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Dynamic speed limits on Flemish motorways

Effects on crashes and the balance against the costs

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Summary

Dynamic speed limit systems are widely applied in order to account of the real time traffic, road and weather conditions. On the basis of the traffic volume and other environmental conditions, the speed limit can be adapted, which is denoted by electronic signs that are housed within gantries situated above lanes. Dynamic speed limits try to harmonize traffic flows, which can improve capacity. Furthermore these systems try to improve traffic safety, through the reduction of manoeuvres.

The present study evaluates the traffic safety effects of dynamic speed limit systems in Flanders, Belgium, and compares the benefits of this measure in terms of traffic safety effects against the costs of these systems. In order to analyse the traffic safety effects, the number of crashes after the implementation of the dynamic speed limits were compared with the number of crashes before the implementation. General trend effects and chance were taken into account in this comparison. At first all crashes were studied (irrespective of the severity of the injuries); secondly, a separate analysis was applied for severe crashes (i.e. fatal and serious injury crashes). Furthermore, the injury crashes were subdivided according to the type of crash and the three main crash types were analysed: (1) rear-end crashes; (2) side crashes; (3) single-vehicle crashes.
Five road segments with dynamic speed limit systems were analysed, which were located at motorways and had a total length of almost 60 km. The before-and-after study of the crash numbers showed that the injury crashes significantly decreased by 18%. A non-significant decrease of 6% was found in the number of serious and fatal injury crashes. A distinction according to the crash type showed an almost significant decrease of 20% in the number of rear-end crashes. The number of single-vehicle crashes decreased non-significantly by 15%. No effect was found for side crashes.

In addition to the analysis of the effects, a cost-benefit analysis was applied. The costs of the implementation of these systems were compared with the benefits of crash prevention. Using unit values from the international literature for the valuation of crash prevention, the cost-benefit analyses of the crash effects showed a benefits-to-costs ratio of approximately 0.7, which means that the costs exceed the benefits. Taking into account the important margins of uncertainty with respect to both costs and benefits, we have also explored how the net benefits are affected by some key assumptions. The general conclusion is that there is no convincing evidence that the cost of the system outweighs the expected benefits in terms of crash prevention. However, as this analysis is based on an ex post assessment of systems that were implemented over the course of the last decade, one should be careful in drawing conclusions regarding the expected benefits of new systems that would be based on current state-of-the-art technology.

Nederlandstalige samenvatting

Dynamische rijstrooksignalisatie is een maatregel die meer en meer wordt toegepast op Vlaamse autosnelwegen. Op een portiek boven elke rijstrook is een dynamisch bord aangebracht dat de vaste maximum snelheidslimiet kan verlagen en afstemmen op de heersende situatie. Door middel van deze aangepaste snelheid wordt getracht om de verkeersafwikkeling vlotter te laten verlopen, en files te vermijden en bestaande files sneller op te lossen. Ook kan dit systeem helpen om manoeuvres te voorkomen en de verkeersveiligheid te bevorderen.

In voorliggende studie werd onderzocht welke verkeersveiligheidseffecten deze maatregel voortbrengt en wordt aansluitend een kosten-batenanalyse uitgevoerd.
Het effect op de verkeersveiligheid werd onderzocht door het aantal ongevallen na het plaatsen van rijstrooksignalisatie te vergelijken met het aantal ongevallen voor het invoeren van deze maatregel. Hierbij werd ook rekening gehouden met algemene trendeffecten en met de toevalsfactor die meespeelt in het ontstaan van ongevallen. In totaal werden vijf autosnelwegsegmenten met rijstrooksignalisatie onderzocht, met een totale lengte van bijna 60 km. In de analyses werden enerzijds letselongevallen en anderzijds ernstige ongevallen (= ongevallen met doden of zwaar gewonden) geanalyseerd. Daarnaast werden de letselongevallen onderverdeeld naar type aanrijding en werden de drie types die het meest voorkomen op autosnelwegen onderzocht, namelijk kop-staartaanrijdingen, flankaanrijdingen en eenzijdige aanrijdingen. De letselongevallen vertoonden een significante daling van 18% na het plaatsen van rijstrooksignalisatie. Voor de ernstige ongevallen werd een niet-significante daling van 6% gevonden. Het aantal kop-staartaanrijdingen daalde met 20%. Het aantal eenzijdige aanrijdingen daalde na het invoeren van de maatregel met 15%, maar dit resultaat was niet significant. Dit wijst er op dat dit gevonden resultaat niet noodzakelijk te wijten was aan het plaatsen van rijstrooksignalisatie maar dat hier ook andere factoren een rol speelden. Er werden geen effecten gevonden op het aantal flankaanrijdingen.

Aansluitend op deze effectiviteitsstudie werd een kosten-baten analyse uitgevoerd van de effecten op ongevallen. In deze analyse werden de kosten die het implementeren van deze systemen met zich meebrengen afgezet tegen de baten van ongevalpreventie. Voor de waardering van deze baten hebben we gebruik gemaakt van eenheidswaarden uit de internationale literatuur. Een afweging van de baten ten opzichte van de kosten, resulteerde in een ratio van 0.7, wat aangeeft dat de kosten de baten overschrijden. Omwille van de grote mate van onzekerheid met betrekking tot zowel de baten als de kosten, hebben we ook nagezien hoe gevoelig de netto baten zijn voor veranderingen in bepaalde sleutelparameters. Op basis daarvan kunnen we besluiten dat er geen overtuigend bewijs is dat de baten van het bestaand systeem opwegen tegen de kosten, tenminste vanuit het perspectief van de verkeersveiligheid. Men moet wel voor ogen houden dat onze analyse enkel een ex post evaluatie inhoudt van systemen die in de loop van het afgelopen decennium in gebruik werden genomen. Men kan deze resultaten daarom niet direct toepassen in een ex ante analyse van systemen die gebaseerd zijn op huidige state-of-the-art technologie.

