universiteit hasselt
KNOWLEDGE IN ACTION

2015 | School for Transportation Sciences

DOCTORAL DISSERTATION

The effect evaluation of traffic safety measures. A before-and-after study approach.

Doctoral dissertation submitted to obtain the degree of Doctor of Transportation Sciences, to be defended by

Ellen De Pauw

Promoter: Prof. Dr Tom Brijs | UHasselt
Co-promoters: Prof. Dr Stijn Daniels | UHasselt
Prof. Dr Geert Wets | UHasselt

D/2015/2451/4

universiteit hasselt | imob
INSTITUUT VOOR MOBILITEIT

ACKNOWLEDGEMENT/ DANKWOORD

Vier jaar geleden startte ik een compleet nieuw hoofdstuk in mijn leven. Met de start van een doctoraat aan de universiteit van Hasselt veranderde ik niet alleen van job, maar verhuisde ik ook meteen naar het verre, mooie Limburg. De afgelopen vier jaar waren op verschillende vlakken een enorm boeiende ervaring. Zowel op professioneel vlak, als op persoonlijk vlak heb ik heel wat kennis en vaardigheden verworven. Het was niet steeds een even gemakkelijke weg, maar ik ben enorm blij dat ik heb doorgezet. Ik had hier dan ook nooit gestaan, zonder de hulp en steun van verschillende mensen.

First of all, I would like to thank all the members of the jury for their time reading my thesis, their constructive comments and their helpful suggestions that improved the scientific quality of this dissertation. Dr. Yannis, Dr. Schepers, thank you for your presence here. Dr. Elvik, thank you for the wealth of interesting papers, from which I learned a lot. Ook mijn promotor Tom, copromotor Geert, en Elke wil ik bedanken. Bedankt voor het vertrouwen, en de kans die ik kreeg om hier een doctoraat te starten. Bedankt ook voor jullie deskundige advies en jullie innovatieve ideeën bij het voeren van het onderzoek.

Furthermore I want to thank all my colleagues. It was a real pleasure to work at IMOB, with so many great people. You are all hardworking, nice persons, and I have a lot of respect for each of you.
Kristel, Edith, Tamara, André en Nadine, jullie stonden steeds klaar met raad en daad om alle vragen en problemen meteen op te lossen. Bedankt daarvoor.
Lieve, Hanne, Kris, Lotte en Marijke, bedankt voor het fijne gezelschap tijdens de vele activiteiten. De amusante lunchdates, spelletjesavonden en ladies nights waren altijd heel gezellig.
IT'ers Dirk, Marc, Raf en Roeland, mercikes voor de ontspannende, soms absurde, gesprekken tijdens de middagpauze. Een lunch met jullie was altijd een hele belevenis.
Evelien en Tim, als bureaucollega's hebben jullie de goede, maar ook de stresserende momenten van dichtbij meegemaakt. Bedankt voor het luisterend

oor op momenten dat het even moeilijk ging, het enthousiasme op momenten dat het goed ging, en voor de fijne babbels tussendoor.
Katrien, bedankt om steeds meteen klaar te staan bij (statistische) vragen. Het was super om met jou samen te mogen werken. Hetzelfde geldt ook voor Joris en Aline. Jullie inzet zorgde voor een heel vlotte samenwerking, de gezellige babbels zorgden dan weer voor de nodige ontspanning tussendoor.
An, bedankt voor het luisterend oor, voor de fijne reisjes naar New York, Frankrijk en Noorwegen, voor de sportactiviteiten (al dan niet met bezoekjes aan de spoed achteraf), de spelletjesavonden en zo veel meer.

Ook wil ik enkele vrienden bedanken.
De ladies van het middelbaar, Kim, Nora, Aline, Eline, Karen, Katrijn, Leen en Lies. Jullie zijn allemaal fantastische vriendinnen, die ik niet meer zou kunnen missen. Bedankt voor de talloze leuke activiteiten, maar ook bedankt voor de bemoedigende woorden op momenten dat ik het even niet meer zag zitten. Ik weet dat jullie er steeds voor mij waren, en dat apprecieer ik enorm.
Evelyn, vriendin sinds meer dan 20 jaar, bedankt voor de gezellige avonden en je onvoorwaardelijke steun gedurende al die jaren.
Griet, bedankt voor je bezorgdheden, en voor de vele leuke feestjes, die zeer welkom waren op stressvolle momenten.
Ook Wendy, bedankt voor de fijne babbels tijdens onze loopjes, voor het luisterend oor en je enthousiasme bij elke mijlpaal die ik bereikte in mijn doctoraat.

Tenslotte wil ik nog enkele mensen in het bijzonder bedanken.
Stijn, bedankt voor al jouw steun tijdens de afgelopen jaren. Je was een fantastische begeleider, die altijd klaar stond op momenten dat ik hulp nodig had. Je hebt me enorm veel bijgeleerd en je hebt een belangrijke bijdrage geleverd in het behalen van dit doctoraat.
Mama en papa, bedankt dat jullie me de kans hebben gegeven om te studeren, bedankt voor jullie wijze woorden en vooral dikke merci voor jullie steun. De oppeppende babbels, de momenten dat ik even mijn hart kon luchten waren voor mij enorm belangrijk om nadien terug met volle moed verder te kunnen gaan.

En broer, jouw humor zorgde op stresserende momenten voor de nodige ontspanning, jouw rake opmerkingen zorgden er dan weer voor dat ik de zaken kon relativeren. Bedankt dat je er altijd was.

Een belangrijk en enorm leerrijk hoofdstuk uit mijn leven wordt hier nu afgesloten. Bedankt aan iedereen die me hierin gesteund en geholpen heeft. Ik hoop dat ik jullie nog vaak mag terugzien in het volgende hoofdstuk!

Ellen De Pauw

February 11, 2015

SUMMARY

One of the important steps in setting up an effective road safety management is evaluation. This evaluation gives information on the effectiveness of implemented traffic safety measures, helps to make well-based decisions, improves the effectiveness of future initiatives and serves as a controlling instrument for the appropriateness of safety management efforts. The value and importance of the evaluation of traffic safety measures has become more apparent and is growing in relative importance. According to the OECD, there is a lack of understanding the value, importance and usage of effect evaluation in road safety decision making. The present dissertation therefore aims to bring the importance of effect evaluation to the attention, and tries to fill the gaps in knowledge on the effectiveness of several traffic safety measures. In total eight measures were selected, which are implemented in Flanders, Belgium:

- Traffic safety improvement at intersections
  - (1) Black spot treatment programme
  - (2) Left-turn protection at signalized intersections
- Reducing speed limits
  - (3) Reduction of the maximum speed limit from 90 km/h to 70 km/h
  - (4) Variable speed limits on motorways
- Speed and red light running enforcement on highways
  - (5) Speed cameras on highways
  - (6) Combined speed and red light cameras
- Speed enforcement on motorways
  - (7) Automated section speed control
  - (8) Speed cameras on motorways

For all measures, except for average speed control, the effects on the occurrence of crashes were analysed. For the speed enforcement on motorways, also the behavioural effects were studied.

The importance of effect evaluation and the research objectives are described in chapter 1.

In order to analyse the traffic safety effects of the different measures a before-and-after study approach was applied, which compares the number of crashes after the implementation of a measure with the number of crashes at the same location before the implementation. Within those before-and-after studies, different methods can be used, which mainly differ in the extent they control for confounding variables. Ideally, the empirical Bayes before-and-after study approach is applied. However, a number of methodological issues occurred with the application of this method.

A statistical problem that was present in all studies, is the occurrence of zero crashes in the before or the after period, through which it was impossible to calculate the effect. Up to now, no sufficient method is found yet to solve this problem. In the present dissertation, this problem was solved through the application of an EB estimation for the after period. However, further research is necessary to validate this method.

A second methodological issue that occurred during this PhD research is the absence of traffic volume data. The application of an empirical Bayes before-and-after study requires volume data, in order to calculate the expected number of crashes at similar entities and subsequently to control for the regression to the mean phenomenon. However, in Flanders there is only limited data available about the traffic flows and thus it was not possible to control for regression to the mean in all studies.

In order to calculate the overall effect of different locations with the same traffic safety measure, a meta-analysis is applied. Some authors state that the individual effects should be summed in order to calculate this overall effect, others indicate that a weighted method should be applied. In this dissertation the preference was given to the weighted method, in which locations with a high number of crashes are given a higher weight. More weight is given to the effect estimations with a higher number of crashes, as small crash samples lead to a greater variation in the effect estimations. The weighed method subsequently leads to more balanced results, compared to the summation method.

The methodology and the solution for the problems that occurred when this method was applied, are described in chapter 2. This chapter also describes how the effects on casualties and the driving behaviour were analysed.

In chapter 3 two studies are described that analysed the effects of infrastructural changes at dangerous intersections. The first study includes the effect evaluation of the Flemish black spot programme. In total, around 800 black spots were selected, from which 134 locations, redesigned between 2004 and 2007, were studied in the present dissertation. The adopted approach is an empirical Bayes before-and-after study that accounts for effects of general trends and for the stochastic nature of crashes, including regression to the mean. The black spot programme was found to be effective, both for the injury crashes, for which a decrease of 24%–27% (dependent on the comparison group that was used to control for the general trend effect) was found, as for the fatal and serious injury crashes, which decreased by 46%-57%. The highest effects were found for the implementation of changes in the layout of priority-controlled intersections and for the installation of traffic signals. The black spot programme generated a favourable effect on each of the road user categories (car occupants, moped riders, cyclists, motorcyclist, pedestrians and truck drivers).

One of the measures from the black spot programme, the implementation of left-turn protection at signalized intersections, was analysed in a more in-depth manner in the second study. A protected left-turn signal is often installed at intersections with a high number of left-turn crashes and gives vehicles turning left the right to enter the intersection free from conflict with opposing drivers and pedestrians. In the before-and-after comparison of traffic crashes the general trend effect and regression to the mean were controlled for. The analysis of 103 signalised intersections, where protected left-turn signals were installed between 2004 and 2009, showed a significant decrease by 37% in the number of injury crashes from the before to the after period. This was particularly attributable to a decrease in left-turn crashes of 50%. A larger effect was identified for fatal and serious injury crashes: -59%. Furthermore, the effect of left-turn phasing on the number of injured car occupants, cyclists, moped riders and motor cyclists was examined, and favourable effects were found for each of these groups.

The focus in chapter 4 is on two studies through which the traffic safety effects of the reduction of the maximum speed limits were analysed. In the first study the traffic safety effects of the reduction of speed limits from 90 km/h to 70 km/h were analysed. Sixty-one road sections with a total length of 116 km were included. The speed limits for those locations were restricted in 2001 and 2002. General trend effects were controlled using a comparison group; regression to the mean could not be controlled for. The comparison group consisted of 19 road sections with a total length of 53 km and an unchanged speed limit of 90 km/h throughout the research period. Taking the general trend into account, the analyses showed a non-significant decrease in the crash rates after the speed limit restriction. A greater effect was identified in the case of crashes involving serious injuries and fatalities, which showed a significant decrease of 33%. Separate analyses between crashes at intersections and at road sections showed a higher effectiveness at road sections.

The second measure includes the reduction of maximum speed limits on motorways, through a dynamic system. When the inductive loops and cameras at the motorways detect a high occupancy together with a low speed, the speed limits are reduced. In this study five road segments (with a total length of 60 km) were included, where dynamic speed limit systems were installed between 2003 and 2009. The adopted approach is an empirical Bayes before-and-after study. The analyses resulted in a significant decrease of 18% in the number of 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 significant results were found for side crashes. Serious and fatal injury crashes changed non-significantly by 3%.

In chapter 5 two enforcement measures on highways were studied: speed cameras on road sections and combined speed and red light cameras on intersections. The study on speed cameras included 65 fixed speed cameras, installed between 2002 and 2007. In the before-and-after comparison of traffic crashes it was only possible to control for general trend effects. The analyses showed a non-significant decrease of 8% in the number of injury crashes at a distance up to 500 m from the speed camera. In the case of the more severe crashes with serious and fatal injuries, a significant decrease of 29% was found. An analysis of the effects at different distances from the camera showed that the effect on the number of injury crashes is mainly due to the effect at a distance of 250-500 m from the camera. The severe crashes showed somewhat other results, for which the highest effects were found at a distance of 250 m from the camera. At a longer distance (500-1000 m from the camera), a tendency to an increase in crash rates (both for the injury crashes as the severe crashes) appears. A favourable effect is found for all road user categories (car occupants, cyclists, moped riders, motorcyclists and pedestrians).

In the second study of this chapter 253 intersections with combined speed and red light cameras, installed between 2002 and 2007, were studied. A before-and-after comparison of crashes with control for the general trend effect, resulted in a slight, non-significant increase of 5% in the number of injury crashes. This was mainly attributable to an increase in the number of rear-end crashes (+44%), whereas a non-significant decrease was found for the number of side crashes (-6%). The severe crashes decreased by 14%, which can be ascribed to a decrease in the number of severe side crashes (-24%). An effect estimation on the level of casualties showed a decrease in the number of injured cyclists only.

In chapter 6 two enforcement measures that tackle the speeding problem on motorways were studied extensively: speed cameras and automated section speed control.
The study on the automated section speed control is one of the first peer-reviewed studies on this subject. Whereas in the other studies of this dissertation the effects on traffic crashes were analysed, the focus in this study is on speed effects. Automated section speed control is a relatively 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, an increased headway, more homogenised traffic flow and an increased traffic capacity. The study evaluates the speed effect of two section speed control systems, which were installed in March 2013. Both sections have a length of 7.4 km, and 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, and data were collected during one week before the measure was implemented (March 2012) and during one week after the systems were installed (April 2013). General time trends and fluctuations were controlled through the analysis of speeds at comparison locations. Three outcomes were analysed: (1) average speed, (2) the odds of drivers exceeding the speed limit and (3) the odds of drivers exceeding the speed limit by more than 10%. 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 upstream 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.

Next to the automated section speed control, also the effects of speed cameras installed on motorways were studied. Whereas most previous studies analysed the speed effects at the speed camera, this study also analyses the speed effects of speed cameras at a greater distance from these cameras. Two locations where speed cameras were installed in 2011, were extensively examined in a quasi-experiment: (1) a two-lane motorway and (2) a three-lane motorway, each with a posted speed limit of 120 km/h and sited in Flanders, Belgium. The effect is analysed on the same manner than the study on the average speed control, i.e. a before-and-after comparison of travel speeds, with control for the general trends effects. At each of the two roads, data were gathered at five measurement points from 3 km upstream to 3.8 km downstream of the camera. Speeds decreased on average by 6.4 km/h at the camera locations. Both the odds of drivers exceeding the speed limit (-80%) and the odds of drivers exceeding the speed limit by more than 10% (-86%) decreased considerably. However, before and beyond the cameras the speeds hardly, if at all, reduced. Moreover, the analyses of the speed profiles before and beyond the cameras show that drivers do slow down quite abruptly before the camera and speed up again after passing the camera.

In addition to the speed effects, also the effects on crashes were examined. In accordance with the analyses of the effects on the driving speed, crashes were selected at different distances from the camera. The study included 26 locations with fixed speed cameras, installed between 2007 and 2010 on Flemish motorways. The traffic safety effect was evaluated through an empirical Bayes before-and-after analysis of the number of crashes. The effects are analysed at different distances from the camera, from 1200 m upstream up to 5000 m downstream from the camera locations. Upstream from and nearby the camera locations (-1200 m up to +200 m) significant increases are found in the number of PDO crashes (+55%) and injury crashes (+33%). Downstream from the camera (+200 m up to +5000 m), the results are ambiguous with significant decreases in the number of injury crashes (-17%), but still increases in the number of PDO crashes (+28%). A separate analysis according to the crash type generally shows increases in the number of side and rear-end crashes and decreases in the number of crashes against an obstacle outside the roadway (single-vehicle crashes).
A comparison of the effects on the crashes with the effects on the driving speeds show that the increase of the crashes upstream from and at the camera location can be linked to the sudden braking behaviour before and at the camera. Beyond the camera, the speed differences were found to be smaller, and in accordance with this finding smaller increases for PDO crashes and decreases for the number of injury crashes were found.

In chapter 7 a table with the key characteristics of each study is displayed. Furthermore, an overview of the results of the effect estimations is given, and the impacts of these results for practice are described. Based on the results that were found in the different studies, some general implications per theme are formulated and several recommendations for further research are defined:

- The black spot programme was found to be an effective traffic safety measure. However, it is conceivable that on a certain moment the most dangerous spots will have been handled, and further investments in black spots will not lead to additional benefits in traffic safety.
- The reduction of the fixed speed limit was found to be effective for the number of severe crashes at road sections. However at the intersections no effect and even an increase in the number of injury crashes was found. Future research is necessary to examine the speed limit compliance after this has been reduced, through which also the causation of the difference in the effect between road sections and intersections could be identified.
- The study on the traffic safety effects of a dynamic speed limit system was one of the first that applied an empirical study with observed data. The study showed favourable effects on crashes that were related to manoeuvres. However, it is recommended to do this research again with a higher number and a diverse set of locations. Furthermore, it would be interesting to analyse the driving behaviour at locations with dynamic systems, in order to analyse the speed limit compliance.
- The study on the effectiveness of combined speed and red light cameras showed favourable effects for fatal and serious injury crashes, but high increases were found in the number of, however less severe, rear-end crashes (+44%). Future research is necessary to study the circumstances of these crashes and to develop measures in order to tackle this unintended effect.
- The study on the automated section speed control is one of the first peer-reviewed papers, which resulted in strong decreases of the driving speed. Future research is necessary to analyse whether the speed effect will persist after a longer period, whether also an effect could be observed at a longer distance (further than 6 km) from the section, and to study the effects on crash occurrence.
- The speed profile at speed cameras on motorways clearly showed a V-profile with the highest effects at the speed camera, but smaller and even

unfavourable effects at the locations upstream and downstream from the camera. Future research in other countries is necessary in order to study whether similar results can be found. Furthermore, it would be interesting to study whether the effect evolves over time and to analyse the effects at different moments after the installation of the speed camera.

