was applied in which all moments were included. As can be seen from Table 4 , the results are close to the results of the analyses with traffic condition A, but the decreases in the average speed were less high. However the effects on the odds of drivers exceeding the speed limit and the odds of drivers exceeding the speed limit by more than 10% are nearly similar. Only at the measurement point at 6.4 km downstream in the direction of Brussels higher decreases were found in the analyses with all data, compared to the analyses that included traffic condition A. As explained before, this can be ascribed to differences in the traffic situation (i.e. traffic jams) between the before and the after period.

4.2. Comparison according to time

In addition to the general effects, the results were compared according to next time periods: week/weekend; day/night; peak/off-peak. For these analyses only traffic condition A was selected. Table 5 shows the results of these comparisons. Columns 2, 3, 5 and 6 show the differences in the average speed and in the odds of drivers exceeding the speed limit from before to after the installation of the ASSC systems. Columns 4 and 7 show the results of the regression models in which the time variable was included as third independent variable, and a three-way interaction model was applied (see Eq. (3). Through this regression model it was possible to determine whether there was a significant difference in the effect between the two time variables, for example week and weekend. For these analyses only the speed data that were measured on the section were used.

A comparison of the effect between week and weekend showed no large differences. Slightly higher decreases were found during the week (except for the average speed in the direction of Brussels). However, the differences are small. A comparison of day and night showed slightly higher decreases in the average speed during the night. The differences in the effects on the speed limit violations were small. A comparison of the effects during the peak and the off-peak hours showed higher decreases during the peak hours, both for the average speed as the odds of speed limit violations.

4.3. Effect on speed variance

Furthermore also the speed variances were compared from before to after the installation of ASSC. Also for these analyses traffic condition A was selected. Table 6 shows the results of the speed standard deviation at the different locations. At all the data collection points the standard deviation was lower in the after period compared to the before period. The highest differences were found on the enforced section. The homogeneity of variance test (using the Levene's test) showed that all differences were significant. In Table 7 the standard deviations are shown for the data collection points on the enforced sections and the comparison locations, subdivided to the different time periods. The speed deviation decreased during all these time periods. Furthermore, no clear differences were found according to the time period.

Table 7
Standard deviation (in km/h) on the ASSC and the comparison locations during traffic condition A, subdivided into the different time periods.

	Week		Weekend	
	Before	After	Before	After
Direction of Brussels	12.75	9.23	13.13	9.54
Direction of Ghent	13.28	8.98	13.27	9.15
Comparison locations	13.48	13.14	13.64	13.14
	Day		Night	
	Before	After	Before	After
Direction of Brussels	12.64	9.19	14.35	10.25
Direction of Ghent	12.97	8.95	13.63	9.71
Comparison locations	13.25	12.89	15.95	15.24
	Off-peak		Peak	
	Before	After	Before	After
Direction of Brussels	12.96	9.45	12.15	8.15
Direction of Ghent	13.32	9.09	12.71	8.5
Comparison locations	13.73	13.32	12.72	12.32

Table 8
Speed behaviour of passenger cars at different locations on the enforced section of the E17 motorway.

	At the entrance	Middle of the section	490 m before the exit of the section
Average speed (km/h)	87.4	85.2	84.3
Proportion of drivers exceeding the speed limit	22.2%	11.4%	7.4%
Proportion of drivers exceeding the speed limit by > 10%	9.3%	1.8%	1.3%

5. Discussion

The present study analysed the effect of ASSC on speed behaviour. This was an extensive study which included on average 200,000 vehicles during the before and during the after period at the different measurement points, taking only moments into account with free-flow to conditioned flow. On the enforced sections the speed decreased by an average of 5.84 km/h (−4.29 km/h in the direction of Brussels and −7.39 km/h in the direction of Ghent). The odds of drivers exceeding the speed limit decreased on average by 74% (−70% and −78%), for the odds of drivers exceeding the speed limit by more than 10% this was −86% (−83% and −89%). Only a limited number of studies analysed this effect, and thus it is difficult to compare the effects of ASSC on Flemish roads with international studies. A literature review of both published and grey literature generally concluded that the installation of ASSC is related with reductions up to 90% in the proportion of vehicles exceeding the speed limit (Soole et al., 2013). The results in the present study are more limited, however also decreases up to 78% of the odds of drivers exceeding the speed limit were found. It should however be noted that in the present study only the effect at one point on the ASSC was measured and it was unclear what the average speed was over the whole segment.