1 Introduction

On the majority of the roads, fixed speed limits represent the appropriate speed for average conditions. However, in order to take account of the real time traffic, road and weather conditions dynamic speed limits (DSLs) can be applied (European Commission, 2010). DSL systems are activated on a given time, as a consequence of traffic volume or other environmental conditions (Islam et al., 2013; OECD, 2006).

Variable speed limits are often used as a synonym for DSLs. However, according to the OECD (2006) the term 'variable speed limits' refers to systems that are activated through general criteria (e.g. time of the day, season and certain weather conditions), which are usually set at the national level. In some countries the speed limit is reduced in case of rain, or speed limits nearby school zones are reduced at entering or exiting times. However, the focus of the present study is on DSLs, which are adapted as a consequence of the real time situation. Through these systems speed limits can be adapted from a distance, automatically or manually, which makes it possible to show different speed limits at different times of the day and different days of the week (van Nes et al., 2010). DSLs harmonize traffic flows, which improves capacity and traffic safety. This traffic safety improvement is reached through reductions in speed variations within and across lanes and between upstream and downstream flows (Lee et al., 2004; Islam et al., 2013; Habtemichael & de Picado Santos; 2013). DSLs are sometimes used in order to reduce vehicle emissions and road noise (Papageorgiou et al., 2008).

DSL systems are also applied on Flemish motorways (Belgium). The speed limit is denoted by electronic signs which are housed within gantries situated above motorway lanes. DSL systems in Flanders are compulsory and have three main objectives (Vlaams Verkeerscentrum, 2015):

(1) Increase safety: upstream from an incident (e.g. traffic jams, crashes, road works) speed limits can be lowered in order to reduce the mean speed, lead the traffic smoothly to the incident and avoid the occurrence of crashes;

(2) Indicate obstructions: DSLs can lead away traffic from a blocked lane;

(3) Improve traffic flow through homogenization of speed: at moments with a high traffic flow, speed limits will be reduced, which will lead to a more homogeneous traffic flow and to less manoeuvres. Furthermore the headway is smaller, so that the available space is used more efficiently and the probability of traffic jams is subsequently lower.

The speeds that are displayed at the dynamic signs are based on the data gathered by the loop detectors and by automatic incident detection cameras at that location. Data on speed and occupancy of the lane are used to set the appropriate DSLs. When the loops and cameras detect a high occupancy together with a low speed the DSLs are reduced. At the locations upstream from this incident the speed is gradually reduced in order to prevent sudden braking. Speed is reduced from 120 km/h to 110 km/h, 90 km/h, 70 km/h and 50 km/h as lowest speed limit. Weather conditions are not taken into account in the calculation of the appropriate DSL.

In this paper the focus is on the traffic safety effect of DSL systems. Whereas measures such as DSL systems seek to optimize the use of available capacity and to increase the throughput, it is stated that safety improvement is the main purpose of DSL systems (Corthout, Tampère, & Deknudt, 2010). Despite the fact that some studies anticipate a positive effect on the efficiency of traffic flow (because of more efficient lane use and fewer lane changes), there is no indisputable proof for this based on previous field operational tests (Corthout, Tampère, & Deknudt, 2010).

Up to now, several studies analysed the effects of DSLs through simulation models and driving simulator studies. A few empirical studies were applied, which mainly focused on the effects of the DSLs on the traffic flow. However, no peer reviewed empirical studies were found that analysed the impact on traffic safety. Furthermore, to our knowledge, no literature is available on the cost-effectiveness of DSL systems. The present study therefore analyses the traffic safety effect of DSL systems in Flanders, Belgium, based on an empirical analysis of observed crash data. The effects are analysed through an empirical Bayes before-and-after study, which compares the crashes after the implementation of the measure with the number of crashes before, and controls for confounding variables. The empirical analysis is complemented by a social cost-benefit analysis of the Flemish DSL system. The costs of the implementation of these systems were compared with the costs of the prevented crashes.

In chapter 2 an overview is given on previous studies that analysed the effects of DSL systems. Both studies that analysed the effects on the traffic flow, as studies that analysed the traffic safety effects are included in this chapter. In chapter 3 the data, the methodology and the results of the evaluation of the effects on traffic safety are described; chapter 4 describes the cost-benefit analysis. In chapter 5 the results of the two studies are discussed and in chapter 6 the main conclusions are described.

2 Literature review

Several peer reviewed studies analysed the effects of DSL systems, which differ in the applied methodology and the study objectives. The majority of the studies used simulation models in order to analyse the effects on mobility on the one hand and traffic safety on the other hand. Islam et al. (2013) studied the effects on mobility; Fudala and Fontaine (2010) did this for work zones specifically; Habtemichael and de Picado Santos (2013) analysed the operational benefits of DSLs under different traffic conditions. Furthermore a large number of studies analysed the impacts of DSLs on traffic safety. Lee et al. (2004) used a real time crash prediction model integrated with a microscopic traffic simulation model. They found that temporarily reducing speed limits during risky traffic conditions can reduce the crash potential. The greatest reduction occurred at the location with a high traffic turbulence. Abdel-Aty et al. (2006) studied how traffic safety could be increased at a motorway in Orlando. They found DSLs can be used to improve safety, through the implementation of lower speed limits upstream and higher speed limits downstream of the location where crash likelihood is observed in real time. This improvement was present in the case of medium-to-high-speed regimes but not in low-speed situations. They furthermore analysed the potential for crash migration and found that the crash potential relocates to a location downstream of the detector of interest. Overall the safety of the freeway was improved (Abdel-Aty et al., 2006). In a later study, Abdel-Aty et al. (2008) went further on this research and found that DSLs can be used to reduce crash risk and prevent crash occurrence in free-flow conditions and conditions approaching congestion. Habtemichael and de Picado Santos (2013) found however somewhat different results. In their study the highest traffic safety effects were found during highly congested traffic conditions, followed by lightly congested conditions and the least during uncongested situations. Furthermore, they found that the effects are highly dependent on the level of driver compliance.