- In addition, the speed effects of cameras on highways should be analysed. It was found that speed cameras on highways lead to more favourable effects on crashes compared to speed cameras on motorways. However, based on the crash effects at the different distances from the camera, probably the kangaroo effect is present at this road too, but the impact on crashes might be less high.

Next to the evaluation of a number of traffic safety measures and the impact for practice and future research, the present dissertation wants to emphasize the importance of effect estimation as part of an effective road safety management. However, the implementation of effect estimation might bring several challenges. Effect evaluation might prove that important road safety investments had limited or no impact, which can be a barrier for road authorities to evaluate the effects of traffic safety measures. Furthermore, the effect evaluation of traffic safety measures should be seen as part of a larger efficiency assessment tool, in which also the costs and the public support need to be taken into account.

The growing interest and increasing application of effect estimation of traffic safety measures is an opportunity to increase international cooperation in the development and sharing of crash modification factors. Therefore it is important to put enough effort in the application of proper study designs and reporting, which is however often costly to perform.

NEDERLANDSTALIGE SAMENVATTING

Een belangrijke stap binnen het voeren van een effectief verkeersveiligheidsbeleid is evaluatie. Deze evaluatie geeft informatie omtrent de effectiviteit van ingevoerde verkeersveiligheidsmaatregelen, zorgt dat beslissingen op een gefundeerde manier kunnen genomen worden, verbetert de effectiviteit van toekomstige initiatieven en kan gebruikt worden om te controleren of middelen goed geïnvesteerd werden. Er wordt dan ook steeds meer aandacht gevestigd op het belang van de effectevaluatie van verkeersveiligheidsmaatregelen. Volgens de OESO is er te weinig aandacht voor de waarde, het belang en het gebruik van effectevaluatie in het verkeersveiligheidsbeleid. Deze doctoraatsthesis wil daarom het belang van effectevaluatie onder de aandacht brengen, en tracht om leemtes in de kennis aangaande de effectiviteit van verschillende verkeersveiligheidsmaatregelen op te vullen. Daartoe werden acht maatregelen geselecteerd, allen geïmplementeerd in Vlaanderen, die kunnen ondergebracht worden in vier thema's:

- Verkeersveiligheid op kruispunten
    - (1) Het gevaarlijke puntenprogramma
    - (2) Conflictvrije kruispunten
- Verlagen van snelheidslimieten
    - (3) Verlagen van de toegelaten snelheidslimiet van 90 km/u naar 70 km/u
    - (4) Dynamische rijstrooksignalisatie op autosnelwegen
- Handhaving van snelheid en roodlichtnegatie op gewestwegen
    - (5) Snelheidscamera's op gewestwegen
    - (6) Roodlichtcamera's
- Snelheidshandhaving op autosnelwegen
    - (7) Trajectcontrole
    - (8) Snelheidscamera's op autosnelwegen

Voor alle maatregelen, behalve de trajectcontrole, werden de effecten op het aantal en de ernst van de ongevallen onderzocht. Daarnaast werden van de twee maatregelen ter handhaving van de snelheid op autosnelwegen, ook effecten op de gereden snelheid geanalyseerd.

Het belang van effectevaluatie en de doelstellingen van deze thesis zijn beschreven in hoofdstuk 1.

Om de effecten van de verschillende verkeersveiligheidsmaatregelen te evalueren werd een voor- en nastudie toegepast, waarbij het aantal ongevallen na het implementeren van de maatregel werd vergeleken met het aantal ongevallen op dezelfde locatie vóór dat de maatregel werd toegepast. Belangrijk bij het toepassen van voor- en nastudies is het controleren voor mogelijke vertekenende factoren. Idealiter wordt de empirical Bayes voor- en nastudie toegepast. Hierbij traden echter verschillende methodologische problemen op.
Eén van die problemen was dat er op bepaalde locaties geen ongevallen gebeurden in de voor- of naperiode, waardoor het niet mogelijk was om het effect te meten. Tot op heden is echter nog geen afdoende methode gevonden om dit probleem op te lossen. In deze doctoraatsthesis werd een empricial Bayes schatting toegepast in de naperiode. Verder onderzoek is echter nodig om deze methode te valideren.
In Vlaanderen zijn, zeker indien een aantal jaren terug gegaan wordt, slechts beperkte data aangaande verkeersvolumes aanwezig. Bij het toepassen van de empirical Bayes methode zijn volumedata echter nodig om een risicomodel te berekenen en zo te controleren voor regressie naar het gemiddelde. Dit heeft als gevolg dat het niet mogelijk was om in elke studie te controleren voor regressie naar het gemiddelde.
Naast het effect per locatie (bijvoorbeeld het effect van het plaatsen van een roodlichtcamera op een bepaald kruispunt), werd in elke studie een meta-analyse toegepast om het totale effect op alle locaties waar de onderzochte maatregel geïmplementeerd werd, te berekenen. Sommige onderzoekers geven aan dat, om het effect te berekenen, alle ongevallen van de voorperiode en de naperiode dienen opgesomd te worden, waarna het effect kan berekend worden. In dit doctoraat werd echter de voorkeur gegeven aan de gewogen methode, waarin locaties met een hoger aantal ongevallen een hoger gewicht kregen. Op locaties met een hoger aantal ongevallen is de variatie namelijk beperkter dan

op locaties met een lager aantal ongevallen. Deze gewogen methode leidt daarom tot meer gebalanceerde resultaten in vergelijking met de sommen.
De methodologie en de problemen die opdoken bij het toepassen van de empirical Bayes methode zijn beschreven in hoofdstuk 2. Daarnaast wordt in dit hoofdstuk beschreven hoe de effecten op de verkeersslachtoffers werden onderzocht, waarbij een onderscheid werd gemaakt naar vervoersmodus. Tenslotte beschrijft dit hoofdstuk hoe het effect op het snelheidsgedrag geanalyseerd werd.

In hoofdstuk 3 worden twee studies beschreven waarin de effecten van infrastructurele aanpassingen van gevaarlijke kruispunten onderzocht werden. De eerste studie omvat de effectevaluatie van de gevaarlijke punten studie. In totaal werden 800 locaties opgenomen in het gevaarlijke punten programma, waarvan er 134 werden geanalyseerd binnen deze studie. Dit waren allemaal kruispunten, aangepast tussen 2004 en 2007. Het effect werd onderzocht door middel van een empirical Bayes voor- en nastudie, waarbij gecontroleerd werd voor trendeffecten en regressie naar het gemiddelde. Het gevaarlijke punten programma blijkt duidelijk effectief te zijn. Het aantal letselongevallen daalde met 24% tot 27% (afhankelijk van de vergelijkingsgroep die werd gebruikt ter controle voor de trend), het aantal ongevallen met doden en zwaar gewonden daalde met 46% tot zelfs 57%. De hoogste effecten werden gevonden op voorrangsgeregelde kruispunten waarbij aanpassingen werden uitgevoerd in de lay-out van het kruispunt en op voorrangsgeregelde kruispunten waar verkeerslichten werden geplaatst. Het gevaarlijke punten programma bracht bovendien gunstige effecten teweeg voor alle vervoersmodi (voetgangers, fietsers, bromfietsers, motorfietsers, personenwagens, vrachtwagens).

Eén van de maatregelen binnen het gevaarlijke punten programma, namelijk de invoering van conflictvrije verkeerslichten, wordt meer gedetailleerd bestudeerd in een tweede studie. Dergelijke installaties zorgen er voor dat links afslaande bewegingen beveiligd kunnen verlopen. Hierbij krijgt de bestuurder die links afslaat een groene pijl, terwijl de tegenligger een rood licht krijgt. De voor- en navergelijking van het aantal ongevallen, waarbij werd gecontroleerd voor regressie naar het gemiddelde en algemene trendeffecten, toonde duidelijk gunstige resultaten. Een analyse van 103 lichtengeregelde kruispunten, waar tussen 2004 en 2009 conflictvrije lichten geplaatst werden, vertoonde een significante daling in het aantal letselongevallen van 37%, waarbij voornamelijk een daling in het aantal ongevallen met links afslaande voertuigen werd vastgesteld (-50%). Het effect op de ernstige ongevallen was nog hoger: -59%. Daarnaast werden gunstige effecten gevonden op het aantal gewonde fietsers, bromfietsers, motorfietsers en personenwagens.

In hoofdstuk 4 worden twee maatregelen beschreven waarbij de toegelaten maximum snelheid verlaagd werd. In een eerste studie wordt het verkeersveiligheidseffect van de verlaging van een snelheidslimiet van 90 km/u naar 70 km/u op de Vlaamse gewestwegen beschreven. In totaal werden 61 weglengtes met een totaal van 116 km geanalyseerd. De snelheidslimieten op deze weglengtes werden verlaagd in 2001 of 2002. Algemene trendeffecten werden gecontroleerd door middel van een vergelijkingsgroep, maar het was niet mogelijk om te controleren voor regressie naar het gemiddelde. De analyses resulteerden in een niet-significante daling van het aantal letselongevallen. Wel werd een significant effect gevonden op het aantal ongevallen met doden en zwaar gewonden (-33%). Daarnaast werd een duidelijk hoger effect gevonden op de weglengtes in vergelijking met de kruispunten.

De tweede maatregel die binnen dit hoofdstuk onderzocht werd, is dynamische rijstrooksignalisatie. Wanneer op basis van informatie vanwege camera's en lussen in het wegdek een hoge bezettingsgraad samen met een lage snelheid wordt vastgesteld, worden de snelheidslimieten op de dynamische borden verlaagd. In dit onderzoek werden vijf weglengtes op de Vlaamse autosnelwegen geselecteerd (totaal 60 km), waar dynamische rijstrooksignalisatie werd geplaatst tussen 2003 en 2009. Het effect van deze maatregel werd onderzocht door middel van de empirical Bayes voor- en nastudie. De analyses resulteerden in een significante daling van 18% in het aantal letselongevallen. Een onderscheid naar het type aanrijding toonde een daling van 20% in het aantal kop-staartaanrijdingen, maar dit resultaat was slechts randsignificant. Voor de eenzijdige aanrijdingen werd een niet-significante daling van 15% gevonden.

Daarnaast werd een niet-significant daling gevonden van 3% in het aantal ongevallen met doden en zwaargewonden.

In hoofdstuk 5 worden twee handhavingsmaatregelen op gewestwegen geanalyseerd: snelheidscamera's en roodlichtcamera's.
In een eerste studie werden 65 locaties met snelheidscamera's geanalyseerd, geïnstalleerd tussen 2002 en 2007. In de voor- en navergelijking van het aantal ongevallen was het enkel mogelijk om te controleren voor algemene trendeffecten. Tot op een afstand van 500 m van de camera werd een daling gevonden van 8% in het aantal letselongevallen. Het aantal ongevallen met doden en zwaar gewonden vertoonde een daling met 29%. Een analyse van de effecten op verschillende afstanden van de camera toonde aan dat het effect op het aantal letselongevallen vooral te wijten is aan het effect op een afstand van 250-500 m van de camera. Voor de ernstige ongevallen werden ietwat andere resultaten gevonden, met de hoogste effecten tot op 250 m van de camera. Op langere afstand van de camera (500-1000m) waren eerder stijgingen in het aantal ongevallen terug te vinden. Daarnaast werden voor alle vervoersmodi gunstige resultaten gevonden.

In een tweede studie binnen hoofdstuk 5 werden 253 kruispunten met roodlichtcamera's onderzocht. Deze roodlichtcamera's detecteren zowel roodlichtnegatie als overdreven snelheid en werden geplaatst tussen 2002 en 2007. Een voor- en navergelijking van het aantal ongevallen met controle voor de trend toonde een beperkte, niet-significante stijging van 5% in het aantal letselongevallen. Deze stijging was vooral het gevolg van een stijging in het aantal kop-staartaanrijdingen (+44%), terwijl een niet-significante daling in het aantal flankaanrijdingen werd teruggevonden (-6%). Het aantal ernstige ongevallen daalde met 14%, wat voornamelijk kan toegeschreven worden aan een daling in het aantal flankaanrijdingen (-24%). Een voor- en navergelijking van het aantal gewonden per vervoersmodus toonde enkel een gunstig effect voor het aantal fietsers.

In hoofdstuk 6 worden de effecten van twee maatregelen ter handhaving van de snelheid op autosnelwegen onderzocht: trajectcontrole en snelheidscamera's.

De studie aangaande trajectcontrole is één van de eerste 'peer-reviewed' studies aangaande dit onderwerp. In dit onderzoek werden de effecten op de gereden snelheid onderzocht. Trajectcontrole is een relatief nieuwe maatregel, die meer en meer wordt toegepast ter handhaving van de snelheidslimieten. Het voordeel van dit systeem is dat de snelheid van het voertuig over een gehele weglengte gemeten wordt, wat zou leiden tot een lager aantal snelheidsovertredingen en tot een daling in de snelheidsverschillen, verhoogde volgafstanden, meer homogeen verkeer en verhoogde capaciteit van het weggennet. In deze studie werd de trajectcontrole op de E40, in beide richtingen tussen Wetteren en Erpe-Mere, en geïnstalleerd in maart 2013, onderzocht. Deze autosnelweg heeft drie rijstroken en een toegelaten snelheidslimiet van 120 km/u. De snelheden werden geanalyseerd op verschillende punten: van 6 km voor de start van het traject tot 6 km voorbij het einde van het traject. De snelheden werden verzameld gedurende één week voor dat de trajectcontrole (maart 2012) werd geïnstalleerd en gedurende één week nadat de trajectcontrole reeds werd ingevoerd (april 2013). Algemene trendeffecten en fluctuaties werden in rekening genomen door een analyse van de snelheid op vergelijkbare locaties. Het effect op de gereden snelheid werd onderzocht door een analyse van: (1) gemiddelde snelheid; (2) odds van bestuurders die de snelheid overtreden; (3) odds van de bestuurders die de snelheid met meer dan 10% overtreden. Op het traject daalde de snelheid gemiddeld met 5.84 km/u, de odds van weggebruikers die de snelheid overtreden daalde met 74%, de odds van de weggebruikers die de snelheid met meer dan 10% overtreden daalde met 86%. Op de locaties stroomopwaarts en stroomafwaarts werden ook sterke dalingen gevonden in elk van de drie outcomes. Daarnaast daalden ook de snelheidsverschillen na het invoeren van de trajectcontrole.

Naast de trajectcontrole, werd ook het effect van snelheidscamera's op autosnelwegen onderzocht. Daar waar vorige onderzoeken het effect op de gereden snelheid vooral ter hoogte van de camera onderzochten, werden in deze studie ook de effecten op langere afstanden van de camera geanalyseerd. Twee locaties, waar in 2011 snelheidscamera's werden geplaatst, werden opgenomen in dit onderzoek: (1) E19 ter hoogte van Brasschaat en (2) E40 ter hoogte van Boutersem. Beide wegen hebben respectievelijk twee en drie rijstroken en een toegelaten snelheid van 120 km/u. Het effect werd, net zoals bij de trajectcontrole, onderzocht door de gereden snelheid voor het plaatsen van de camera te vergelijken met de gereden snelheid na het plaatsen van de camera. Op elk van de twee locaties werden snelheden verzameld op vijf meetpunten: van 3 km stroomopwaarts van de camera tot 3.8 km stroomafwaarts. Ter hoogte van de camera daalde de snelheid met gemiddeld 6.4 km, de odds van het aantal overtreders daalde met 80%, voor het aantal bestuurders dat de snelheid met meer dan 10% overtrad was dit 86%. Stroomopwaarts en –afwaarts van de camera werden geen effecten gevonden op de gereden snelheid. Daarnaast was duidelijk te zien dat bestuurders afremmen vlak voor de camera en terug versnellen eens ze de camera gepasseerd zijn.

Naast de effecten op de snelheid, werden ook de effecten op de ongevallen onderzocht van snelheidscamera's geplaatst op autosnelwegen. In de studie werden 26 locaties met snelheidscamera's (geplaatst tussen 2007 en 2010) opgenomen, waarvan het effect werd onderzocht door middel van een empirical Bayes voor- en nastudie. In lijn met de snelheidsanalyses werden de ongevallen geselecteerd op verschillende afstanden van de camera, van 1200 m stroomopwaarts van de camera tot 5000 m stroomafwaarts. Stroomopwaarts tot aan de camera (-1200 m tot +200 m) werden significante stijgingen gevonden in het aantal ongevallen met stoffelijke schade (+55%) en het aantal letselongevallen (+33%). Stroomafwaarts van de camera (+200 m tot +5000 m) werd enerzijds een daling gevonden in het aantal letselongevallen (-17%), maar werd nog steeds een stijging gevonden in het aantal ongevallen met stoffelijke schade (+28%). Een aparte analyse naar het aanrijdingstype toont aan dat het aantal flankaanrijdingen en kop-staartaanrijdingen steeg, maar dat het aantal aanrijdingen tegen een hindernis buiten de rijbaan daalde.
Een vergelijking van het effect op ongevallen met het effect op de gereden snelheid toont aan dat de stijging in het aantal ongevallen stroomopwaarts en ter hoogte van de camera kan gerelateerd worden aan het plotse remgedrag van bestuurders vlak voor de camera. De snelheidsverschillen voorbij de camera zijn minder hoog, en bijgevolg werden ook minder hoge stijgingen gevonden in het

aantal ongevallen met stoffelijke schade en werd zelfs een daling gevonden in het aantal letselongevallen.