Soole et al. (2013)furthermore concluded that there is still limited evidence that ASSC influences the speeding behaviour outside the immediate vicinity of the enforced section. The present study found favourable effects up to 6 km before and after the enforced section. These effects ranged from a decrease of minimal 2.32 km/h to maximal 6.59 km/h, and from minimal −40% in the odds of speed limit violations to maximal −72%. The ASSC devices are however not clearly visible for the drivers, since these are installed at a bridge at the entrance and at the exit of the enforced section. Subsequently drivers may be unsure about the starting and the ending point of the section. Furthermore there is a weigh-in-motion device present at 3 km before the entrance of the enforced section in the direction of Ghent. We can expect that some drivers confuse these weigh-in-motion devices with the ASSC devices. However this weigh-in-motion system was already present during the before period. At the other side of the section, in both directions, there were dynamic speed limit systems present from 2 km after the exit of the section (in the direction of Ghent) and up to 2 km before the entrance of the section (in the direction of Brussels). Nevertheless it can be expected that the influence of this measure on the results in the present study was limited. The dynamic speed limit system is used at moments of road works, crash incidents or traffic jams. In the present study moments with free-flow to conditioned flow were separately analysed, during which no incidents occurred. We can thus conclude that the weigh-in-motion and the dynamic speed limit installations could have had an influence on the driving speed upstream and downstream from the section, but that this effect was limited and that the largest part of the speed decreases can be ascribed to the ASSC systems. It can however be stated that 6 km is still a limited distance. Therefore it would be interesting to analyse the effect at larger distances from the section.

Not only absolute speed, but also speed variance has been found to relate to crash numbers. Previous studies found that larger speed variances are related with higher crash rates (Aarts and Van Schagen, 2006). In the present study the variance of speeds decreased from before the installation of the ASSC systems to after the installation. The highest effects were found on the section, but also favourable effects were found at the points up- and downstream from the section. Previous research found that ASSC leads to reductions in speed variability, which results in more homogenised traffic flows, improved traffic density and reduced journey travel times (Cascetta et al., 2011; Soole et al., 2013).

Since the ASSC system was operational in March 2013 and the study was applied in June 2013 speed data could only be gathered at one moment shortly after the installation. Speed data was collected one month after the ASSC became operational. Subsequently it was not possible to determine whether the speed effects will persist after a longer period. Further research should be applied in order to analyse the effects on a longer term.

Furthermore it was not possible to analyse the effects on the number of crashes, because of the short after period. Previous research (Soole et al., 2013; Montella et al., 2012a) generally found favourable effects in all crash types, especially for the most severe crashes. It would be interesting to analyse the crash effects of the ASSC on Flemish roads in future research.

The study included two comparison locations in order to control for confounding factors. These comparison locations were included as besides the effects of the treatment itself, a range of other factors has possibly had an effect on the driving speed and thus need to be corrected for. Examples of those confounding factors are widely implemented traffic safety measures, seasonal factors and weather conditions. If we do not include these comparison locations, we cannot be sure whether the effect that we measured on the locations upstream, downstream and on the section was attributable to the installation of ASSC or whether it was attributable to other factors that that had an influence on the driving speed. However, in order to control for these confounding variables the locations in the comparison group have to be comparable to the treated locations on a couple of characteristics. In order to select locations that are similar to the treated locations on infrastructural characteristics and traffic volume, we selected locations at the same motorway, but 35 km away from the treated locations. In order to get a clear view on the influence of the comparison locations on the results, we reported the speed data of the treated and comparison locations separately. As can be seen from Fig. 1, the speed is slightly lower in the after period compared to the before period. From this we can conclude that the effects would have been stronger (i.e. higher decreases in the average speed and the odds of drivers exceeding the speed limit) if the data of the comparison locations would not have been used.

We found spill over effects, which should be taken into account in the selection of the comparison locations. However, it should be noted that this spill over effect might for a part be attributable to the unclear location of the starting and the ending point of the section. In addition, we only found these spill over effects at a relatively short distance from the ASSC, i.e. at maximum 6 km upstream and downstream from the starting and ending point.

In order to exclude possible spill over effects, speed data was gathered at a substantial longer distance from the ASSC, namely 35 km.