These studies however give no indication about the impact of this measure in real traffic conditions. Lee et al. (2006) studied the safety benefits of DSLs and used simulated traffic conditions on a freeway in Toronto. They found that real time DSLs can reduce the overall crash potential by 5%-17%. Also Islam et al. (2013) analysed this impact. They proposed a model predictive DSL control strategy. The safety impact was quantified through a real time crash prediction model for an urban freeway corridor in Alberta. The results indicated that the DSL can improve safety by 50%.

Next to the application of simulation models, driving simulator studies were used which analysed the effects on driving behaviour. Lee and Abdel-Aty (2008) studied the effectiveness of warning messages and DSLs at speed variation. Hoogendoorn et al. (2012) studied the influence of the content, implementation, location and frequency of signs on the drivers’ perception, mental workload and compliance. Van Nes et al. (2010) analysed the effects on the homogeneity, the credibility of the posted speed limits and the acceptance of the different DSL systems.

The effect of DSL systems was also analysed through empirical studies. Kwon et al. (2007) studied the effect of DSLs at a work zone in Minnesota. Papageorgiou et al. (2008) investigated the effect of DSLs on aggregate traffic flow behaviour through traffic data from a European motorway, where a flow-speed threshold-based DSL control algorithm was used. They collected data from a moment where the DSL activations were relatively sparse, because of rather loose threshold values. During this period no DSL measurements were available, also at relatively high occupancy levels. The data of this moment were compared with data that were gathered at the same locations, at a later moment after the system was fine-tuned. During this period, the DSL systems were activated more often. This study found that DSL systems decrease the slope of the flow-occupancy diagram at undercritical conditions, shift the critical occupancy to higher values, and enable higher flows at the same occupancy values in overcritical conditions. A Flemish study comes from Corthout et al. (2010), who focused on the detection rate and the false alarm rate from the drivers' perspective, in order to evaluate the performance of the DSLs by the effectiveness to warn drivers for downstream incidents. The detection rate indicates how often drivers are not (appropriately) warned for dangerous situations; the false alarm rate gives information on the credibility of the system (a low rate indicates that the drivers are encouraged to reduce speed and increase their alertness, a high rate causes drivers to ignore warnings, which will lead to a reduction in safety). The authors evaluated the DSL system around Antwerp and they found that the performance of the system is good, with a reasonably high detection rate and very low false alarm rate. The authors suggested to improve the short-term predictions, in order to avoid missed detections at queue tails and to stabilize DSL during congestion in order to avoid volatility and mild missed detections (Corthout et al., 2010).

3 Evaluation of the traffic safety effect

3.1 Data

In 2003 the first DSL systems were installed at the Flemish motorways. Motorways are defined here as roads for motorized vehicles only with a median barrier and no at-grade junctions (Elvik et al., 2009). The fixed maximum speed limit on Flemish motorways is 120 km/h. The entrance is forbidden for pedestrians, cyclists, moped riders and all vehicles that cannot drive faster than 70 km/h. Crash data, which are gathered by the police and reported digitally, were available up until 2011. In order to have at least one year of crash data available in the after period, all DSL systems that were installed and operational up until 2010 could be included. In total five road segments with DSLs could be included, which cover a total distance of 59.54 km. These five segments are located at access roads of the ring road of Antwerp, which is one of the two busiest ring roads in Belgium. Table 1 gives an overview of the characteristics of the treated locations; Figure 1 gives a graphical overview of the locations. Each dot represents a gantry with DSLs.

The comparison group, which is selected in order to control for the general trend effects, included all crashes that occurred on Flemish motorways, at least 10 km away from locations with DSLs.

Table 1 Characteristics of the treated segments

	Road segment	Total length	Year of installation	No. of lanes
1	E17 Ghent-Antwerp	7.30	2004	3
2	E19 Breda-Antwerp	4.44	2004	2
3	E19 Brussels-Antwerp	6.00	2003	3
4	E313 Geel-Ranst	31.80	2009	2
5	E34/E313 Ranst-Antwerp	10.00	2003	2