In hoofdstuk 7 worden de belangrijkste kenmerken van elk van de studies weergegeven in een overzichtstabel. Daarnaast wordt een overzicht gegeven van de resultaten van de verschillende effectschattingen, en wordt beschreven wat de impact van deze resultaten betekenen voor de praktijk. Op basis van de resultaten uit de verschillende studies kunnen verschillende aanbevelingen voor verder onderzoek geformuleerd worden:

- Het gevaarlijke punten programma blijkt een effectieve maatregel te zijn om de verkeersveiligheid te verbeteren. Niettemin moet hier rekening gehouden worden met het feit dat op een bepaald moment de meest gevaarlijke kruispunten aangepakt zullen zijn en dat verdere investering in gevaarlijke punten niet zal leiden tot bijkomende voordelen in de verkeersveiligheid.
- De daling van de toegelaten snelheidslimiet op gewestwegen bracht gunstige effecten teweeg op het aantal ernstige ongevallen op wegvakken. Verder onderzoek is echter nodig om te analyseren in welke mate dat bestuurders de nieuwe toegelaten snelheidslimiet volgen, en om na te gaan waarom enkel een gunstig effect werd teruggevonden op de wegvakken en niet op de kruispunten.
- De studie waarbij het effect van rijstrooksignalisatie werd onderzocht, was één van de eerste waarbij een empirische studie met geobserveerde data werd toegepast. Deze studie resulteerde in gunstige effecten op ongevallen die gerelateerd zijn aan manoeuvres. Om na te gaan of gelijkaardige effecten worden teruggevonden op andere locaties, is verder onderzoek nodig, waarbij een hoger en divers aantal wegen wordt opgenomen. Daarnaast zou het interessant zijn om na te gaan in welke mate dat bestuurders de afgebeelde dynamische snelheden volgen.
- De studie waarbij het effect werd onderzocht van roodlichtcamera's resulteerde in gunstige effecten in het aantal ernstige ongevallen, maar toonde ongunstige effecten in het aantal kop-staartaanrijdingen. Toekomstig onderzoek zou moeten nagaan in welke omstandigheden

deze ongevallen gebeuren en welke maatregelen het ontstaan van deze kop-staartaanrijdingen kunnen inperken.

- De studie aangaande de trajectcontrole is één van de eerste wetenschappelijke studies, waaruit duidelijk gunstige effecten werden teruggevonden op de gereden snelheid en het aantal overtredingen. Toekomstig onderzoek is nodig om te analyseren of deze effecten ook aanwezig blijven op langere termijn en of er ook gunstige effecten kunnen worden waargenomen op langere afstand van het traject. Ook is onderzoek aangaande het effect op het aantal ongevallen aangewezen.
- Een analyse van het snelheidsprofiel ter hoogte van snelheidscamera's op autosnelwegen toonde duidelijk een V-profiel met de hoogste effecten ter hoogte van de camera, maar kleinere en zelfs ongunstige effecten ter hoogte van de locaties stroomopwaarts en stroomafwaarts van de camera. Toekomstig internationaal onderzoek is noodzakelijk om na te gaan of gelijkaardige resultaten kunnen teruggevonden worden. Daarnaast zou het ook interessant zijn om na te gaan hoe het effect van snelheidscamera's evolueert overheen de tijd, en of er verschillen vast te stellen zijn naargelang de tijd dat de camera geïnstalleerd is.
- Daarnaast zou het ook interessant zijn om de snelheidseffecten van camera's op gewestwegen te analyseren. De analyses van de ongevallen tonen aan dat snelheidscamera's op gewestwegen tot gunstigere effecten leiden dan snelheidscamera's op autosnelwegen. Een analyse van de snelheden ter hoogte van de camera's op gewestwegen zou mogelijks een beter inzicht kunnen bieden in de oorzaken van deze verschillen.

Het doel van de doctoraatsthesis was niet alleen het analyseren van de effecten van verschillende verkeersveiligheidsmaatregelen, maar ook het belang benadrukken van effectschatting als deel van een effectief verkeersveiligheidsbeleid. Het invoeren van dergelijke effectschatting in de praktijk leidt kan echter belangrijke uitdagingen meebrengen.
Het analyseren van de effecten van verkeersveiligheidsmaatregelen kan immers aantonen dat bepaalde investeringen geen of beperkte effecten hadden. Dit kan dan ook een belangrijke barrière voor het beleid vormen om (dure) maatregelen te evalueren. Daarnaast is het ook belangrijk dat effectschattingen niet enkel op

zich gezien worden, maar dat deze worden geïmplementeerd als onderdeel van een ruimere evaluatiemethode, waarin ook de kosten en de publieke ondersteuning in rekening genomen worden.
De stijgende interesse en toepassing van effectschatting biedt de mogelijkheid om internationale samenwerkingsverbanden op te stellen in het evalueren van verkeersveiligheidsmaatregelen. Het is daarom belangrijk om te werken aan kwaliteitsvol, wetenschappelijk gefundeerd onderzoek en een uitgebreide rapportering van de methodiek en resultaten. Nadeel is echter dat dergelijke onderzoek vaak veel middelen vraagt.

ABBREVIATIONS

ASSC	Automated Section Speed Control
CI	Confidence interval
CMF	Crash modification factor
DSL	Dynamic speed limit
EB	Empirical Bayes
OR	Odds ratio
PDO	Property damage only
RTM	Regression to the mean
s	Standard deviation
SPF	Safety performance function
SRLC	Speed and red light camera

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 EVALUATION AS PART OF AN EFFECTIVE ROAD SAFETY MANAGEMENT

In 2013, 384 people lost their lives in a road crash in Flanders and 3,442 got severely injured. In the European Union 26,025 people died as a consequence of a crash. These crashes not only affect the involved road users but also bring a lot of stress to their surroundings. A scientifically based road safety management system is needed to face these challenges. In this system, a concert of adequate and efficient strategies, tools and measures are developed and implemented (Schulze & Koßmann, 2010). Evaluation is an important step in an effective road safety management. This evaluation can give information on the effectiveness of current programmes and can identify the remedial action required if they are not (Cammack, Cairney, Turner, & Steinmetz, 2012). Furthermore, the knowledge that results from such evaluation will allow more effective programmes to be developed in the future (Cammack et al., 2012). Information on the effectiveness of different measures that target the same traffic safety problem can help to make well-based decisions. An effect evaluation allows a synthesis of diverse evaluation results that in turn allows for more universal understanding and application of traffic safety effectiveness measures (OECD, 2012). In addition, a good evaluation is also important to monitor the impact of road safety management tools in order to serve as a controlling instrument for the appropriateness of safety management efforts (Schulze & Koßmann, 2010). The justification of investments in a field of road safety, where large investments can potentially bring little or no results (and on rare occasions unfavourable results) is necessary (Hasson, Kauppila, Assing, Yannis, & Lassarre, 2012).

Often clear road safety targets are set and the policy makers try to adopt road safety strategies to achieve these targets within the constraints of the established priorities and the resources available. Therefore, efficiency assessment of traffic safety measures is considered to be an extremely useful tool (OECD, 2012). It is stated that the stronger road safety policies are science-based, the more efficient they will be in the reduction of fatalities and the severity of road crashes (Schulze & Koßmann, 2010).

1.2 Research objectives

Evaluation is an important step in an effective traffic safety management system. These evaluations are growing in relative importance more recently as their value and importance in safety analysis has become more apparent (OECD, 2012). The overall objective of this dissertation is the effect evaluation of several traffic safety measures through a before-and-after study approach. Despite all efforts, certain traffic safety problems remain a challenge for many countries over the world (e.g. speeding). It is therefore important to study the effects of the measures that tackle these problems, in order to get a clear view on what is effective and how future initiatives can be made more effective. On the one hand measures are studied which have been evaluated in previous studies, but the focus is on specific elements that were not analysed before. This PhD dissertation tries to fill the gaps in knowledge. On the other hand, measures are studied from which the traffic safety effects are unclear up to now. We are living in a fast evolving world, which not only leads to new traffic safety problems (e.g. use of mobile phone behind the wheel) and thus to new challenges, but also to new possibilities for traffic safety measures (e.g. variable speed limits, average speed control). It is therefore necessary to evaluate the effects of these new measures as soon as possible after they have been implemented. According to the OECD there is a lack of understanding the value, importance and usage of effect estimation in road safety decision making (OECD, 2012). The present dissertation emphasizes the importance of evaluation in an effective traffic safety policy and estimates the effects of several road safety measures.

In the evaluation of road safety measures there are at least three possible approaches: (1) crash reductions; (2) changes in road user behaviour and (3) community reactions to measures. Crash reductions are however the most direct measure of what traffic safety measures are likely to achieve (Cammack et al., 2012). Therefore, the best method to apply a reliable estimation of the effect is by monitoring the effects of treatments which have been applied in real traffic situations. The focus of the present PhD dissertation is on the analysis of the crash effects and changes in the behaviour.

All the measures that were studied in this dissertation are implemented in Flanders. Flanders is the Dutch speaking, Northern part of Belgium and has an own government and parliament. In cooperation with the Flemish government traffic safety measures were selected, from which the effects were not studied before in Flanders. In addition, the international literature was scanned, in search for gaps in knowledge of traffic safety measures that were studied before and to search for new traffic safety measures from which the effects were unknown.
In total eight traffic safety measures were analysed, which can be subdivided into four main themes:

- Traffic safety improvement at intersections
    - (1) Black spot treatment programme
    - (2) Left-turn protection at signalized intersections
- Reducing speed limits
    - (3) Reduction of the maximum speed limit from 90 km/h to 70 km/h
    - (4) Variable speed limits on motorways
- Speed and red light running enforcement on highways
    - (5) Speed cameras on highways
    - (6) Combined speed and red light cameras
- Speed enforcement on motorways
    - (7) Automated section speed control
    - (8) Speed cameras on motorways

More information on each of the measures is given in the next chapter, where they furthermore are placed in the broader context of the traffic safety situation in Flanders.

1.3 The examined traffic safety measures in a broader context

1.3.1 Traffic safety situation in Flanders

The eight measures that were studied in the present dissertation are all implemented in the Flemish region of Belgium. Flanders counts 883 km of motorways, 6,040 km of highways and 64,564 km of local roads. Five measures that were examined in the present dissertation are implemented on highways, three are implemented on motorways.

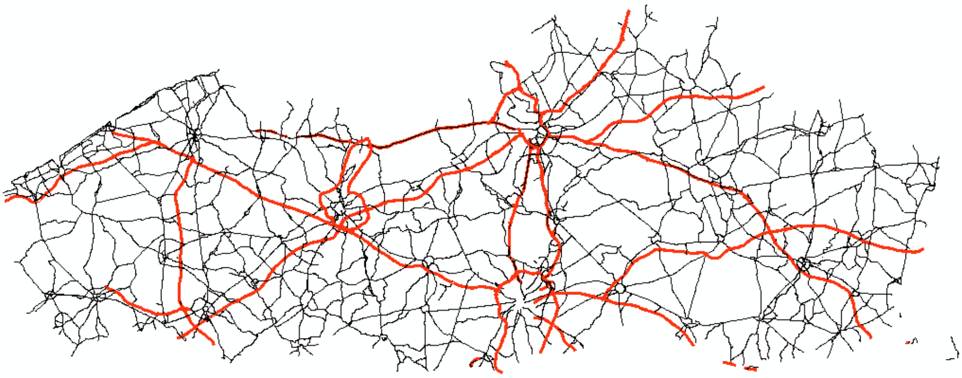


Figure 1-1 Overview of motorways (red) and highways (black) in Flanders

Figure 1-2 shows the number of injury crashes in Flanders from 1991 (the first year the crash data were systematically gathered) up to 2013. During this period the number of injury crashes decreased by 40%. During 2000-2010 (which is the period that is used as research period in the majority of the case studies), a decrease of 23% could be observed.

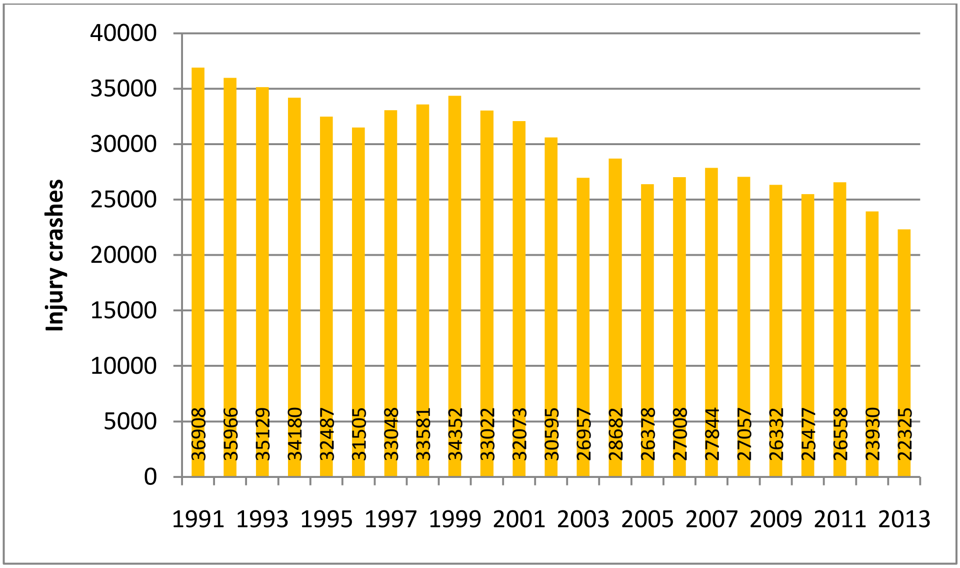


Figure 1-2 Number of injury crashes in Flanders (1991-2013)

Figure 1-3 shows the evolution of the number of the severe injury crashes, i.e. the crashes with deadly or severely injured persons. For these crashes, a decrease of 68% could be observed between 1991 and 2013. Between 2000 and 2010 this was -42%.

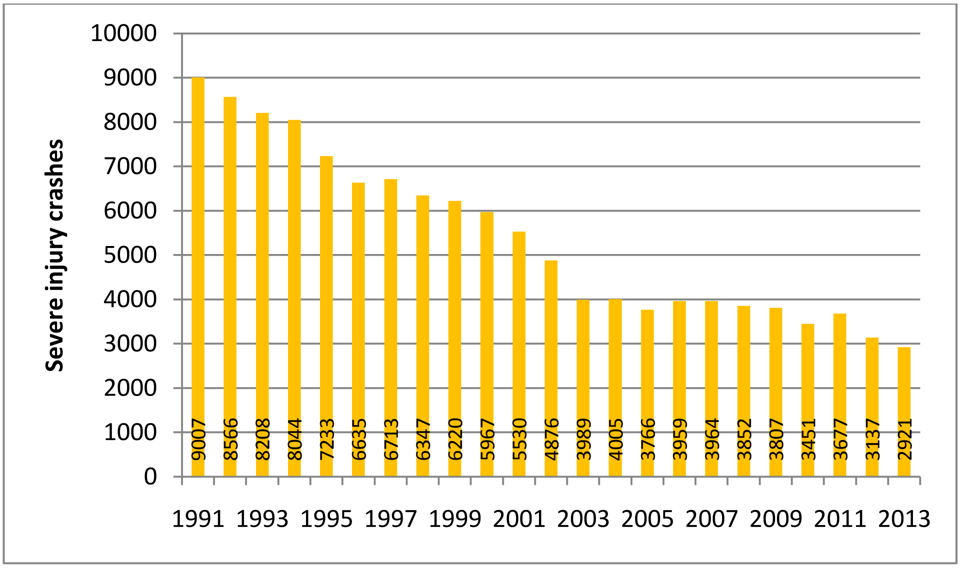


Figure 1-3 Number of severe injury crashes in Flanders (1991-2013)

Figure 1-4 shows the number of injury crashes on highways and motorways, from 2002 (first year the crashes were geographically located) up to 2012. The number of injury crashes decreased between 2002 and 2012 by 22% on highways. On motorways a decrease of 14% could be observed.