A study of different sections in Norway found higher speed decreases at the entrance and the exit of the section, compared to the middle of the section (Ragnøy, 2011). It was not possible to apply such comparison in the presently investigated sections as speeds were measured at only one data collection point on the enforced section. However, within the framework of the present study, more detailed data were available on the speed behaviour at a 1.9 km long enforced section of the E17 motorway with a posted speed limit of 90 km/h. Data were collected at three different measurement points, the first at the entrance, the second in the middle and the third near the end (490 m before the exit) of the enforced section. The results showed that the average speed as the odds of drivers (i.e. passenger cars) that violated the speed limit decreased gradually throughout the section. The odds of drivers that exceeded the speed limit decreased from 22.2% at the entrance of the section to 11.4% at the middle and 7.4% at 490 m before the exit of the section (see Table 8). These analyses showed that speeds are relatively homogeneous with a tendency to decrease gradually from the entrance to the exit of the section. Nevertheless it should be studied what effects can be found at sections of a different length.

The present study analysed two locations with ASSC. Both locations are similar concerning infrastructural characteristics, as they are located at the same motorway, but in an opposite direction. However, larger effects were found for one of the roads. This could be ascribed to the situation in the before period. The speeding behaviour during the before period was clearly higher at the locations for which the highest effects were found.

6. Conclusions

- The installation of ASSC led to favourable effects on the average speed, the odds of drivers exceeding the speed limit and the odds of drivers exceeding the speed limit by more than 10%.
- Favourable effects were found up to 6 km before and after the enforced section.
- The speed variability decreased after the installation of ASSC.
- Within an enforced section, speeds are relatively homogenous with a tendency to decrease gradually from the entrance to the exit of the section.

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References

Aarts, L., Van Schagen, I., 2006. Driving speed and the risk of road crashes: a review. Accident Anal. Prev. 38 (2), 215–224. doi:http://dx.doi.org/10.1016/j.aap.2005.07.004.
Cascetta, E., Punzo, V., Montanino, M., 2011. Empirical analysis of effects of automated section speed enforcement system on traffic flow at freeway bottlenecks. Transp. Res. Rec.: J. Transp. Res. Board 2260, 83–93. doi:http://dx.doi.org/10.3141/2260–10.
Cascetta, E., Sorvillo, R., Punzo, V., 2010. Impact on vehicle speeds and pollutant emissions of a fully automated section speed control scheme on the Naples urban motorway. The 89th Annual Meeting of the Transportation Research Board, Washington, D.C.
Elvik, R., Christensen, P., Amundsen, A., 2004. Speed and Road Accidents. An Evaluation of the Power Model (No. 740 /2004). Oslo Institute of Transport.
Elvik, R., Høye, A., Vaa, T., Sørensen, M., 2009. The Handbook of Road Safety Measures, second ed. Emerald Group Publishing Limited, Bingley.
I.B.M. (2011), IBM SPSS Statistics 20 Algorithms.
Montella, A., Persaud, B., D'Apuzzo, M., Imbriani, L.L., 2012a. Safety evaluation of automated section speed enforcement system. Transp. Res. Rec.: J. Transp. Res. Board 2281, 16–25. doi:http://dx.doi.org/10.3141/2281–03.
Montella, A., Punzo, V., Montanino, M., 2012b. Analysis of drivers' compliance to speed limits enforced with an automated section speed enforcement system. The 91st Transportation Research Board Annual Meeting, Washington, D C..
Mountain, L.J., Hirst, W.M., Maher, M.J., 2004. Costing lives or saving lives: a detailed evaluation of the impact of speed cameras. Traffic Eng. Control 45 (8), 280–287.
Ragnøy, A., 2011. Automatic Section Speed Control. Results of Evaluation. (No. 2010: 2625). Oslo Directorate of Public Roads.
SARTRE consortium, 2004. European drivers and road risk. The SARTRE 3 survey.
SARTRE consortium, 2012. European road users' risk perception and mobility. The SARTRE 4 survey.
Soole, D.W., Watson, B.C., Fleiter, J.J., 2013. Effects of average speed enforcement on speed compliance and crashes: a review of the literature. Accident Anal. Prev. 54, 46–56. doi:http://dx.doi.org/10.1016/j.aap.2013.01.018.