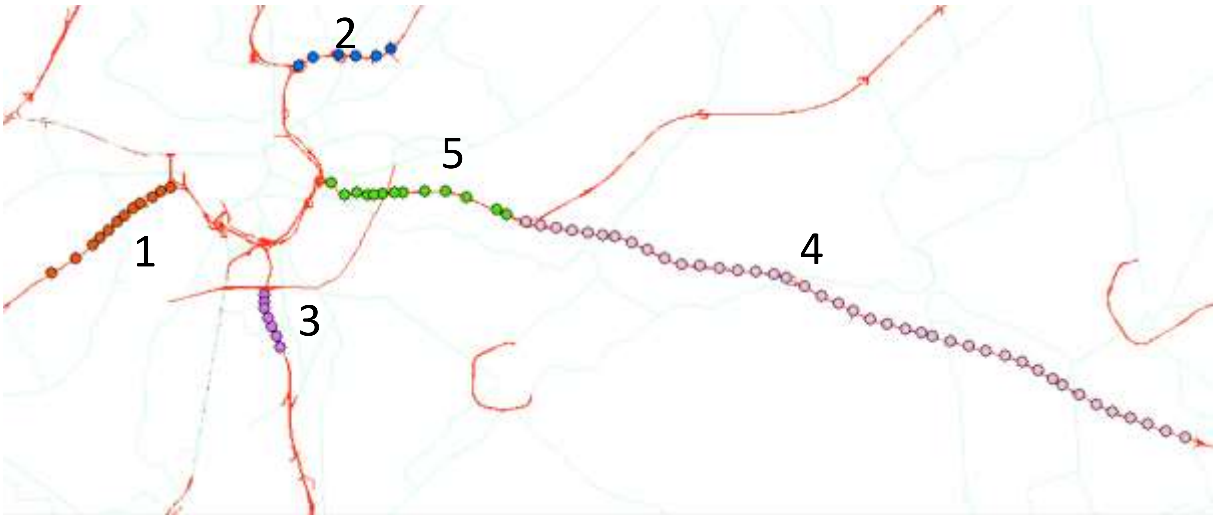

Figure 1 Geographical location of the treated segments

All crashes from 1999 up to 2011 were used. The crashes from the year 2003 were excluded from the study, since there were problems with the crash registration in that year. Also the crashes from the years 2004-2005 were excluded since road works were carried out on the ring road of Antwerp, to which the five treated segments lead. The road works had a high impact on mobility in and around Antwerp, and for that reason these years were excluded from the study. Subsequently, for the segments where DSL systems were installed in 2003-2004 (segments 1, 2, 3 and 5) the before period included the crashes from 1999 up to 2002 and the after period included crashes from 2006 up to 2011. For the segment where a DSL system was installed in 2009 (segment 4) the before period included 2006-2008 and the after period 2010-2011. Through this selection the most recent available years of crash data were used. The before period amounted to 3.8 years on average; the after period amounted to 5.2 years. The crashes were subdivided according to their severity: (1) injury crashes; (2) severe injury crashes which included crashes with severely injured persons (every person who needed more than 24 hours of hospitalization as a result of a crash) and fatally injured persons (every person who died within 30 days after the crash as a consequence of the crash).

The injury crashes in the treated group decreased from 115 in 1999 to 84 in 2011; the severe crashes had a range from 26 in 1999 to 19 in 2011. The crash numbers in the comparison group decreased throughout 1999-2011 from 1970 to 1220; the severe crashes had a range from 451 in 1999 to 320 in 2011. Table 2 gives an overview of the average number of crashes at the treated locations per year in the before and the after period. These numbers clearly show that the rear-end crash is the crash type that occurs most frequent.

Table 2 Average number of crashes/year that occurred at the treated locations during the before and the after period

	Injury crashes	Severe crashes	Rear-end injury crashes	Single-vehicle injury crashes	Side injury crashes
Before	108.7	22.9	51.1	31.6	13.7
After	61.3	15.4	31.3	17.7	8.3

Crashes with property damage only (PDO) are not gathered systematically, except on motorways. Information on these crashes are also reported by the police, who comes to the location of the crash. However, these data are only available from 2004. Therefore it was not possible to analyse the effects on PDO crashes at locations 1, 2, 3 and 5, since the DSLs were installed in 2003/2004, and thus no data were available for the before period. Only for location 4 the effect on PDO crashes was analysed, which is described in annex.

3.2 Method

The traffic safety effect is studied through an empirical Bayes (EB) before-and-after study, which compares the crash numbers after the implementation of the measure with before and increases the precision of estimation and corrects for the regression-to-the-mean (RTM)[1] bias (Hauer et al., 2002).

3.2.1 Evaluation per segment

First the effect per segment is calculated (see table 1 and figure 1, for more information on the location of the five segments). The analysis per segment (further referred to as 'location') can be expressed through an odds ratio, which results in an estimation of the index of effectiveness (θ_l):

$$\theta_l = \frac{L_l / E[\kappa|K]_l}{N / M} \qquad [1]$$

$E[\kappa|K]_l$ = the expected number of crashes at the treated location L during the before period, controlled for RTM
L_l = the observed number of crashes at the treated location L during the after period
M= the observed number of crashes in the comparison group during the before period
N= the observed number of crashes in the comparison group during the after period

In order to increase the precision of the estimates, the empirical Bayes method makes joint use of two information sources on the safety of a location: the crash record of that location and the crash frequency expected at similar locations. A weighted average combines these two sources (Hauer et al., 2002):

$$E[\kappa|K]_l = w * E[\kappa] * T + (1 - w) * K_l \qquad [2]$$

with
w= the weight (between 0 and 1) that is given to the crashes at similar entities
$E[\kappa]$ = average number of crashes in the before period at similar entities
T = number of years during the before period
1-w= the weight given to the crashes at the treated location L
K_l= observed number of crashes in the before period at the treated location L.

To calculate the average number of crashes at similar entities ($E[\kappa]$) in eq. [2], a Safety Performance Function (SPF) is used that has been developed for crash occurrence of injury crashes at Flemish motorways. This study developed an SPF per motorway segment on the basis of several variables: (1) traffic volume, (2) length of road segment, (3) type of road segment and (4) number of lanes. The type of road segment included two main categories: road segments at entries/exits and interchanges and road segments between two entries/exits or interchanges. The model has a negative binomial probability distribution with a log link function and is calculated using the SPSS GENLIN procedure.

$$E[\kappa] = e^{\alpha} \; L^{\beta} \, V^{\gamma} e^{\sum_{i=1}^{n} \delta_i x_i} \qquad [3]$$

with

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[1] Regression to the mean (RTM) is defined as one of the main important confounding variables if the locations for treatment were selected because of the crash numbers during the before period (Hauer, 1997). Elvik and Vaa (2004) defined it as follows: "Regression-to-the-mean denotes the tendency for an abnormally high number of accidents to return to values closer to the long term mean; conversely abnormally low numbers of accidents tend to be succeeded by higher numbers. RTM occurs as a result of random fluctuation in the recorded number of accidents around the long-term expected number of accidents". As the decision to implement a measure is often based on a high crash rate during a relatively short period (e.g. 1 year), it is plausible that the number of crashes will decrease afterwards, irrespective of the measure. In those cases RTM will lead to an overestimation of the treatment effectiveness, when not appropriately taken into account.