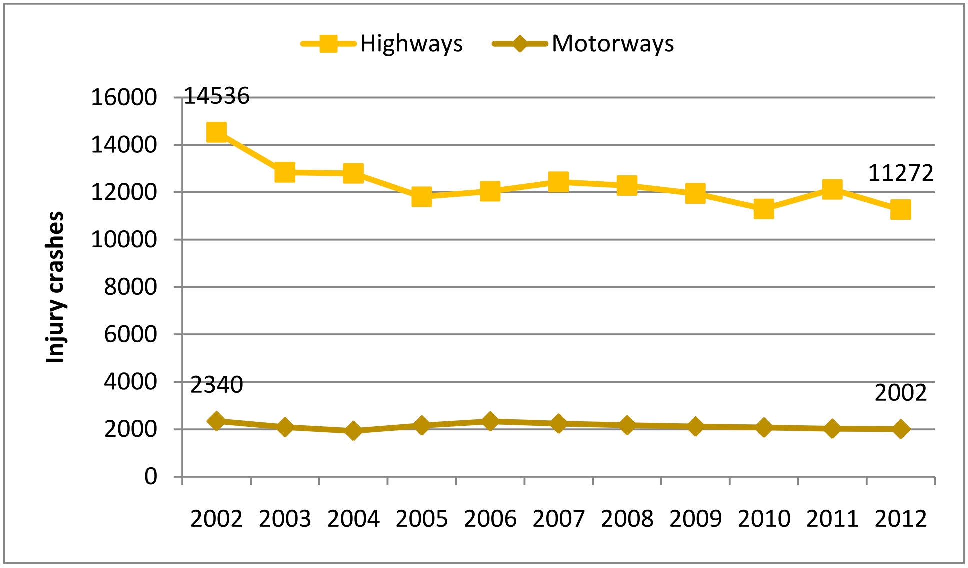


Figure 1-4 Number of injury crashes on highways and motorways

Despite the fact that Flanders made a lot of progress, they are still far behind the countries that perform the best in Europe. Figure 1-5 shows the number of deaths per million inhabitants for the EU28 in 2013. When Flanders is added to this chart, it can be seen that with 60 deaths per million inhabitants, it is far above the average (51 million deaths per million inhabitants). The number is even double as high compared to the best performing countries, i.e. Sweden and the United Kingdom.

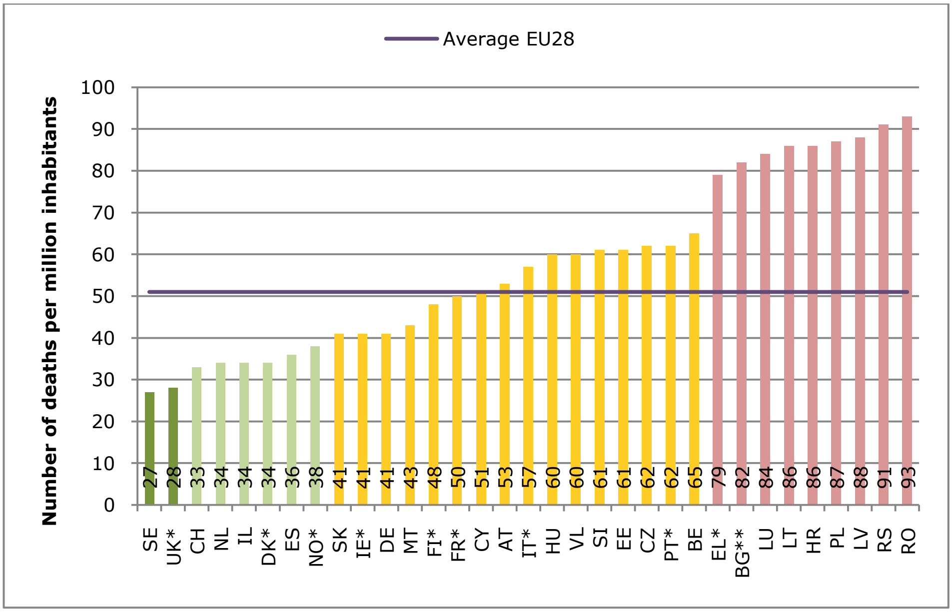


Figure 1-5 Number of deaths per million inhabitants for EU28 in 2013 (Jost & Allsop, 2014)

*National provisional estimates used for 2013, as the final figures for 2013 were not yet available at the time the report was published

**ETSC estimates based on EC CARE Quick indicator

1.3.2 THE FLEMISH TRAFFIC SAFETY POLICY

The improvement of the traffic safety is since a long time an important purpose of the Flemish government. Up to now, investments remain necessary, as the number of crashes and injuries in Flanders are still high above the European average. Furthermore traffic safety is a very important concern for many citizens. Generally, the implemented measures can be subdivided into three main themes: education, engineering and enforcement. Examples of measures in the field of education are theoretical lessons in school, mass media campaigns via television and social media, adaptation in the system to get a driving licence etc. These measures are often implemented all over Flanders, and focus on specific target groups (e.g. children, novice drivers, elder drivers, motor riders) or on specific themes (e.g. drunk driving, speeding, seat belt use). Furthermore, several measures were applied in the field of enforcement, which mainly focus on speeding, driving under the influence of alcohol and drugs, and seat-belt use, but also headways between trucks and overloaded trucks. In addition, the infrastructure was improved at different points in the roadway network, for example resurfacing the road, changes in cycle facilities and safer junctions.

In the present dissertation a selection of these traffic safety measures, implemented between 2002 and 2013, are studied. In order to calculate solely the effect of the measure under evaluation, it is important to exclude the effects of other measure, as otherwise the effect could be overestimated. In order to control for measures that are widely implemented (e.g. public campaigns, legislation, safer cars etc.), crashes are selected at locations that are similar to the treated locations, but where the measure under evaluation has not been implemented. This gives a clear indication of the general trend effect, and how the crashes evolved over time. In some studies, the crashes of all Flemish roads were selected, when it was not possible to select similar locations.
This method does not control for other locally implemented measures. For example, together with the installation of protected left-turn signals or the installation of red light cameras, other infrastructural measures were implemented. In these cases, a separate analysis was applied for locations at which the effects of the measure only could be studied, and for locations at which multiple measures were studied. Per study a description is given on how this is adapted.

Table 1-1 gives an overview of the traffic safety measures studied in this dissertation. The table describes which measure is studied per chapter, and gives more information on the type of treatment, the analysed outcome, the location where the measure was implemented, and the research period, together with the implementation period. Some of these measures are however still implemented up to now, and were not restricted up to a certain period in time (for example black spot treatment, speed cameras, red light cameras). However, in order to have a sufficient number of years of crash data in the after period, only the locations where the measure was implemented up to certain moment in time, could be studied. For the red light cameras for example, all cameras that were installed up to 2007 were studied.

The majority of the measures focus on speed and speeding (chapter 4.1 up to 6.3). This is an important traffic safety problem, which remains a challenge for many countries. Half of the measures are engineering measures (chapter 3.1 up to 4.2), the other half are enforcement measures (chapter 5.1 up to 6.3). These two types of measures are very suitable to apply a before-and-after study of traffic crashes or road user behaviour. Measures such as education, public campaigns, in-vehicle applications, etc, are less suitable to use this method, and are therefore not studied in this dissertation.

For all measures, except for one (automated section speed control), the effects on the number of crashes were analysed. For two measures (automated section speed control and speed cameras on motorways) also the intermediate objectives were studied, namely the effects on the speed behaviour.
All these measures are mutually exclusive, meaning that it were all different measures, implemented at different locations. The only exception are the studies of chapter 3, where the intersections with protected left-turn signals (chapter 3.2) consist of a subset of the black spot programme (chapter 3.1). However, in chapter 3.2 the research period is longer, and thus, next to the locations with protected left-turn phasing from chapter 3.1, additional locations were selected in chapter 3.2.

Table 1-1 Overview of traffic safety measures studied in this dissertation

Chapter	Measure	Type of treatment	Outcome	Study locations	Research period (implementation period)
3.1	Black spot treatments	Engineering	Injury crashes (severity; characteristics of location) Casualties	134 intersections on highways	2000-2008 (2004-2007)
3.2	Protected left-turn phasing at signalized intersections	Engineering	Injury crashes (severity; type of crash) Casualties	103 signalized intersections on highways	2003-2010 (2004-2009)
4.1	Reducing the speed limit from 90km/h to 70 km/h	Engineering	Injury crashes (severity)	61 road sections with a total length of 116 km on highways	1996-2007 (2001-2002)
4.2	Dynamic speed limits	Engineering	Injury crashes (severity; type of crash)	Five road sections with a total length of 60 km on motorways	1999-2011 (2003-2009)
5.1	Fixed speed cameras on highways	Enforcement	Injury crashes (severity; distance from the camera; characteristics of location) Casualties	65 locations with speed cameras on highways	2000-2008 (2002-2007)
5.2	Combined speed and red light cameras	Enforcement	Injury crashes (severity; type of crash; characteristics of location) Casualties	253 intersections with combined speed and red light cameras on highways	2000-2008 (2002-2007)
6.1	Automated section speed control	Enforcement	Driving speed (average speed; number of speed limit violations)	Two sections of 7.4 km on motorways	2012-2013 (2013)
6.2	Fixed speed cameras on motorways	Enforcement	Driving speed (average speed; number of speed limit violations)	Two locations with speed cameras on motorways	2010-2013 (2011)
6.3	Fixed speed cameras on motorways	Enforcement	PDO and injury crashes (severity; distance from camera; type of crash)	26 locations with speed cameras on motorways	2003-2011 (2007-2010)

1.4 OUTLINE OF THE DISSERTATION

This chapter situates the content of this dissertation in the general domain of traffic safety and describes the research objectives of this dissertation.

In **chapter 2** the applied methodology is described in detail. The effects of the traffic safety measures are generally studied through a before-and-after evaluation of traffic crashes. However when this method is applied, several confounding factors should be controlled for. An overview of these confounding factors and the methods to control for these factors are described in this chapter.

Next to the effects on crashes the effects on casualty level are studied and the effects on the driving speeds were analysed. A short description of these methods can also be found in chapter 2.

Chapter 3 includes the evaluation of two engineering measures. In the first study the effects on the occurrence of crashes of a black spot treatment programme is analysed. Through this programme the infrastructure at the most dangerous intersections in Flanders was adapted, in order to make these safer. Often multiple changes were applied at one intersection. The second study specifically targeted one measure, namely left-turn phasing at signalized intersections.

In **chapter 4** the effects of two measures that focus on the reduction of speed limits are described. The first study includes an effect evaluation of the speed limit reduction from 90 km/h to 70 km/h on highways; in the second study the traffic safety effect of the implementation of a dynamic speed limit system on motorways is analysed. For both measures the effects on the occurrence of crashes are studied.

In **chapter 5** the crash effects of two speed enforcement measures on highways are analysed. The first measure includes a fixed speed camera that is installed at road sections; the second measure includes a fixed camera that is installed at signalized intersections and that detects speeding and red light running behaviour.

Chapter 6 describes the results of two speed enforcement measures on motorways: fixed speed cameras and automated section speed control. For both measures, the effects on the driving speed were studied. For the speed cameras, also the effects on the occurrence of crashes were analysed.

Chapter 7 gives an overall view of the results of the studies and describes the policy implications, the need for further research and the methodological issues that occurred during these studies. Finally, some future challenges for effect estimation as part of an effective road safety management are described.

CHAPTER 2

APPLIED METHODOLOGY: BEFORE-AND-AFTER STUDY DESIGN

2.1 BEFORE-AND-AFTER COMPARISON OF TRAFFIC CRASHES

Different methods are used to examine the effects of traffic safety measures, however before-and-after studies, and more specifically empirical Bayes methods are widely accepted as the best standard in the evaluation of traffic safety measures (Elvik, 2008b; Elvik, 2012; 2012; Hauer, 1997; Persaud & Lyon, 2007). The methods that are applied in the present PhD dissertation are thoroughly described in this chapter.

2.1.1 BEFORE-AND-AFTER STUDIES IN TRAFFIC SAFETY EVALUATION

The evaluation of traffic safety measures are often observational studies, which can be categorized into two groups: before-and-after studies and cross-sectional studies. To evaluate the effectiveness of a traffic safety measure, the most commonly used study design is a before-and-after study (Elvik, 2002; Shinar, 2007), which compares the number of crashes after the implementation of a measure with the number of crashes at the same location before the implementation. The before-and-after evaluation of traffic crashes can be expressed in an index of effectiveness (θ) (Hauer, 1997), and can be calculated though the next equation, which shows the relative change in the crash rates from after with before:

$$\theta_l = \frac{L_l}{K_l} \qquad \text{(Eq. 2-1)}$$

with

L_l = observed number of crashes at the treated location L in the after period

K_l = observed number of crashes at the treated location L in the before period

When the index is lower than 1, this shows that the crashes decreased and the measure had a favourable effect on traffic safety. An index higher than 1 indicates a higher crash rate after the implementation of the measure, compared to before.

Within those before-and-after studies, different methods can be used, which mainly differ in the extent they control for confounding variables. A confounding variable is defined as any exogenous variable affecting the number of crashes or injuries whose effects, if not estimated, can be confounded with the measure under evaluation (Elvik, 2002; Hauer, 1997). Potentially confounding factors in observational before-and-after studies of road safety measures are (Elvik, 2002):

<u>Regression to the mean</u>

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.

<u>Long term trends affecting the number of crashes</u>

Many factors that can influence the occurrence of crashes change autonomously over time. Examples of these factors are driver demography, road user behaviour, weather and vehicle fleet (Hauer, 1997). The effects in crashes from before to after also include the effects of these factors, and thus need to be taken into account. In addition, the degree of reporting crashes may vary over time.

General changes of the number of crashes from before to after the road safety measure is introduced

The general number of crashes can change because of traffic safety measures that are implemented at a wider scale. Besides the treatment that is studied, various other treatments and programmes may have been implemented at various times during the before or after periods (Hauer, 1997). Examples are changes in legislation, general educational campaigns, more enforcement etc.

Changes in traffic volume

As a result of the implementation of the measure, and more generally because of general trend effects, traffic volumes can change over time. According to Elvik (2002), traffic volumes do not need to be accounted for explicitly in a before-and-after study and it is sufficient to use a large comparison group, from which the total crash frequency encompasses several hundred. The changes in the number of crashes in the comparison group include the effects of all factors that had an influence on the number of crashes, including traffic growth.

However, not only the general changes in traffic volume should be taken into account, but also the effects on the traffic flow as a result of the implementation of the measure should be controlled for. In order to account for the changes in the traffic flow one needs to know how the expected number of crashes depends on the traffic flow. This means that one needs to have a safety performance function, linking the expected crash frequency to the traffic flow (Hauer, 1997). A problem that might occur is that traffic flow is often imperfectly known, as these are often obtained from short-duration traffic counts. Therefore, an assessment is needed about how accurate the factor of interest is known (Hauer, 1997).

The Flemish road structure gives however only limited opportunity for drivers to choose alternative roads, as these mainly include local roads with lower speed limits. The evaluated measures were implemented at the upper category of roads, and therefore will probably have had a limited effect on the rerouting choices of the driver.

Any other specific events introduced at the same time the road safety measures were implemented

Besides the measures that are applied on a wider scale, also the more locally implemented measures that are applied at the location with the measure that is being evaluated, should be taken into account. This can be done through a separate analysis of the locations at which the effects of the measure only could be studied, and for locations at which multiple measures were studied.

In general two main approaches can be taken to control for these confounding variables: (1) a statistical estimation of the effects of a confounding variable and (2) a comparison group (Elvik, 2002).

2.1.2 THE SELECTION OF A COMPARISON GROUP TO CONTROL FOR GENERAL TRENDS

An evaluation of a traffic safety measure through a before-and-after evaluation is only possible if it is clear what would have been the safety of an entity in the after period had the treatment not been applied. In order to control for the long-term trends and general changes in the number of crashes (as discussed in the second and third point in the previous paragraph and further referred to as 'general trend effects') a comparison group can be used.

2.1.2.1 COMPARABILITY OF THE COMPARISON GROUP

According to Hauer (1997) a comparison group should meet following requirements:

- the before and the after periods for the treatment and the comparison group should be the same
- the change in the factors influencing safety is similar in the treatment and comparison groups
- the crash counts should be sufficiently large
- when a sequence of sample odds ratios are calculated from historical crash counts, their sample mean is close to one and their variance is small.

The locations in the comparison group have to be similar to the treated group on a couple of characteristics, which is for example geometric design, traffic volumes and vehicle fleet (Persaud & Lyon, 2007). The comparability of the comparison group can be examined through the calculation of the odds-ratio (OR) for the crash rates during the years before the measure.

$$\mathrm{OR} = \frac{R_t / R_{t-1}}{C_t / C_{t-1}} \qquad \text{(Eq. 2-2)}$$

with R_t = number of crashes in the treated group in year t

R_{t-1} = number of crashes in the treated group in year t-1

C_t = number of crashes in the comparison group in year t

C_{t-1} = number of crashes in the comparison group in year t-1

When the OR is near to 1, the comparison group is comparable to the treated locations. Maximum standard deviation should not be higher than 0.20 (Hauer, 1997).

It is however difficult to select a comparison group that is comparable to the treated locations and is large enough to include a sufficient number of crashes. For example, the comparison group in chapter 4.1 is smaller compared to the treated group, as it was not possible to find other, comparable locations. Also the length of the before or the after period can be limited, for example because crash data are only available from or until a certain moment. As a result, there is a higher chance of randomness in a comparison group with a lower number of crashes compared to a larger comparison group.

2.1.2.2 EFFECT ESTIMATION

The effect estimation as described in Eq. 2-1 thus needs to be adapted for trend effects. Therefore, it is assumed that the treated locations followed the same trend as the comparison group. This trend is reflected by the evolution of the crash rates from after to before in the comparison group. Consequently, the effect estimate can be expressed as:

$$\theta_l = \frac{L_l / K_l}{N / M} \qquad \text{(Eq. 2-3)}$$

with

L_l = observed number of crashes at the treated location L in the after period

K_l = observed number of crashes at the treated location L in the before period

N = observed number of crashes in the comparison group in the after period

M = observed number of crashes in the comparison group in the before period

2.1.3 THE EMPIRICAL BAYES METHOD TO CONTROL FOR REGRESSION TO THE MEAN

In order to increase the precision of the estimation and to correct for the RTM bias, the empirical Bayes (EB) method can be used (Hauer, Harwood, Council, & Griffith, 2002). This is widely accepted as the best standard in the evaluation of traffic safety measures (Elvik, 2008b, Elvik 2012; Hauer, 1997; Persaud & Lyon, 2007). The EB method compares the crash numbers after the implementation of the measure with before, increases the precision of estimation and corrects for the RTM bias (Hauer et al., 2002). In order to increase the precision of the estimates, the crash counts of the treated location and the crash frequency expected at similar entities are used (Hauer et al., 2002):

$$E[\kappa|K]_l = w * E[\kappa] + (1- w) * K_l \qquad \text{(Eq. 2-4)}$$

with $E[\kappa|K]_l$ = expected number of crashes at the treated location L given the observed crash frequency K_l

w = the weight that is given to the crashes at similar entities

$E[\kappa]$ = expected number of crashes at similar entities

1-w = the weight that is given to the crashes at the treated location L

K_l = observed number of crashes at the treated location L

The expected number of crashes at similar entities ($E[\kappa]$) is determined by the safety performance function (SPF). An SPF can be defined as an equation that is used to predict the average number of crashes per year at a location as a function of exposure and in some cases roadway or intersection characteristics (Federal Highway Administration, U.S. Department of Transportation, 2013). The estimated number of crashes reflects the average number of crashes per km-year (or per intersection-year) as a function of some trait values (e.g. traffic volume, length of segment ...) and of several regression parameters. These SPFs are calibrated from data by statistical techniques. It is assumed that the crash counts come from a negative binomial distribution (Hauer et al., 2002).

In order to fully assess how well the method fitted the data, next to the variables that result from the model (e.g. overdispersion), the Elvik-index can be used as a goodness-of-fit (Fridstrøm et al., 1995). The amount of overdispersion in a data set can be described in the overdispersion parameter, which can be calculated as next:

$$Var(x) = \lambda*(1+\mu\lambda) \qquad \text{(Eq. 2-5)}$$

where μ is the overdispersion parameter, which can be written as follows:

$$\mu = \frac{\frac{Var(x)}{\lambda}-1}{\lambda} \qquad \text{(Eq. 2-6)}$$

Defining μ_{crude} as the overdispersion parameter of the raw data and μ_{model} as the overdispersion parameter of the model, the Elvik index of goodness-of-fit can be described as follows:

$$1-\frac{\mu_{model}}{\mu_{crude}} \qquad \text{(Eq. 2-7)}$$

The index indicates the share of systematic variation in the crash count explained by the model.

The best estimate of the weight is based on the assumption that the expected number of crashes is gamma distributed with shape parameter *k* and the recorded number of crashes of each study unit is Poisson distributed (Elvik, 2008b). The weight (*w*) can subsequently be calculated through the following equation:

$$w = \frac{1}{1+\frac{E[\kappa]}{k}} \qquad \text{(Eq. 2-8)}$$

with *k* the inverse value of the overdispersion (i.e. variance is larger than the mean) parameter of the model, which is estimated per unit of length (Elvik, 2008b).

The combination of the control for the general trend and the RTM, leads to the next equation (see Eq. 2-3 and Eq. 2-4):

$$\theta_l = \frac{L_l / E[\kappa|K]_l}{N / M} \quad \text{(Eq. 2-9)}$$

with

L_l = observed number of crashes at the treated location L in the after period

$E[\kappa|K]_l$ = expected number of crashes at the treated location L given the observed crash frequency K_l

N = observed number of crashes in the comparison group in the after period

M = observed number of crashes in the comparison group in the before period

As θ_l has a lognormal distribution (i.e. the logarithm of the index is normally distributed) (Fleiss, 1981), the variance s_l^2 of $\ln(\theta_l)$, which is the natural logarithm of θ_l, can be calculated as

$$s_l^2 = \frac{1}{E[\kappa|K]_l} + \frac{1}{L_l} + \frac{1}{M} + \frac{1}{N} \quad \text{(Eq. 2-10)}$$

And a 95% confidence interval (CI):

$\theta_{l,\text{below limit}} = \exp[\ln(\theta_l) - 1.96 * s]$

$\theta_{l,\text{above limit}} = \exp[\ln(\theta_l) + 1.96 * s]$ (Eq. 2-11)

2.1.4 THREE METHODS TO CONTROL FOR ZERO CRASHES

There is a chance that, especially for the severe crashes, the observed number of crashes at a treated location equals zero. In this case, it is impossible to calculate the index of effectiveness (see Eq. 2-9) and the variance (see Eq. 2-10). Also intuitively, the presence of a zero level of crashes is not very likely to be a correct long-term average as it would be equal to a 'perfect' safety. This problem will mainly occur for the observed number of crashes at the treated location L in the after period. In order to solve this problem, three methods were applied.

2.1.4.1 CONSTANT CONTINUITY CORRECTION: ADDED VALUE OF 0.5

In the estimation of the log of the odds ratio or the log of the risk ratio, usually a continuity correction, by addition of 0.5, is considered for studies with zero counts (Subbiah & Srinivasan, 2008). This continuity correction is added to each cell of the 2x2 table for the studies with zero events in either arm (Sweeting, Sutton, & Lambert, 2004). This means that a factor of 0.5 needs to be applied to all variables of Eq. 2-9 and Eq. 2-10 when one of these variables is zero. This method is applied in one of the first studies that was performed in this dissertation (see chapter 4.1).

Previous research however indicated that applying such a continuity factor can lead to deviant results in meta-analyses (Sweeting et al., 2004). However, no sufficient method is found yet. In this PhD dissertation, this problem was solved through the application of an EB-approach in the after period (see 2.1.4.3). In one of the last papers, also the empirical continuity correction was applied, as explained in the next paragraph.

2.1.4.2 EMPIRICAL CONTINUITY CORRECTION

Sweeting et al. (2004) proposed to use a continuity factor, which is based on the pooled effect size, instead of using a constant continuity factor. This pooled effect size is calculated using all locations without zero events. This estimate will then be used to calculate a continuity correction, which is added to the four factors when one of these factors equals zero.

The continuity correction can be calculated for the before period (k_b) and for the after period (k_a).

- $k_b = \frac{M/N}{M/N + \hat{\theta}}$ (Eq. 2-12)

- $k_a = \frac{\hat{\theta}}{M/N + \hat{\theta}}$ (Eq. 2-13)

with k_b = continuity correction for the before period; k_a= continuity correction for the after period; and the sum of both factors is equal to one

M = observed number of crashes in the comparison group in the before period

N = observed number of crashes in the comparison group in the after period

$\hat{\theta}$ = index of effectiveness without the locations with zero counts

Subsequently these corrections are added to each of the four factors of the locations, when one of the factors equals zero, and which leads to the next equation:

$$\theta_l = \frac{L_l + k_a / E[\kappa|K]_l + k_b}{N + k_a / M + k_b} \qquad \text{(Eq. 2-14)}$$

This method is applied in one of the last studies of this dissertation (chapter 6.3).

2.1.4.3 EB ESTIMATION

For the majority of the studies the problem of zero counts was solved through the application of an EB-approach in the after period (see chapter 3.1, 3.2, 5.1, 5.2 and 6.3). This method does not only take the problem of the zero crashes into account, but also increases the precision of the resulting estimates (Hauer et al., 2002). This is particularly true when only one or two years of crash data are available.

In line with Eq. 2-4, this formula is applied to the crashes of the after period as follows:

$$L_{l,\text{estimated,after}} = w * \lambda_{\text{after}} + (1\text{-}w) * L_{l,\text{after}} \qquad \text{(Eq. 2-15)}$$

with $L_{l,\text{estimated,after}}$ = estimated number of crashes at the treated location L during the after period

1-w = the weight that is given to the crashes at the treated location L

$L_{l,\text{after}}$ = observed number of crashes that occurred at the treated location L during the after period

To calculate λ_{after} a different method is applied compared to the standard method. In this PhD dissertation, two methods were used to calculate this factor:

(1) An SPF for the after period

In line with the formulas that were applied in the before period (see Eq. 2-4), a model can be calculated for the after period. However, the difference with "real" control for RTM in the before period, is that in the model for the after period only the crash data from the treated locations are included, whereas in the model for the before period data was used from a large number of comparable locations. This method is applied in chapter 3.1 and 6.3.

(2) Crash data from the treated locations only

In some cases it was not possible to apply an SPF to the after period, as the necessary data was not available. When for example traffic volume data are not available, it is impossible to calculate an SPF. Therefore, an EB method is applied, through which no SPF was used, but the average number of crashes that occurred at all treated locations during the after period are used. This method is applied in chapter 3.2, 5.1 and 5.2.

Subsequently

λ_{after} = estimated number of crashes during the after period, based on an SPF in which only crash data of the treated locations are used / average number of crashes at the treated locations during the after period

w= the weight that is given to the estimated number of crashes / to the average number of crashes of the treated locations during the after period

With

$$w = \frac{1}{1 + \frac{\lambda_{\text{after}}}{k_{\text{after}}}} \qquad \text{(Eq. 2-16)}$$

And k is the inverse value of the overdispersion parameter (Elvik, 2008).

$$k_{\text{after}} = \frac{\frac{Var(x)_{after}}{\lambda_{after}} - 1}{\lambda_{after}} \qquad \text{(Eq. 2-17)}$$

or which is calculated through the SPF.

These calculations subsequently lead to a result that is close to the observed number of crashes ($L_{l,\text{after}}$), but is slightly different and put to a more average number.

Subsequently Eq. 2-9 will be replaced by next equation, in which the general trend and the RTM are controlled for, and the problem of the occurrence of zero crashes during the after period at the treated locations is taken into account

$$\theta_l = \frac{L_{l,\text{estimated after}} / E[\kappa|K]_l}{N/M} \quad \text{(Eq. 2-18)}$$

with

$L_{l,\text{estimated,after}}$ = estimated number of crashes at the treated location L in the after period

$E[\kappa|K]_l$ = expected number of crashes at the treated location L given the observed crash frequency K_l

N = observed number of crashes in the comparison group in the after period

M = observed number of crashes in the comparison group in the before period

And the variance s_l^2 can be calculated as:

$$s_l^2 = \frac{1}{E[\kappa|K]_l} + \frac{1}{L_{l,\text{estimated after}}} + \frac{1}{M} + \frac{1}{N} \quad \text{(Eq. 2-19)}$$

In some cases the EB method as described in Eq. 2-4 and Eq. 2-9 up to 2-11 is not applicable. This is mainly the case when not enough data are available (e.g. traffic volume data) in order to apply an SPF. Subsequently the observed number of crashes from the before period will be used, as shown in Eq. 2-3. However in the cases the observed number of crashes from the before period are used, the problem of zero crashes will possibly also occur in the before period. Therefore also a correction need to be applied for the before period. This is done in chapter 5.1 and 5.2.

$$L_{l,\text{estimated,before}} = w * \lambda_{\text{before}} + (1-w) * L_{l,\text{before}} \quad \text{(Eq. 2-20)}$$

with $L_{l,\text{estimated,before}}$ = estimated number of crashes at the treated location L during the before period *w*= the weight that is given to the estimated number of crashes during the before period/ to the average number of crashes at the treated locations during the before period

λ_{before} =estimated number of crashes during the before period, based on an SPF in which only crash data of the treated locations are used / average number of crashes at the treated locations during the before period

1-*w*= the weight that is given to the crashes at the treated location L

$L_{l,\text{before}}$= observed number of crashes that occurred at the treated location L during the before period

And the weight can be calculated as follows:

$$w = \frac{1}{1 + \frac{\lambda_{\text{before}}}{k_{\text{before}}}} \qquad \text{(Eq. 2-21)}$$

And k is the inverse value of the overdispersion parameter (Elvik, 2008b):

$$k_{\text{before}} = \frac{\frac{Var(x)_{\text{before}}}{\lambda_{\text{before}}} - 1}{\lambda_{\text{before}}} \qquad \text{(Eq. 2-22)}$$

These calculations subsequently lead to a result that is close to the observed number of crashes ($L_{l,\text{before}}$), but is slightly different and put to a more average number.

Subsequently Eq. 2-3 will be replaced by next equation, in which the general trend is controlled for, but the RTM is not, and the problem of the occurrence of zero crashes during the before and the after period are taken into account.

$$\theta_l = \frac{L_{l,\text{estimated after}} / L_{l,\text{estimated before}}}{N/M} \quad \text{(Eq. 2-23)}$$

with

$L_{l,\text{estimated,after}}$ = estimated number of crashes at the treated location L in the after period

$L_{l,\text{estimated,before}}$ = estimated number of crashes at the treated location L in the before period

N = observed number of crashes in the comparison group in the after period

M = observed number of crashes in the comparison group in the before period

And the variance s_l^2 can be calculated as:

$$s_l^2 = \frac{1}{L_{l,\text{estimated,before}}} + \frac{1}{L_{l,\text{estimated after}}} + \frac{1}{M} + \frac{1}{N} \quad \text{(Eq. 2-24)}$$

2.1.5 FIXED-EFFECTS META-ANALYSIS TO CALCULATE THE OVERALL EFFECT

The evaluation of each location separately has only limited significance. Therefore, a fixed effects meta-analysis was carried out, which results in one overall effect estimate and in more statistically reliable outcomes (Fleiss, 1981). Every location within the meta-analysis gets a weight, which is the inverted value of the variance. Subsequently, locations at which many crashes occurred, are given a higher weight.

$$w_l = \frac{1}{s_l^2} \quad \text{(Eq. 2-25)}$$

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

$$\theta = \exp\left[\frac{\sum_{l=1}^{n} w_l * \ln(\theta_l)}{\sum_{l=1}^{n} w_l}\right] \quad \text{(Eq. 2-26)}$$

The estimation of a 95% CI is

$$\theta_{\text{below limit}} = \exp\left[\frac{\sum_{l=1}^{n} w_l * \ln(\theta_l)}{\sum_{l=1}^{n} w_l} - 1.96 * \frac{1}{\sqrt{\sum_{l=1}^{n} w_l}}\right] \quad \text{(Eq. 2-27)}$$

$$\theta_{\text{above limit}} = \exp\left[\frac{\sum_{l=1}^{n} w_l * \ln(\theta_l)}{\sum_{l=1}^{n} w_l} + 1.96 * \frac{1}{\sqrt{\sum_{l=1}^{n} w_l}}\right] \quad \text{(Eq. 2-28)}$$

2.1.6 **FLEMISH CRASH DATA**

In order to analyse the effects of the different measures, data from the official crash dataset are used. This dataset includes all injury crashes that are reported by the police. The police gathers the crash data through a crash form and subsequently reports this digitally. Afterwards these data are controlled by the Federal Public Service Economy, and supplemented with data of deaths (any person who, as a result of a traffic crash, died within 30 days of the crash) provided by the public prosecutor.

In general, there are three categories of severity:

- Slightly injured person = any person who got injured, but cannot be defined as severely or fatally injured
- Severely injured persons = any person who needed more than 24 h of hospitalization
- Fatally injured persons = any person who died at the location of the crash or within 30 days after the crash

Based on the severity of the injuries, the crash data are divided into two groups

(1) All injury crashes, which include all crashes with injured persons
(2) Severe injury crashes, which include crashes with at least one severely or fatally injured person.

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. Therefore, PDO crashes are only analysed in the study in which the effects of speed cameras on motorways are studied (chapter 6.3).

2.2 BEFORE-AND-AFTER COMPARISON OF CASUALTIES

In some studies also the effect on the number of injuries was analysed. The effect was analysed for each road user category: car occupants, cyclists, moped riders, motorcyclists, pedestrians and truck drivers. The general trend effect was controlled through the inclusion of a comparison group. However, it was not possible to control for the RTM effect. Therefore, the results of these analyses should be taken into account with caution. Nevertheless, these effects give an indication of the differential effect on the different road user categories.

2.3 BEFORE-AND-AFTER COMPARISON OF SPEED

For seven out of the eight traffic safety measures that were studied in this PhD dissertation the effects on crashes were studied. The favourable effects on traffic crashes are the final purpose of all traffic safety measures. However, before these final measures can be reached, changes in road user behaviours need to be achieved. In this PhD dissertation, the effects on the driving speeds were analysed for two measures: speed cameras and automated section speed control on motorways. Since the crash effects of the speed camera on motorways were difficult to interpret, it was studied what effects this measure had on the intermediate objective, i.e. speed behaviour. For the automated section speed control on the other hand the after period was too short to analyse the effects on crashes. Therefore, in order to get a first estimation, the effects on the speed behaviour were studied.

In order to analyse the speed effect of the traffic safety measure, a quasi-experiment was set up. Speeds were measured before the measure was applied and after the implementation of the measure. The speed effects were calculated through a comparison of the speeds after with before. Other factors that could have had an influence on the driving speeds were controlled through the analysis of speeds during the same periods at similar locations.

Regression models were applied in order to analyze whether the implementation of a traffic safety measure (independent variable) had an effect on the driving speed (dependent variable). Multiple regression models were applied as speed will depend on several variables (Vaa, 1997). Not only the presence measure under evaluation, but also other factors will have influenced the driving speed between the two periods (before and after the installation), for example weather conditions and other traffic safety measures implemented on national level. Therefore, the speed data were collected from comparable locations, which was included as a second independent variable (treated/comparison location) in the regression analysis. The effect of the installation of speed cameras, taking general trend effects into account, can be found in the interaction effect of these two variables.