$E[\kappa]$= expected annual number of crashes
α, β, γ, δ = model parameters
L= length of road segment (in m)
V= Traffic volume (in vehicles/24h)
x_1 = Segment type (0= at entries/exits and interchanges, 1 = between entries/exits and interchanges)
x_2 = Number of lanes (1..3)

Traffic volume data were gathered through double inductive loops in the pavement. All segments with inductive loops at the Flemish motorways were included in the SPF. During recent years the government started with the installation of double inductive loops in the pavement of motorways, which increased over the years. In total 292 segments were included for 2008, 381 segments for 2009 and 544 segments for 2010. The road segments included in the SPF have an average length of 2448 m (stand dev. 2726 m) and an average daily traffic volume of 36047 (st. dev. 20045). Table 3 displays the final results of the SPFs for the injury crashes and the severe crashes. The segment type and the number of lanes were not significant and thus not included in the final model.

Table 3 Results of the SPF

	Injury crashes	Severe crashes
α	-16.792 (SE:0.623)***	-18.493 (SE: 1.030)***
Length of segment (β)	0.939 (SE:0.029)***	0.951 (SE: 0.047)***
Traffic volume (γ)	1.011 (SE:0.049)***	1.035 (SE: 0.080)***
Over dispersion	0.313 (SE:0.031)	0.325 (SE:0.070)
Likelihood ratio test statistic (χ^2)	1013.5***	500.6***

*** significant at 1% level

The model was based on crash data from 2008-2010. However, the before period in the present study was 1999-2002 for the locations at which DSL systems were installed in 2003 or 2004 and was 2006-2008 for the location at which DSLs were installed in 2009. Therefore the estimated number of crashes was multiplied with an adjustment factor to match the time frame of the observed data with the time frame of the SPF. This adjustment factor was expressed as the proportion of the annual average number of crashes during the before period to the annual average number of crashes that occurred in 2008-2010.

To calculate the weight (w) in eq. [2], next equation can be used:

$$w = \frac{1}{1 + \frac{E[\kappa] * T}{k}} \qquad [4]$$

with k the inverse value of the overdispersion parameter of the model, which is estimated per unit of length (Elvik, 2008).

3.2.2 Overall effect estimation

The evaluation of each location separately has only limited significance. Therefore a fixed effects meta-analysis was carried out, which resulted in one overall effect estimate and more statistically reliable outcomes (Fleiss, 1981). Every location within the meta-analysis receives a weight, which is the inverted value of the variance. The variance is, based on the variables in eq. [1], calculated as next:

$$s_l^2 = \frac{1}{E[\kappa|K]_l} + \frac{1}{L_l} + \frac{1}{M} + \frac{1}{N} \qquad [5]$$

The weight can be calculated as follows:

$$w_l = \frac{1}{s_l^2} \quad [6]$$

Subsequently locations at which many crashes occurred are given higher weights.

Supposing that the measure is executed at n different places, the weighted mean index of effectiveness of the measure over all places θ is as follows:

$$\theta = \exp\left[\frac{\sum_{l=1}^{n} w_l * \ln(\theta_l)}{\sum_{l=1}^{n} w_l}\right] \quad [7]$$

The estimation of a 95% CI is as follows:

$$95\%\ \mathrm{CI} = \exp\left[\frac{\sum_{l=1}^{n} w_l * \ln(\theta_l)}{\sum_{l=1}^{n} w_l} \pm 1.96 * \frac{1}{\sqrt{\sum_{l=1}^{n} w_l}}\right] \quad [8]$$

3.3 Results

A meta-analysis of the injury crashes showed a significant decrease of 18% as a result of the implementation of DSLs (see table 4). The injury crashes were subdivided according to the type of crash and the three main crash types were analysed: (1) rear-end crashes; (2) side crashes; (3) single-vehicle crashes. As can be seen from table 4, no effect on the number of side crashes could be found. A decrease was found for the number of rear-end crashes (-20%) which was almost significant as the upper limit of the 95% confidence interval is close to one. The number of single-vehicle crashes decreased by 15%, which was however not significant. An analysis of the fatal and serious injury crashes showed no significant effects. The detailed results per road segment are described in annex.

Table 4 Results of meta-analyses of the crash effects

	Effect [95%CI]
Injury crashes	0.82 [0.70; 0.96]**
Rear-end crashes	0.80 [0.64;1.01]*
Side crashes	1.00 [0.64; 1.56]
Single-vehicle crashes	0.85 [0.64;1.13]
Severe crashes	0.94 [0.68; 1.29]

** significant at 5% level
* significant at 10% level

4 Cost-benefit analysis

4.1 Introduction

As already discussed above, DSL systems are introduced for several reasons. We will stick here to the general approach of the paper, and limit ourselves to a discussion of their benefits in terms of crash reduction. As a result, this approach will tend to underestimate the benefits.

It is not clear how large the bias in terms of benefit estimation is. The improvement of traffic flows discussed in section 1 will have an indirect impact on congestion levels, on the environment, and on fuel consumption. While there is an extensive literature on the impact of congestion on crash risk and severity, we are not aware of systematic studies of the inverse effect. These indirect effects will not be considered further. Moreover, the data that are available for Belgium do not cover crashes with material damages only. This is another factor that will lead to an underestimation of the social benefit of reducing road crashes.

4.2 The social benefits of the reduced crash risk

In this section we calculate the social benefits of the reduced crash risk that was estimated in Table 4. First, we present the monetary values of the social costs of crashes that are proposed in the literature. Next, we apply these values to the impacts of DSL in Flanders.