The effect on the average speed was analysed through a linear regression model with normal distribution and identity link function (using the SPSS GENLIN procedure). For each data collection point a model was calculated, which can be expressed as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 \qquad \text{(Eq. 2-29)}$$

with y = average speed

x_1 = location (dummy variable: treated/comparison location)

x_2 = period (dummy variable: before/ 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 influenced the driving speed between the before and the after period 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 with binomial distribution and logit link function (SPSS GENLIN). For these analyses, the same independent variables were used, as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 \qquad \text{(Eq. 2-30)}$$

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 (treated/comparison location); x_2 = period (before/after period)

β_3 = interaction-effect, which indicates the difference in the odds of drivers exceeding the speed limit between the before and the after period in the treated group, with control for other factors that influenced the driving speed between the before and the after period 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 abovementioned formulas were applied. However, in order to analyse the difference between the two time periods (for example week and weekend), this was included as the third independent variable, which can be expressed through the next formula:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1 x_2 + \beta_5 x_2 x_3 + \beta_6 x_1 x_3 + \beta_7 x_1 x_2 x_3 \qquad \text{(Eq. 2-31)}$$

with x_1 = location (treated/comparison location); x_2 = period (before/after period);

x_3 = time (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 is similar for both periods.

CHAPTER 3

TRAFFIC SAFETY IMPROVEMENT AT INTERSECTIONS

3.1 SAFETY EFFECTS OF AN EXTENSIVE BLACK SPOT TREATMENT PROGRAMME IN FLANDERS-BELGIUM

This chapter is based on:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). Safety effects of an extensive black spot treatment programme in Flanders-Belgium. *Accident Analysis & Prevention, 66*, 72-79. doi: 10.1016/j.aap.2014.01.019

Dutch report:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2012). *Het programma voor de herinrichting van de gevaarlijke punten op gewestwegen in Vlaanderen: een effectevaluatie*. (RA-MOW-2011-021). Diepenbeek: Steunpunt Mobiliteit en Openbare Werken, Spoor Verkeersveiligheid.

Proceedings:

Daniels, S., De Pauw, E., Brijs, T., Hermans, E., & Wets, G. (2012). 10 jaar aanpak van gevaarlijke punten in Vlaanderen. In *Jaarboek Verkeersveiligheid 2012*. Paper presented at the Flemish traffic safety conference, Ghent.

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). Redesigning black spots in traffic: An effect evaluation. In *TRB 92nd Annual Meeting Compendium of Papers*. Paper presented at the Transportation Research Board, Washington DC.

Other publications:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). Safety evaluation of a black spot treatment programme in Flanders. *The World Road Association (PIARC), 359*, 78-83.

3.1.1 INTRODUCTION

In an attempt to work to a better traffic safety, different countries introduced a black spot management (BITRE, 2012; Sørensen & Elvik, 2007). The term black spot refers to locations that have a higher expected number of crashes than other similar locations, because of local risk factors (Elvik, 2007). The purpose of a black spot programme is to reduce the number and severity of crashes, through infrastructural changes of these dangerous spots.

In 2002, the Flemish Government decided to manage the most dangerous traffic spots as one of the main ways to reach the traffic safety goals. This programme included 809 black spots that were selected based on the number and the severity of the crashes. Ninety-nine percent were intersections, all located on highways. Every location at which at least three injury crashes occurred during the period 1997-1999 was selected, and a priority score was calculated. This score was based on the number of injured road users: every slightly injured person got a weight of one, every severely injured person 3 and every fatally injured person 5. A definition of the different severities can be found in section 2.1.6. A total priority score of minimum 15 was necessary to be selected as a dangerous spot.

$$\text{Priority score} = 1^{*} X + 3^{*} Y + 5^{*} Z \qquad \text{(Eq. 3-1)}$$

with X= number of slightly injured persons

Y= number of severely injured persons

Z= number of fatally injured persons

The main research question in this study is: what have been the effects of the Flemish black spot treatment programme on the number of crashes on the adapted sites?

3.1.2 PREVIOUS STUDIES

Different previous studies examined the outcomes of black spot management in terms of the effect on crashes. Elvik, Høye, Vaa and Sørensen (2009) carried out a meta-analysis of studies that examined the traffic safety effect of black spot management through a before-and-after comparison of traffic crashes. They found that studies that did not controlled for RTM resulted in higher crash reductions than studies that did controlled for this confounding variable. As the selection of black spots is based on high crash counts, these locations are especially prone to RTM. For this reason, Elvik et al. (2009) included only studies that controlled for this confounding variable. The authors found a decrease of 26% in the number of injury crashes as a result of black spot treatment. When only European studies were included, a decrease of 22% was found. A distinction between black spot treatment and black section treatment resulted in a higher effect for black spot treatment. The injury crashes on the latter decreased by 33%, whereas the crashes on black sections decreased by 28%. An extensive and recent Australian study (BITRE, 2012) examined 1599 black spot projects, which is 62% of the 2578 funded black spot projects approved and completed during the seven-year period 1996–97 to 2002–03. This study showed a reduction of 30% in fatal and casualty crashes and 26% in PDO crashes. Trend effects were controlled through inclusion of the total number of crashes in each state or territory. In order to control for RTM, pre-treatment crash data were selected during the interval of time between the date on which the funding application was submitted to the Australian Government and the date on which work on the project commenced.

3.1.3 **DATA**

In order to make an analysis possible, a geographical location of the crashes is necessary. At the time of the present study, geographically located crash data were available up to and including 2008. We considered it necessary to have available at least one year of crash data before and one year of data after the treatment of each black spot in order to make a before-and-after evaluation possible. Subsequently, black spots treated and open for traffic up to and including 2007 could be evaluated, and a final research group of 134 black spots was selected. A graphical presentation of the selection process for the treated group and the comparison group is shown in Figure 3-1. The graph can be explained as follows: in total the Flemish government selected 809 black spots. On 160 of those 809 spots only small measures were planned, such as an alteration of the signal phasing or slightly changed markings. These locations were not selected, as no information was available about the date of those small changes, rendering it impossible to distinguish between the periods before and after the treatment. From the remaining 649 spots, 201 were treated before 2008, which were selected as treated locations. After 2008, 294 locations remained to be treated, which as a result could be included in the comparison group. The latter locations are comparable with the locations in the treated group, but differ in that no treatment was applied yet. The other 154 locations could neither be included in the treated group, nor in the comparison group, as the infrastructural works had started before 2009 (and thus could not be selected for inclusion in the comparison group), but had not been finished yet until 2008 (and thus also could not be included in the treated group). This resulted in the inclusion of 201 locations in the treated group and 294 locations in the comparison group. For some locations traffic volume data was missing, which however was required to calculate an SPF. Subsequently, 69 locations from the treated group and 91 locations from the comparison group were excluded. Some black spots comprised two intersections, which were mainly intersections at the on- and off ramps of a highway. Since these locations were very close to each other, they were treated in the black spot programme as one location. In the present study each intersection was analysed separately, and therefore the treated group had two locations extra and the comparison group eight locations.

This eventually resulted in 134 treated locations, all being intersections. Depending on the location, different treatments were applied. Generally, six sorts of treatments could be distinguished:

(1) Signalized intersection → implementation of left-turn phasing: The majority of the treated locations (53) were signalized intersections at which protected left turn signals were implemented.
(2) Signalized intersection → changes in the layout: Fifteen intersections that were signal controlled during the before period mainly got changes in the layout. Examples of alteration are: improved cycle facilities, separation of turning lanes and the installation of speed cameras.

(3) Signalized intersection → roundabout: Five locations were changed from a signalized intersection into a roundabout.
(4) Priority-controlled intersection → changes in the layout: Of the locations that were priority controlled during the before period, 26 remained priority controlled but changes were made in the layout. Examples of these changes are: provision of cycle facilities, improved delineation and construction of traffic islands or medians.
(5) Priority-controlled intersection → signalized intersection: At nine locations that were previously priority controlled, traffic signals were installed, six of them with protected left turns.
(6) Priority-controlled intersection → roundabout: Eight priority-controlled locations were converted into a roundabout.

The final comparison group comprised 211 locations, all intersections. These locations can be expected to be comparable with the treated locations for certain characteristics (for example traffic volumes, maximum speed limit, …), whereas they differ in that there were no traffic safety measures implemented during the research period. As it is unclear whether a certain order in the treatment of black spots is present, and thus a certain distortion could be observed, a second comparison group was applied. This comprised all injury crashes in Flanders.

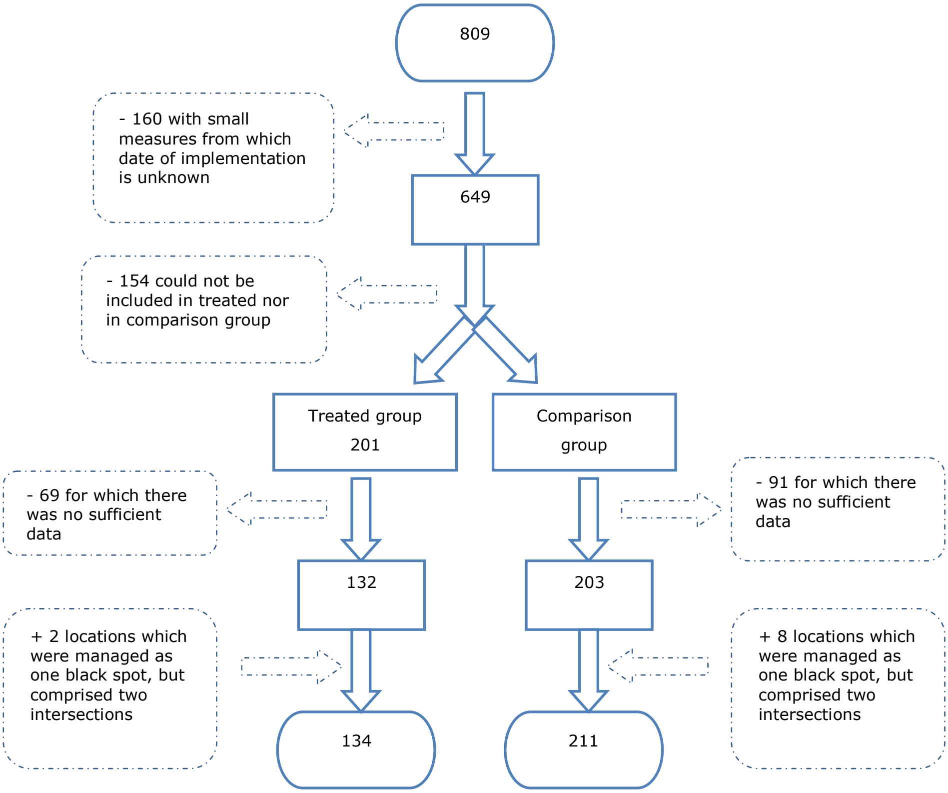


Figure 3-1 Flow chart of the selection of treated and comparison black spot locations

All crashes in a radius of 100 m around the black spot were selected. Consequently, it can be expected that all crashes related to the black spot were included, also at the larger intersections and roundabouts. As the selection of the black spots was based on crash data from 1997-1999, these data were excluded from the research, in order to control for the RTM effect. Subsequently, the research period for this study ran from 2000 to 2008. Two groups of crash data were included: (1) all injury crashes; (2) severe injury crashes.

The comparability of the comparison group with the treated group was analysed through the odds ratios of the crash frequencies from the years of the before period (see 2.1.2.1). The results of these calculations are shown in Table 3-1. As the first spots were treated in 2004, the odds ratio is calculated until that year.

The calculations show that comparison group 1 (black spots treated after 2008) and comparison group 2 (all crashes in Flanders) are comparable with the treated group, both for all injury crashes, as for the more severe crashes.

Table 3-1 Odds ratios of the crash numbers during the before period

	Comparison group 1		**Comparison group 2**	
	All injury crashes	Severe crashes	All injury crashes	Severe crashes
00-01	1.02	0.92	0.95	0.86
01-02	1.04	1.14	1.11	0.93
02-03	1.14	1.13	0.94	0.90
Average	1.07	1.06	1.00	0.90

Furthermore, the qualitative characteristics of comparison group 1 were compared with the treated group. The following equation is used to examine this:

$$\frac{\frac{\text{number of locations in research group with a certain characteristic}}{\text{total number of locations in research group}}}{\frac{\text{number of locations in comparison group with a certain characteristic}}{\text{total number of locations in comparison group}}} \quad \text{(Eq. 3-2)}$$

Four characteristics were compared, that is location inside/outside the urban area, the type of intersection during the before period (priority-controlled or signalized), and the legally imposed speed limit and number of lanes on the main and secondary road of the intersection. No strong differences were found. Only intersections with a speed limit of 90 km/h on the main road were significantly more present in the treated group compared to the comparison group (Fisher's Exact Test: 1.53 p=0.041).

From these analyses, it can be concluded that both comparison groups are comparable with the treated group.

3.1.4 **METHOD**

The EB method as described in chapter 2 was applied in order to estimate the effect on the occurrence of crashes. RTM and trend effects were controlled, the problem of zero crashes in the after period was solved through an EB estimation (see Eq. 2-18).

To calculate the average number of crashes at similar entities (*E[κ]*, see Eq. 2-4), an SPF is used that has been developed based on the current dataset that included both treated and comparison locations (De Ceunynck et al., 2011). The dependent value of the model was the number of crashes that occurred during the period 2000-2003. This period was selected in such a way that it was not subject to the effect of RTM (as it was after the period that was used to select the black spots, i.e. 1997-1999) and furthermore this period clearly reflects the before period as the first locations were only adapted in 2004. In a first model estimation, traffic volumes at the major and minor road of the intersection and the traffic control variable (priority-controlled vs. signalized intersections) were included as independent variables, however the latter variable was found to be insignificant. The model that was applied in the present research, estimates the number of injury crashes and severe crashes through traffic volumes (based on 514 intersections):

$$E[\kappa]_{\text{injury}} = \mathrm{e}^{-1.7131}\, Q_{\text{Maj}}^{0.3231} Q_{\text{Min}}^{0.2463} \qquad \text{(Eq. 3-3)}$$

$$E[\kappa]_{\text{severe}} = \mathrm{e}^{-3.2138}\, Q_{\text{Maj}}^{0.3327} Q_{\text{Min}}^{0.2009} \qquad \text{(Eq. 3-4)}$$

with $E[\kappa]$= expected annual number of crashes (dependent variable), with $E[\kappa]_{\text{injury}}$ are all injury crashes, and $E[\kappa]_{\text{injury}}$ are severe and fatal injury crashes

Q_{maj} = traffic volume on the major road of the intersection (Min: 26 vehicles/h; Max: 5840 vehicles/h; Mean: 1508 vehicles/h; Med: 1378 vehicles/h).

Q_{min} = traffic volume on the minor road of the intersection (Min: 4 vehicles/h; Max: 3424 vehicles/h; Mean: 537 vehicles/h; Med: 383 vehicles/h).

Table 3-2 gives more information on each of the models.

Table 3-2 Results of the model and criteria for goodness of fit of the SPFs

	Injury crashes	Severe crashes
Intercept	-1.7131 (SE 0.3786)	-3.2138 (0.5747)
Q_{maj}	0.3231 (SE 0.0462)	0.3327 (0.0707)
Q_{min}	0.2463 (0.0228)	0.2009 (0.0341)
Overdispersion	0.2635 (SE 0.0231)	0.2026 (0.0452)
Elvik index of goodness-of-fit	0.4363	0.4167
Deviance	516.57	540.94
Pearson chi-square	576.43	483.05
Log Likelihood	9396.60	-187.61

In order to control for the zero crashes of the after period an EB estimation was applied for the after period (see Eq. 2-15). The model was based on the crash data that were gathered at the treated locations during the after period. In total 138 locations were included in the model estimation. The analyses resulted in the following equation, valid for the group of injury crashes

$$E[\kappa]_{\text{injury}} = \mathrm{e}^{-6.1395}\, Q_{\text{Maj}}^{0.55} Q_{\text{Min}}^{0.345} \qquad \text{(Eq. 3-5)}$$

Table 3-3 Results of the model for the after period and criteria for goodness of fit of the SPFs

	Injury crashes
Intercept	-6.1395 (SE 1.1553)
Q_{maj}	0.5500 (SE 0.1407)
Q_{min}	0.3450 (0.0765)
Overdispersion	0.0752 (SE 0.0717)
Elvik index of goodness-of-fit	0.9115
Deviance	140.52
Pearson chi-square	135.19
Log Likelihood	-72.33

A similar model for the severe crashes could not be fit, as the convergence was questionable, which was probably due to a very low sample mean and a too high number of zero crashes. Therefore the model of all injury crashes was applied and it was multiplied with the proportion of the severe crash numbers to all injury crash numbers from the after period.

The general trend effect was taken into account using a comparison group and as explained before, the final effect estimation per location was calculated as displayed in Eq. 2-18.
A fixed effects meta-analysis was carried out as described in Eq. 2-25 – Eq. 2-28.

3.1.5 RESULTS

A meta-analysis of the 134 black spots, using comparison group 1 (i.e. black spots treated after 2008) to control for the trend, showed a decrease in the number of injury crashes of 24%, which was significant at the 1% level (see Table 3-4). A decrease of 27% was found, also significant at the 1% level, when the trend was controlled through comparison group 2 (i.e. the total number of crashes in Flanders).