We use the figures from the 'Update of the Handbook on External Costs of Transport' (Korzhenevych et al., 2014) for the unit costs of crashes with injuries and fatalities. The advantage of this approach is that these figures have been obtained using an internationally recognized methodology.

The following unit values are reported for Belgium (p 23), using the market prices (at Purchasing Power Parity[2]) of 2010.

Table 5 Victim related costs according to Korzhenevych et al. (2014)

Cost category	Estimate in kEUROs
Fatality	2178.0
Severe injury	330.4
Slight injury	21.3

In order to translate these unit costs in total economic benefits of crash prevention, we also need estimates of the number of victims and/or crashes, both the actual number and the number that would have prevailed in the absence of DSL systems (the counterfactual).

In 2010-2011, at the treated locations, the average number of slightly injured persons was 78.50, the average annual number of severely injured persons was 22.50, and the number of fatalities was 2.50.

In order to estimate the counterfactual, we will first apply the central values of the estimates of the index of effectiveness (see Table 4). For "severe injuries" and "fatalities", we will apply the estimate for "severe crashes" (0.94), while for the number of slight injuries, we apply the estimate for "injury crashes" (0.82). This corresponds to 95.73 slightly injured persons, 23.94 severely injured persons and 2.66 fatalities in the counterfactual scenario.

Combining the unit cost figures from Table 5 with the estimated number of fatalities and injuries avoided, we obtain the estimates of the annual economic value of crash prevention due to DSL, as described in table 6.

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[2] In contrast to market exchange rates, Purchasing Power Parities reflect the differences in purchasing power between two currencies. They are thus the relevant metric to convert costs and benefits expressed in one currency in another currency.

Table 6 Total value of prevented injuries, due to DSL (Korzhenevych et al. (2014))

Cost category	Estimate in kEUROs
Fatalities	348
Severe injuries	475
Slight injuries	367
Total	1189

4.3 The social costs of Dynamic Speed Limits

In order to estimate the costs of DSL, we need to consider both investment costs and operational costs. All the cost estimates provided below are based upon in-depth interviews with officials from the Department of Mobility and Public Works. We would like to emphasize that these figures are expert judgments, and not based on detailed cost accounting - however, they are representative for the order of magnitude of the costs.

The cost of installing the equipment is highly location specific. We have taken 269 kEUR as representative for the material investment costs per km of highway covered (including maintenance costs in the first two years of operation). To this material investment cost, we need to add the salary cost of the supervising personnel (47 kEUR per km). As taxes are a transfer, all these sums are net of VAT, income taxes and wage taxes.

With an average distance between gantries of 0.75 km, this results in 237 kEUR as a representative investment cost per gantry. As a total distance of 59.54 km is covered by DSL (see Section 3.1), this implies an initial investment cost of 18817 kEUR.

There are no official estimates of the economic lifetime of the installations. The oldest dynamic displays and DSL systems have been in use since 1999 and 2003, respectively. There is no indication that they will need to be replaced in the foreseeable future. We will assume a lifetime of 25 years.

According to the Department of Mobility and Public Works, total annual maintenance costs (both preventive and curative) correspond to 3% of the investment costs, thus to 561.77 kEUR.

The system is exploited and maintained by the section Traffic Enforcement Systems of the Department Electromechanics and Telematics of the Road and Traffic Agency. The Department of Mobility and Public Works reckons that about six full time equivalents are needed for the exploitation of the system, which counts approximately 300 gates. If we take the very conservative assumption that personnel costs are proportional to the number of gantries, the total net salary cost linked to the exploitation of the gantries under study is 23.57 kEUR (using standard salary costs from the Flemish public service for the personnel categories involved), and amounts thus to 4.2 % of the maintenance costs.

4.4 Results

In order to compare the costs and benefits of the system over its complete life cycle, we calculate its Net Present Value, defined as:

$$NPV = (B_0 - C_0) + \frac{B_1 - C_1}{1+r} + \cdots \frac{B_n - C_n}{(1+r)^n} \qquad [9]$$

Where *n* is the expected lifetime of the system, B_i and C_i are the costs and the benefits in period *i*, respectively, and *r* is the discount rate.

Using a discount rate of 4 percent, the net present value of investment costs, maintenance and exploitation costs is 26.59 million EUR.

The net present value of prevented crashes (using the values proposed by Korzhenevych et al. (2014)) is 19.32 million EUR - this corresponds to a benefits-to-costs ratio of approximately 0.7. Thus, under these unit values, we see that the expected costs of the system exceed the expected benefits. However, we have pointed out before that several benefit categories have not been included in the analysis. Moreover, we have argued that the costs cannot be attributed only to the management of the DSL system under analysis. Furthermore, the precise cost figures are only rough estimates. This raises the question how robust the conclusions are, a question which is tackled in the next paragraph.