In the case of the fatal and serious injury crashes, significant decreases at the 1% level were found. This decrease amounted 46% and 57% when respectively comparison group 1 and comparison group 2 were used.

Table 3-4 Results of the meta-analyses (index of effectiveness [99% CI])

	Injury crashes	Severe crashes
Comparison group 1 (black spots treated after 2008)	0.76 [0.66; 0.87]**	0.54 [0.36; 0.81]**
Comparison group 2 (all injury crashes in Flanders)	0.73 [0.64; 0.84]**	0.43 [0.28; 0.64]**

** Significant at the 1% level

In addition to the overall effect, the effects were analysed according to the characteristics of the locations. Five characteristics were analysed: (1) location inside/outside the urban area, (2) type of intersection during the before period, (3) type of treatment, (4) number of lanes at the main road and (5) maximum speed limit at the main road. The road with the highest road category was selected as the main road. When several roads had the same road category, the roads were ordered according to the traffic volume. These analyses were applied on injury crashes and comparison group 1 was used in order to control for trend effects.

As can be seen from Table 3-5, slightly higher effects were found for locations outside the urban area (-29% vs. -19%). No large differences were found according to the number of lanes and the maximum speed limit. The meta-analyses according to the type of intersection during the before period showed higher effects for intersections that were previously priority controlled (-33%) compared to signalized intersections (-21%). A comparison of the effect according to the type of treatment showed the highest effects for priority-controlled intersections at which the layout was changed (-42%). Furthermore, also high decreases were found for intersections with new traffic signals (-35%). The implementation of left-turn phasing at signalized intersections resulted in a decrease of 22%. Changes in the layout at signalized intersections resulted in a decrease of 11% in the number of injury crashes. The conversion to roundabouts showed a decrease of 21%. A different effect was found according to the type of intersection before the conversion: signalized intersections that were converted to a roundabout showed a decrease of 28%, whereas a decrease of 13% was found for locations that were previously priority controlled.

Table 3-5 Results of the meta-analyses (index of effectiveness [95% CI]) subdivided to the characteristics of the location

Characteristics	Categories	No. of locations	Index of effectiveness [95% CI]
Inside/ outside urban area	Inside	37	0.81 [0.66; 0.98]*
	Outside	86	0.71 [0.63; 0.81]*
Number of lanes	2	68	0.71 [0.60; 0.85]*
	4	64	0.79 [0.69; 0.90]*
Maximum speed limit	50	29	0.79 [0.63; 0.98]*
	70	39	0.73 [0.60; 0.89]*
	90	62	0.77 [0.66; 0.89]*
Type of intersection before	Priority-controlled	55	0.67 [0.55; 0.82]*
	Signalized	74	0.79 [0.70; 0.90]*
Type of treatment	Roundabout	15	0.79 [0.53; 1.18]
	← Signalized	5	0.72 [0.38; 1.36]
	← Priority-controlled	8	0.87 [0.49; 1.57]
	Installation of traffic signals	9	0.65 [0.43; 0.99]*
	Changes in layout of priority-controlled intersection	26	0.58 [0.42; 0.80]*
	Changes in layout of signalized intersections	15	0.89 [0.66; 1.19]
	Implementation of left-turn phasing at signalized intersections	53	0.78 [0.67; 0.89]*

* Significant at the 5% level

In order to analyse whether the differences were statistically significant, maximum likelihood linear regression models (using SPSS GENLIN procedure) were fitted. The dependent variable was the natural logarithm of the effect per intersection $\ln(\theta_l)$. The five characteristics as shown in Table 3-5 were the independent variables, which were dummy-coded. Two extra variables were included: (6) priority score (which indicates the number and severity of injuries during 1997-1999) and (7) traffic volume at the main road. In the dummy coding of the type of treatment, the reference variable was 'changes in the layout of priority-controlled intersections'. This resulted in four parameters: roundabout vs. changes in the layout of priority-controlled intersections; protected left-turn signals vs. changes in the layout of priority-controlled intersections; changes in the layout of signalized intersections vs. changes in the layout of priority-controlled intersections; installation of traffic signals vs. changes in the layout of priority-controlled intersections. In a first regression analysis a high correlation (ρ>0.60) was found between the type of intersection during the before period and two parameters of the type of treatment variable: (1) protected left-turn signals vs. changes in the layout of priority-controlled intersections (ρ=-0.74) and (2) changes in the layout of signalized intersections vs. changes in the layout of priority-controlled intersections (ρ=-0.77). The variable with the smallest contribution to the model fit was eliminated, which was the type of intersection during the before period. A new model was fitted, which again showed a high correlation between two variables: speed limit (50 km/h vs. 90 km/h) and location inside/outside the urban area (ρ=-0.70). The location inside/outside the urban area was the variable with the smallest contribution to the model and was excluded. The results of the model without these variables are shown in Table 3-6. Five significant parameters were found. The parameters with the type of treatment showed three significant results. Changes in the layout of priority-controlled intersections performed significantly ($p<0.05$) better compared to:

- the implementation of protected left-turn signals at signalized intersections (parameter estimate: 0.27).
- changes in the layout of signalized intersections (parameter estimate: 0.47)
- conversion to roundabouts (parameter estimate: 0.55).

Fourth, the priority score was a significant predictor. The sign of the revealed effect is negative, meaning that higher effects were found as the priority score increases (parameter estimate: -0.01). Furthermore, the effect of the traffic volume was found to be significant. The results showed lower effects as the volume increases (parameter estimate: 0.10).

Table 3-6 Results of the regression analysis

Parameter	Parameter estimate	Standard error	Chi-square	Sig.
Intercept	-0.44	0.14	10.37	0.001**
4 vs. 2 lanes (main road)	-0.09	0.12	0.53	0.47
50 km/h vs. 90 km/h (main road)	-0.05	0.11	0.17	0.68
70 km/h vs. 90 km/h (main road)	-0.15	0.09	2.77	0.10
New traffic signals vs. changes layout priority-controlled	0.05	0.15	0.10	0.75
Protected left-turn signals vs. changes layout priority-controlled	0.27	0.13	4.55	0.03*
Changes layout signalized intersections vs. changes layout priority-controlled	0.47	0.14	12.32	<0.001**
Roundabout vs. changes layout priority-controlled	0.55	0.15	12.91	<0.001**
Priority score	-0.01	0.003	14.69	<0.001**
Traffic volume (ADT*1000)	0.10	0.03	9.15	0.002**

Deviance =16.31; df=99
** Significant at the 1% level
* Significant at the 5% level

In addition to the analyses on crash level, analyses on the level of casualties were performed. The effect on the number of injured road users was analysed, subdivided to the type of road user: car occupants, moped riders, cyclists, motorcyclists, pedestrians and truck drivers. A before-and-after comparison was performed, with control for trend effects through comparison group 1 (i.e. the black spot comparison group). As the relative differences from the before to the after period in Table 3-7 show, higher decreases were found for the treated group compared to the comparison group. This is confirmed by the odds ratio, which is the relative change of the number of injured road users in the treated group, compared to the relative change in the comparison group. As the rightmost column shows, all of these results are smaller than one. From this can be concluded that the black spot programme generated a favourable effect on each of the road user categories.

Table 3-7 The effects on injured road users

Type of road user	Mean number of injured road users per year per black spot						Odds ratio
	Treated group			Comparison group (black spots treated after 2008)			
	Before	*After*	*Difference (%)*	*Before*	*After*	*Difference (%)*	
Car occupants	2.19	1.07	-50.90	1.95	1.59	-18.55	**0.6**
Moped riders	0.30	0.19	-36.43	0.40	0.29	-26.71	**0.87**
Cyclists	0.41	0.29	-29.59	0.45	0.45	+2.16	**0.69**
Motorcyclists	0.16	0.10	-39.55	0.15	0.13	-10.64	**0.68**
Pedestrians	0.07	0.05	-27.20	0.09	0.08	-18.44	**0.89**
Truck drivers	0.05	0.01	-77.63	0.05	0.04	-21.33	**0.28**

3.1.6 DISCUSSION

In order to control for trend effects, two comparison groups were used. The first group included the black spots that were treated after the research period, which can be expected to be similar with the treated locations but at which no treatments were applied yet. As it is unclear whether or not a certain order in the treatment of black spots is present, and thus a certain distortion could be observed, a second comparison group was applied which comprised all crashes that occurred in Flanders. A possible limitation of the comparison group that comprised all crashes in Flanders is that the crashes that occurred at the treated locations were also included in the comparison group. This could lead to an underestimation of the effect, as the result of the black spot programme is included in the general trend. However only 1.1% of all crashes in Flanders occurred on the treated locations. In addition, the results of the analyses using this comparison group were in line with the results of the analyses that used the other comparison group, and were even higher.

The results of the analyses indicated that the treatment of the black spots had a favourable effect on traffic safety. However, the treated group only encompassed 134 of the 809 black spots, from which can be questioned whether these results can be generalized to all black spots in Flanders. At 160 locations only some small changes were implemented. The treated group was not selected randomly from the remaining 649 locations, but the selection was more or less based on the year the black spot was treated, as only the spots were selected that were treated before 2008. When a certain pattern was present in the order of the treatment, the 134 black spots could be different from the other 515 locations. However, an analysis of the comparability of the treated group and the comparison group that comprised black spots treated after 2008, showed no structural differences between both groups. From this can be concluded that the results of the present paper are a good estimation of the total black spot programme in Flanders. Nevertheless, a new evaluation when the entire programme will be finished could provide extra information, as a lot more locations would be included.

In the present study no distinction was made according to the crash type. It could for example have been interesting to analyse what effects the installation of new traffic signals and of protected left-turn signals had on side crashes on the one hand and on rear-end crashes on the other hand. However, this subdivision into different crash types would lead to a low number of crashes, from which it is difficult to make any valid analyses. The study for example included nine locations at which traffic signals were installed, with on average 2.79 crashes/year during the before period and 1.47 crashes/year during the after period. This number is too small to make any further classification. It would however be interesting to analyse this in future research when more locations are treated.

Despite these limitations, we can conclude that the treatment of black spots is an effective traffic safety measure. The meta-analyses showed a significant decrease both for the injury crashes and for the severe crashes. In the case of the injury crashes a decrease of 24%-27% was found. The number of fatal and serious injury crashes decreased by 46%-57%. These are significant and meaningful results, which are in line with previous studies. Through the inclusion of different before-and-after studies that controlled for RTM, Elvik et al. (2009) found a decrease in the number of injury crashes of 26%. However, when only black spots and no black sections were taken into account, the study found a decrease in the number of injury crashes of 33%, which is slightly higher than what was found in the present study. The effect on the severe crashes cannot be compared, as most studies only analysed the effect on the total number of injury crashes. Nevertheless, it can be concluded that the decrease in the number of severe crashes (-46%/-57%) is significantly greater compared to the decrease in the number of all injury crashes (-24%/-27%). A paired sample t-test (SPSS20) showed a statistical significant difference between the effect on all injury crashes and the effect on the severe crashes, both for the analyses that used the black spot comparison group ($t=12.697$; $df=133$; $p<0.001$) and for the analyses that used the crash frequencies in Flanders ($t=18.747$; $df=133$; $p<0.001$). Next to the crash level, also a favourable effect was found on the casualty level for each of the road user categories (car occupants, moped riders, cyclists, motorcyclists, pedestrians and truck drivers).

An analysis of the characteristics of the locations showed five significant parameters. At first, significant differences were found according to the type of treatment. The highest effects were found for priority-controlled intersections with changes in the layout (-42%) or at which traffic signals were installed (-35%). The priority-controlled intersections with changes in the layout performed significantly better compared to signalized intersections at which left-turn protection signals were implemented (-22%) and performed significantly better compared to signalized intersections with changes in the layout (-11%). The conversion to roundabouts of both previously priority-controlled and signalized intersections leaded to a decrease of 21% in the number of injury crashes. These results are different with the results that were found in a recent and extensive effect evaluation study of 1599 black spots in Australia. This study found the highest effects for roundabouts, which showed a decrease of 71% in the number of injury crashes (BITRE, 2012; Meuleners, Hendrie, Lee, & Legge, 2008). A meta-analysis of Elvik et al. (2009) of several studies that analysed the effect of the conversion of intersections to roundabouts, also found highly favourable effects, with a decrease in the number of injury crashes of 46%. A study of 55 intersections that were converted to roundabouts in different states in North America showed a decrease in the number of injury crashes of 76% (Rodegerdts et al., 2007). The result in the present study was however more limited for this treatment. Furthermore, the Australian study found that new signals, especially during the day, and altering the traffic flow direction were the next most highly effective treatments. The study found a decrease of 51% in the number of injury crashes during the day and 36% during the night, after the installation of traffic signals. A study of 100 four-leg intersections in North America showed a more limited result, with a decrease of 23% in the number of injury crashes. A distinction according to the crash type showed a decrease of 67% in the number of right-angle crashes but an increase of 38% in the number of rear-end crashes (McGee, Taori, & Persaud, 2003). A meta-analysis of Elvik et al. (2009) showed a decrease of 15% in the number of injury crashes at three-leg junctions and -30% at four-leg intersections. The intersections in the present study, from which the majority (84% of the treated locations) were four-leg intersections, showed similar effects (-35%) after the installation of traffic signals. It is however difficult to compare the results of the best performing treatment in the present study with previous studies, as the changes in the layout of priority-controlled intersections comprised different treatments (e.g. provision of cycle facilities, improved delineation and construction of traffic islands or medians). Nevertheless, it can be concluded that in the Flemish black spot programme the adaptation of intersections that were priority controlled before the treatment performed better than locations that were signalized. A possible explanation for the higher results for priority-controlled intersections is that these locations can undergo different changes in order to control the traffic flows. Such measures can be expected to have a strong effect on traffic safety. As signalized intersections are already highly controlled, possible changes are limited, and will subsequently be less effective.

Furthermore, also the priority score was found to be a significant parameter. The present study showed that the higher the priority score (i.e. spots were more dangerous during the before period) the higher the effects on the number of injury crashes. This result indicates that particularly the most severe locations profited from the black spot programme.

The last parameter that was found to be a significant predictor is the traffic volume, and lower effects were found with higher traffic volumes. This result can be explained by the selection procedure of the black spots, which is based on the number and severity of injuries. Previous research showed that the traffic volume is the most influencing structural variable for the number of crashes at a certain location (Elvik et al., 2009). As traffic volumes were not taken into account during this selection, an actual chance exists that locations with a high volume were selected because of the high crash frequency as a result of this high intensity. At the intersections with a high crash count but with a lower volume, probably other structural factors could have had an effect, which could be managed more easily through infrastructural measures.

3.1.7 **CONCLUSIONS**

- As a result of the black spot management, a significant and substantial decrease in the number of crashes was found.

- This decrease was higher for the severe crashes (-46%/-57%) compared to all injury crashes (-24%/-27%).
- The highest effects were found for priority-controlled intersections with changes in the layout (-42%) and at which new traffic signals were installed (-35%).
- On the level of casualties, a decrease was found for every road user category.

3.2 THE TRAFFIC SAFETY EFFECT OF PROTECTED LEFT-TURN PHASING AT SIGNALIZED INTERSECTIONS

Proceedings:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). The effect of protected left-turn signals on traffic safety. Paper presented at the ICTCT 2013 workshop, Maribor.

De Pauw, E., Van Herck, S., Daniels, S., & Wets, G. (2014). Conflictvrije verkeersregelinstallaties: het effect op de verkeersveiligheid. In *Jaarboek verkeersveiligheid 2014*. Paper presented at the Flemish road safety conference, Ostend.

3.2.1 INTRODUCTION

The present study goes further into detail on one of the treatment types that were discussed in the study on the black spots: the implementation of left-turn signals. Left-turn crashes occur frequently at signalized intersections and often lead to severe injuries. Although the installation of traffic signals can help to separate traffic flows, some problems remain, for example, left-turn crashes. Left-turn crashes can be defined as crashes between left-turning vehicles and opposing through traffic. These crash types are often severe, possibly due to the relatively high conflicting speeds of the involved vehicles and the angle of impact (Wang & Abdel-Aty, 2008a). Several factors can contribute to the occurrence of these crashes, e.g. traffic flows, the speed limit, the crossing distance of left-turning vehicles and the median of the intersection (Wang & Abdel-Aty, 2008b).
The safety problems encountered by left turning are often addressed through some sort of left-turn protection. This protection eliminates conflicts because left-turning vehicles do not need to yield to opposing through traffic. Generally, two types of left-turn phases can be distinguished: protected only and protected/permitted signal phasing. The advantages of protected/permitted left-turn control are increased left-turn capacity and reduced delay (Ozmen, Tian, & Gibby, 2014; Srinivasan et al., 2012). Nevertheless, there are still conflicts between vehicles turning left and opposing through traffic during the permitted phase.

In the present study, the traffic safety effect of the installation of protected left-turn signals was examined. Through a before-and-after study the effects on injury crashes and on crashes with fatal and serious injuries were examined, and a distinction was made between left-turn crashes and rear-end crashes. Furthermore, the effect on casualty level was examined in order to analyse the effects on the various road user categories.