4.5 Sensitivity analysis

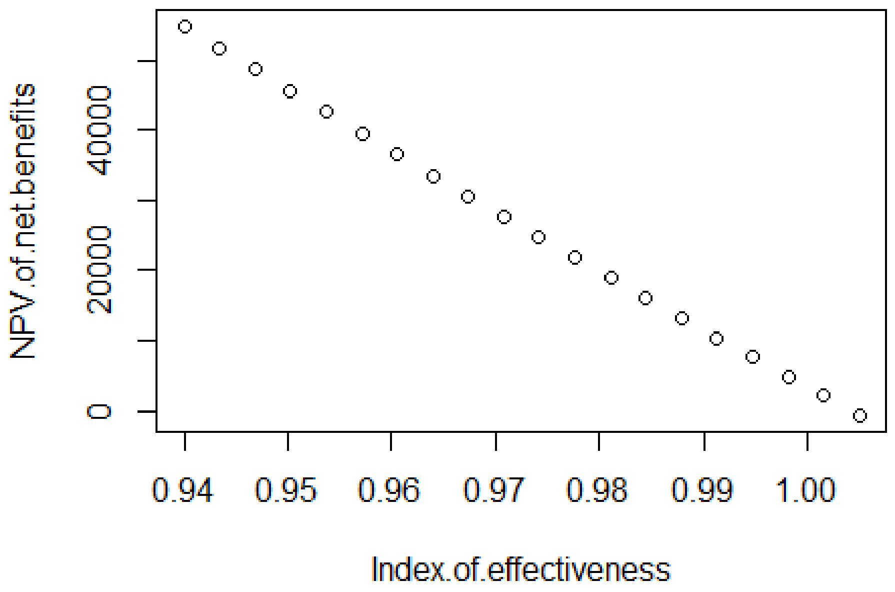
In order to address the robustness of the analysis, we have also considered the unit costs proposed by De Brabander (2007). The material cost per accident (for instance administrative costs and material damages per crash) corresponds to 4527 EUR. The unit victim related cost (including tangible costs such as medical costs but also the monetary equivalent of human suffering due to the crashes and the value of production lost) is 106.9 kEUR for a slight injury, 1455.7 kEUR for a severe injury, and 6799.7 kEUR for a fatality. Using these unit costs and the estimated number of prevented accidents, we obtain an estimated benefit of accident prevention of 5017 kEUR for the victim related costs and 85 kEUR for the crash related costs.

Table 7 Total value of crash prevention according to De Brabander (2007) (kEUR)

	De Brabander - victim costs	De Brabander - accident related costs
Slight injuries	1842	78.01
Severe injuries	2091	6.50
Casualties	1085	0.72
Total	5017	85.23

The costs using the unit values proposed by Korzhenevych et al. (2014) are about 4.3. times smaller than the costs proposed by De Brabander. Using the unit values proposed by De Brabander instead, the net present value of prevented crashes is around 81518.7 kEUR, and we obtain a benefits-to-costs ratio of approximately 3.1.

The crucial parameter turns out to be the unit monetary values for the benefits of crash prevention: under the unit values proposed by De Brabander, the benefits clearly exceed the costs. We should however keep in mind that these benefits have been calculated, using the central value for the estimate of the index of effectiveness, while the estimates for severe crashes are not significantly different from one. As the monetary values for the prevention of severe crashes dominate the monetary values for material damages and slight injuries, we can ask the question: what would be the minimal level of effectiveness required to obtain a break-even with the unit values proposed by De Brabander?



Assuming a constant (at 0.82) level of the index of effectiveness for total injury crashes, we see that the net present value of the benefits of crash reduction remains positive as long as the index of effectiveness for severe crashes does not exceed 1. As the 95% CI for this parameter is (0.68, 1.29), we must conclude that, even with the high unit values proposed by De Brabander, the actual net benefits remain subject to a wide margin of uncertainty.

Summarizing, there is no convincing evidence that the cost of the current system outweighs the expected benefits in terms of crash prevention. A few words of caution should be added to this conclusion. Some providers of navigation and mapping products are already providing "Jam Ahead Warning" features[3] on a commercial basis. A drawback of these systems compared to DSL is that they are currently only available for those willing to pay for these services, while the information of DSL is publicly and freely available. As a result, not all road users are warned of impeding jams. Moreover, these warning systems do not provide enforceable speed restrictions. In a next stage, the same function could be taken over by cooperative vehicle systems techniques, i.e. techniques that allow vehicles to communicate both with each other and with the roadway infrastructure. Pilot projects[4] are currently evaluating their potential to regulate traffic flows.

5 Discussion

As the traffic safety effects of DSLs are unknown up to now, the present study focused on the effects of DSLs on the occurrence of crashes. In addition, the costs of the prevented crashes were compared with the costs of the implementation of these systems.

5.1 Evaluation of the traffic safety effect

The study showed that the introduction of DSLs has a favourable effect on traffic safety. The number of injury crashes decreased by 18%. This effect was mainly attributable to a decrease in the number of rear-end crashes, for which an almost significant decrease of 20% was found. A decrease was also found for the single-vehicle crashes (-15%), which was however not significant.
An evaluation of the fatal and serious injury crashes showed a non-significant decrease of 6%. This can be ascribed to the low number of crashes at the treated locations. Subsequently it would be interesting

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[3] See for instance http://corporate.tomtom.com/releasedetail.cfm?ReleaseID=788391 .

[4] See for instance http://www.spookfiles.nl/ (in Dutch only).

to apply this research again at the moment that more years of crash data are available in the after period and a larger number of Flemish motorways are equipped with the DSL systems.

It is however difficult to compare the results of the present study with previous studies. No peer reviewed studies were found that applied this kind of research, i.e. an evaluation of the traffic safety effect on the basis of the observed number of crashes. Despite this fact it is difficult to compare the results of such traffic safety measure, since the effects are largely dependent on the traffic situation where the DSL systems are installed and thus no systems can be considered as identical.

In future research also the speed effect could be analysed. The traffic safety effects will be highly dependent on the level of driver compliance (Habtemichael & de Picado Santos, 2013). It could be analysed to what extent drivers obey the DSLs and whether speed enforcement leads to higher speed compliance and furthermore to higher effects on the traffic safety level. A first analysis on Flemish motorways (Magis, 2014) indicated that only one fourth of the drivers follow the posted speed limit of 90 km/h and half of them follow the speed limit of 110 km/h. In comparison to moments with a fixed speed limit of 120 km/h the average speed is only 6 km/h lower at moments with a dynamic speed limit of 90 km/h en is even 0,4 km/h higher at moments with a speed limit of 110 km/h. Compared to moments with a speed limit of 120 km/h, the number of drivers that exceed the speed limit is 18 times higher during moments with a speed limit of 90 km/h and 5 times higher when the speed limit is 110 km/h. For the number of drivers that exceed the speed limit by more than 10%, this is respectively 63 and 8.5 times higher.

The reduction of the speed limits through electronic signs does not only has the purpose to reduce the driving speed, but also to warn drivers of the presence of an incident downstream. Therefore, it would be interesting to analyse which effect DSLs have on the attention of the drivers and their behaviour when they approach an incident.

5.2 Cost-benefit analysis

The cost-benefit analyses of the crash effects showed that, using unit values from the international literature for the valuation of crash prevention, the costs exceed the benefits, with a benefits-to-costs ratio of approximately 0.7.

It should be noted that only a part of the benefits of the DSL systems are taken into account in this study. DSL systems bring about more favourable effects than what was included in the cost-benefit analysis. Next to crash effects, this measure could also bring about favourable effects on traffic flows, congestion and travel times, and furthermore also on vehicle emissions and road noise. However, as no significant effects on throughput and capacity were found in previous implementations and experiments (Corthout & Tampère, 2010), we are probably safe in ignoring these effects.

In addition, only the direct costs of crashes were taken into account in order to calculate the benefits. However, the prevention of crashes also leads to favourable effects on congestion levels, the environment, and fuel consumption. It was not possible to take these indirect effects into account. Furthermore, only injury crashes were analysed in this study. However these systems will also have had a favourable effect on property-damage-only crashes. Since these are not gathered systematically it was not possible to analyse the effects on this crash type, which also leads to an underestimation of the benefits.

6 Conclusions

Summarized we can conclude that the DSLs have a favourable effect on injury crashes, and mainly on rear-end crashes. This favourable effect might be ascribed to the lower driving speed and the higher attentiveness of the driver at the moment the lower dynamic speed limits are displayed. A balance of these effects against the costs however shows that there is no convincing evidence that the expected benefits justify the costs of the system. It should however be noted that traffic safety improvement is only one of the objectives of DSLs, but it is stated as the main purpose of DSL systems (Corthout & Tampère, 2010). Nevertheless it would be interesting to analyse the effects of DSLs on the traffic flow at Flemish motorways, in order to have a full view on the impact of these measures. Finally, as this analysis is based on an ex post assessment of systems that were implemented over the course of the last decade, one should be careful in drawing conclusions regarding the expected benefits of new systems that would be based on current state-of-the-art technology.

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ANNEX Effects per road segment

Table 8 shows the effects per road segment, both for injury crashes and severe crashes. In addition, for location 4 the effect on the PDO crashes is calculated (without control for RTM). These results show favourable effects on the E19 Brussels-Antwerp and E313 Geel-Ranst. The results should however be interpreted with caution, because of the low number of crashes, certainly for the severe crashes (see table 10).

Table 8 Effects per road segment, according to the severity of the crash

	Road segment	Effect injury cashes	Effect severe crashes	PDO crashes
1	E17 Ghent-Antwerp	1.25 [0.91; 1.71]	1.18 [0.58; 2.41]	
2	E19 Breda-Antwerp	1.31 [0.72; 2.39]	0.82 [0.28; 2.38]	
3	E19 Brussels-Antwerp	0.66 [0.47; 0.93]**	0.99 [0.47; 2.08]	
4	E313 Geel-Ranst	0.59 [0.43; 0.81]**	0.73 [0.43; 1.26]	0.69 [0.54; 0.88]**
5	E34/E313 Ranst-Antwerp	0.81 [0.60; 1.10]	1.18 [0.56; 2.48]	

** significant at 5% level
* significant at 10% level

Table 9 shows the effects per crash type. It can be seen that the favourable effects on the E19 Brussels-Antwerp and the E313 can mainly be ascribed to the favourable effects on rear-end crashes.

Table 9 Effects per road segment, according to the type of the crash

	Road segment	Effect rear-end crashes	Effect side crashes	Effect single-vehicle crashes
1	E17 Ghent-Antwerp	1.44 [0.94; 2.23]*	1.67 [0.61; 4.55]	0.64 [0.34; 1.18]
2	E19 Breda-Antwerp	1.30 [0.54; 3.11]	1.01 [0.14; 7.18]	1.48 [0.54; 4.07]
3	E19 Brussels-Antwerp	0.38 [0.22; 0.66]**	0.63 [0.29; 1.36]	1.54 [0.79; 2.99]
4	E313 Geel-Ranst	0.63 [0.41; 0.97]**	0.13 [0.02; 0.96]**	0.75 [0.43; 1.31]
5	E34/E313 Ranst-Antwerp	0.81 [0.50; 1.30]	1.51 [0.72; 3.17]	0.69 [0.40; 1.17]

** significant at 5% level
* significant at 10% level

In order to give a view on the number of crashes per road segment, table 10 displays the average number of crashes per year during the before and the after period for each of the segments.

Table 10 Average number of crashes/year that occurred at the treated locations during the before and the after period, subdivided to the road segments

		Injury crashes	Severe crashes	Rear-end injury crashes	Single-vehicle injury crashes	Side injury crashes
E17 Ghent-Antwerp	Before	16.50	3.00	8.00	6.25	1.50
	After	15.83	3.17	10.17	2.83	2.20
E19 Breda-Antwerp	Before	4.00	1.50	2.00	1.50	1.00
	After	4.50	1.40	2.80	1.67	1.00
E19 Brussels-Antwerp	Before	19.75	3.00	9.50	3.50	4.00
	After	10.00	2.67	3.17	3.83	1.83
E313 Geel-Ranst	Before	55.67	15.67	27.33	14.67	5.33
	After	27.50	10.00	16.00	9.00	1.00
E34/E313 Ranst-Antwerp	Before	21.25	3.33	8.50	7.75	3.00
	After	13.67	3.00	6.17	4.00	3.00

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