3.2.2 PREVIOUS STUDIES

A number of studies analysed the traffic safety effects of the implementation of left-turn phasing at signalized intersections. Lyon et al. (2005) analysed the impact of flashing advance-green and left-turn green-arrow signals on injury and fatal left-turn crashes (crashes involving at least one left-turning vehicle) and left-turn side-impact crashes (crashes involving one vehicle turning left and one going straight through from the opposing approach). They studied 35 intersections in the city of Toronto: 15 intersections with flashing green signals and 20 with green-arrow signals. The advance-green and left-turn green-arrow signals were activated at one or more approaches during certain periods of the day. In total, the number of left-turn crashes decreased by 16%, and the number of left-turn side impacts decreased by 19%. Srinivasan et al. (2008) analysed three sites at which the permitted left-turn phase was replaced by a protected/permitted phase. The study showed very little change in crashes involving at least one left-turning vehicle or in total crashes. The authors however stated that the results could not be taken as definitive, because of the small sample size. Furthermore, eight sites were analysed at which a permitted phase was replaced by a protected phase. The number of left-turn crashes decreased significantly, by 97.9%, and the total number of crashes decreased non-significantly, by 2.5%. Because a decrease in the left-turn crashes was found but no effect was found on the total number of crashes, the authors stated that there must have been an increase in non-left-turn crashes. They thought this could have been attributable to an increase in rear-end crashes, but further research would be necessary to examine this in an in-depth manner. A more recent study by these authors (Srinivasan et al., 2012) partially confirmed this assumption. They analysed 59 intersections in Toronto and twelve intersections from North Carolina that were converted from permitted left-turn phasing to protected/permitted left-turn phasing. They found a significant 14% decrease in the number of crashes between left-turn vehicles and through vehicles from the opposing direction. Furthermore, they found a 7.5% increase in the number of rear-end crashes, which was not significant.

3.2.3 DATA

The study included 103 signalized intersections with left-turn signals on highways in Flanders, of which 33 received only changes in the signal control and 70 received additional changes, such as resurfacing the road, changes in cycle facilities, the installation of red light cameras and the construction of traffic islands. At the majority of the intersections, protected only signals were installed. At these intersections the left-turning vehicles only get a green signal, if the opposing through traffic gets red light (see Figure 3-2). A small number of intersections were equipped with protected/permitted signals. At these intersections there is a permitted phase, during which both directions get a green signal and there is a protected phase, during which the left-turning vehicles get a green arrow, and the opposing through traffic gets a red light (as displayed in Figure 3-2). All signalized intersections that were equipped with protected(/permitted) signals up to 2009 were included in this study. At the time of the study, geographical located crash data were available up to 2010. As at least one year of crash data are necessary during the before period and during the after period, only the intersections that were adapted up until 2009 could be included. The left-turn phasing was implemented at four locations in 2004, 24 locations in 2005, 16 locations in 2006, 28 locations in 2007, 17 locations in 2008 and 14 locations in 2009.

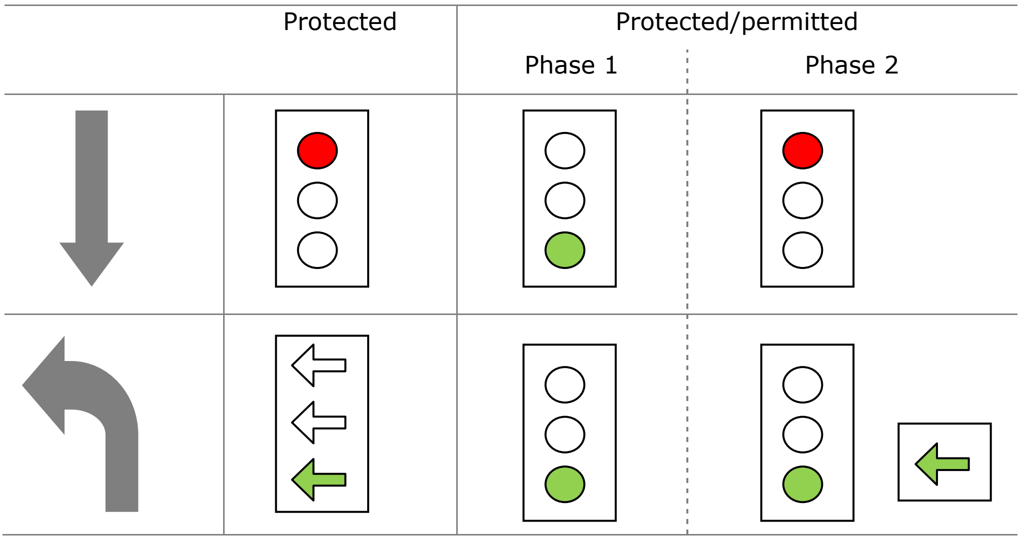


Figure 3-2 Sketch of protected and protected/permitted signal phasing

The comparison group, which was used to control for general trend effects, included all crashes at signalized intersections in Flanders. The treated locations were excluded from this group. This group of comparison sites provides a good indication of the general crash trend at locations that are similar to the treated locations but where no left-turn phasing was implemented during the research period.

At the time of the study, Flemish geo-coded crash data were available up to 2010. In order to select a sufficient long before period, crashes from 2003 were selected. All crashes within a radius of 100 m from the intersection centre were selected. The before period amounted to 3.7 years on average; the after period amounted to 3.30 years on average. Two groups of crash data were included: (1) all injury crashes; (2) severe injury crashes. Furthermore, two types of crashes were differentiated: left-turn crashes and rear-end crashes. Table 3-8 shows the descriptive statistics for the crashes from the treated locations, with a distinction between the before and after periods.

Table 3-8 Descriptive statistics of crashes at the treated locations

	Before			After		
	Min	Max	Mean (st. dev.)	Min	Max	Mean (st. dev.)
Injury crashes	0	45	10.98 (8.45)	0	31	6.79 (5.73)
Left-turn crashes	0	13	2.38 (2.44)	0	9	1.19 (1.62)
Rear-end crashes	0	29	3.45 (4.26)	0	12	2.74 (2.62)
Severe crashes	0	8	1.67 (1.71)	0	4	0.58 (0.86)

3.2.4 **METHOD**

In this study a before-and-after comparison with control for the trend and RTM is applied. The RTM is controlled through the use of a lag period. This is the period after the years that were used to select the sites for treatment (based on their crash records) but before the period the treatment was implemented. This lag period can be used as an unbiased estimate of the true crash rate before the treatment is applied, and instead of comparing the crashes after the treatment with those before, the crashes from after the treatment can be compared with the lag period (Maher & Mountain, 2009). In order to validate the use of a lag period, the crash history was selected of 23 intersections that were adapted after 2006. The before period was divided into three periods, from which the first period included the period which was used to select the high-crash locations that needed treatment. In the first period, 120 crashes per year could be observed, whereas this number was 92 in the second and 84 in the third period.

It is obvious that the number is much higher in the first, compared to the second and third period. Based on this, the use of a lag period can be considered as as a good predictor of the long-term expected number of crashes.
Especially for severe crashes, there is a chance that the observed number of crashes at a treated location in the before or after period will equal zero. Therefore an EB estimate, based on the crash data of the treated locations, was applied both for the before and the after period. Subsequently the effect is calculated as explained in Eq. 2-23.
A fixed effects meta-analysis was carried out as described in Eq. 2-25 – Eq. 2-28.

3.2.5 **RESULTS**

Table 3-9 shows the results of the effects on the crash numbers. In total, the number of injury crashes decreased by 37% after the implementation of a left-turn signal. The intersections at which only a left-turn signal control was implemented showed a decrease of 46%; at the intersections with additional measures, a decrease of 32% was found. Furthermore, a subdivision was made according to crash type. Left-turn crashes decreased by 50% as a result of the implementation of left-turn signals. The results were more favourable for intersections that received a protected left-turn signal only (-60%) than for intersections that received additional measures (-45%). The number of rear-end crashes showed no significant differences from before to after the implementation of the measure.

Furthermore, the effect of the replacement of a permitted phase with a protected phase on severe crashes was measured. At all treated intersections the number of severe crashes decreased by 59%. A decrease of 66% was found at the intersections at which only a protected left-turn signal was installed; at the intersections with additional measures, this was a decrease of 55%.

Table 3-9 Effect on crashes (index of effectiveness [95% CI])

	Left-turn signal control only (33 sites)	Left-turn signal control + additional measures (70 sites)	All intersections (103 sites)
Injury crashes	0.54 [0.45; 0.64]*	0.68 [0.60; 0.77]*	0.63 [0.57; 0.70]*
Left-turn injury crashes	0.40 [0.26; 0.61]*	0.55 [0.42; 0.72]*	0.50 [0.40; 0.63]*
Rear-end injury crashes	1.01 [0.73; 1.39]	0.94 [0.77; 1.16]	0.96 [0.80; 1.14]
Severe crashes	0.34 [0.20; 0.57]*	0.45 [0.31; 0.65]*	0.41 [0.30; 0.55]*

* Significant at the 5% level

In addition to the analysis on crash level, an analysis on the level of casualties was executed. Through this method, it was possible to determine whether this measure had a favourable effect on each of the road user categories. Table 3-10 shows the mean number of injured road users per year, both for the treated group and for the comparison group. The treated group included all 103 intersections because the number of casualties was too low to make separate analyses for the 33 intersections at which only left-turn signal control was applied; the comparison group included all road users injured at signalized intersections in Flanders, except for those injured at the treated sites. The rightmost column shows the odds ratio, which is the relative change of the number of injured road users in the treated group, compared to the relative change in the comparison group. A favourable effect was found for all road user categories, and the results for all categories were comparable. The number of injured car occupants decreased by 47%, injured cyclists decreased by 43%, injured moped riders decreased by 39% and injured motorcyclists decreased by 37%. The numbers of injured pedestrians and truck drivers were too low to perform any analysis on them (on average, 5.75 injured pedestrians and 4.5 injured truck drivers per year).

Table 3-10 The effects on injured road users

Road user category	**Mean number of injured road users per intersection**						**Odds ratio**
	Treated group			**Comparison group**			
	Before	*After*	*Difference (%)*	*Before*	*After*	*Difference (%)*	
Car occupants	2.35	1.32	-43.80	1130	1193	+5.59	**0.53**
Moped riders	0.27	0.15	-44.09	210	193	-8.05	**0.61**
Cyclists	0.44	0.28	-36.64	313	350	+11.58	**0.57**
Motorcyclists	0.16	0.12	-25.18	95	113	+18.40	**0.63**

3.2.6 **DISCUSSION**

The present study analysed the traffic safety effect of the implementation of protected left-turn signals at signalized intersections in Flanders. The study found highly favourable results, with a strong decrease in the total number of injury crashes (-37%). A separate analysis of left-turn crashes indicated that this effect was mainly attributable to a decrease in the number of these crashes (-50%). Although the impact found differs widely between studies, previous research also found favourable effects on the number of left-turn crashes (Lyon et al., 2005*;* Srinivasan et al., 2008; Srinivasan et al., 2012). Previous research further concluded that in addition to the favourable effects on left-turn crashes, adverse effects were also present and that this should be examined in a more in-depth manner (Srinivasan et al., 2008). Therefore, the present study analysed the effect on rear-end crashes, but it did not find adverse effects because the best estimate was a slight decrease of 4%, with a 95% CI [-20%; +14%]. This is slightly different from the results of Srinivasan et al. (2012), who studied the effect of the replacement of a permitted left-turn signal with a protected/permitted left-turn signal and found a non-significant increase in the number of rear-end crashes (7.5%) for all sites together, but a significant increase (9%) at intersections with only one treated approach.

Furthermore, the effect on fatal and serious injury crashes was analysed, which showed greater decreases (-59%) than injury crashes. Because of the low number of severe crashes, it was impossible to separately analyse the effect of left-turn and rear-end crashes. However, it is expected that this decrease was mainly attributable to a decrease in left-turn crashes. An analysis of casualty level also showed favourable effects not only for motorized vehicles but also for the number of injured cyclists.

In addition, it was found that the effects were slightly higher at intersections at which left-turn signal control only was implemented, whereas the decrease was smaller at intersections with additional measures. The problem could have been more complicated at intersections at which several measures were implemented, whereas at intersections at which only protected left-turn signals were installed, the problem was mainly attributable to crashes with left-turning vehicles.

One limitation of the present study is that no distinction was made according to the number of treated legs. Srinivasan et al. (2012) for example, found higher decreases in the left-turn crashes at intersections where a protected/permitted left-turn signal was implemented at more than one leg (-21%) than intersections with only one treated approach (-7.5%). Additionally, the increases in rear-end crashes were less high at intersections with more than one treated approach (+5%) than at intersections with one treated approach (+9%). Such a comparison was not possible in the present study. However, at the majority of the treated intersections, a left-turn signal was installed at two legs of the main road, i.e. the road with the highest traffic intensity.

Another limitation is that all crashes in a radius of 100 m from the intersection centre were selected. Subsequently, crashes that were not related to the crashes that were targeted through the installation of left-turn signals were selected. However, because these crashes were selected in both the before and the after period and no specific efforts were made to tackle other types of crashes, we can expect that the effects were mainly attributable to crashes related to left turns.

3.2.7 **CONCLUSIONS**

- Left-turn signal control had a significant and substantial effect on crashes
    - decrease of 37% [0.57; 0.70] in the number of injury crashes
    - decrease of 59% [0.30; 0.55] in the number of severe injury crashes
- Favourable effect on left-turn crashes, no effect on rear-end crashes
- Favourable effect for every road user category (car occupants, cyclists, moped riders and motorcyclists).

CHAPTER 4

REDUCING SPEED LIMITS

4.1 SAFETY EFFECTS OF REDUCING THE SPEED LIMIT FROM 90 KM/H TO 70 KM/H.

This chapter is based on:

De Pauw, E., Daniels, S., Thierie, M., & Brijs, T. (2014). Safety effects of reducing the speed limit from 90 km/h to 70 km/h. *Accident Analysis & Prevention, 62*, 426–431. doi:10.1016/j.aap.2013.05.003

Proceedings:

De Pauw, E., Thierie, M., Daniels, S., & Brijs, T. (2012). Safety effects of restricting the speed limit from 90 to 70 km/h. In *TRB 91st Annual Meeting Compendium of Papers DVD*. Paper presented at the Transportation Research Board, Washington DC.

De Pauw, E., Thierie, M., Daniels, S., & Brijs, T. (2012). Safety effects of restricting the speed limit from 90 to 70 km/h. Paper presented at the ICTCT 2012 workshop, Hasselt.

De Pauw, E., Daniels, S., Thierie, M., & Brijs, T. (2014). Reduction of the speed limit at highways: An evaluation of the traffic safety effect. Paper presented at the Speed Congress, London.

4.1.1 INTRODUCTION

Speed is defined as an important risk factor in traffic safety (Elvik & Vaa, 2004). Although crashes are caused by different factors and it is difficult to examine the role of speed (Nilsson, 2004), higher speeds are proven to increase the likelihood of getting involved in a crash. Different causes can contribute to this relationship. One of these causes is that drivers have less time to take in information and react, which leads to lower chances of avoiding a crash. At the same time the car covers an extensively prolonged distance before it stops. Not only is there an increased chance of getting involved in a crash, but the severity of the crash also increases with speed, as the degree of kinetic energy at the time of the collision is higher (OECD, 2006). In order to improve the traffic safety, the Flemish government decided to lower the speed limits from 90 km/h to 70 km/h on a large number of highways, based on four main criteria, at least one of which had to be met. Those criteria were (1) road sections without cycle paths or with cycle lanes close to the roadway; (2) road sections with obstacles close to the roadways with a high risk of collision; (3) road sections outside urban areas but with a high building density and a high number of vulnerable road users; (4) road sections on which several severe crashes occurred in the past (Juvyns, pers. comm.). The speed limit was often only restricted at specific sections of roads, for example at sections between two intersections or at sections between two parts of an urban environment. The speed limit reduction was introduced for the majority of the locations in 2001-2002. No enforcement and educational efforts were combined with this change; only the traffic signs were adapted.

The present study analysed the traffic safety effects of this speed limit reduction.

4.1.2 PREVIOUS STUDIES

Previous studies that examined the traffic safety effects of speed limit restriction, commonly showed a favourable effect on traffic safety. A review of Elvik et al. (2009), who analysed 115 studies with 526 estimates, generally found a decrease in crash numbers when the speed limit was reduced. The studies that did find unfavourable effects on traffic safety, were for the most part small studies from which the results are rather unreliable. In the fixed-effect statistical weight these counted for only 5.7%. The effect on crashes is often expressed through a power function to which the difference in speed has to be raised (Elvik, Christensen, & Amundsen, 2004; Nilsson, 2004). Elvik (2009) revised this Power Model and made a distinction between rural roads and freeways on the one hand and urban and residential roads on the other hand. For the category of the freeways/rural roads, which are also the type of roads that are included in the present study, a power estimate of 4.1 was found for fatal crashes. For serious injury crashes, he found a power of 2.6. The analysis of all injury crashes, without a distinction to the severity of the crash, resulted in a power of 1.6. When these powers are applied to the change in speed from 90 km/h to 70 km/h this would lead to a decrease of 64% in the number of fatal crashes, 48% in the severe injury crashes and 33% in all injury crashes. In addition, Elvik (2013) analysed this relationship, according to the initial speed limit, through the application of two models: (1) an exponential function; (2) the Power Model. A slightly higher support was given to the exponential function, which showed an increase of 1.58 in the number of fatal crashes if speed increased by 1 km/h from an initial speed of 85 km/h. The number of injury crashes was estimated to increase by 1.21. Starting from an initial speed of 75 km/h, an increase of 0.79 fatal crashes with an increase by 1 km/h was found, for the injury crashes this was 0.86.

A restriction in the obeyed speed limit will not necessarily lead to a proportional effect on driving speeds. McCarthy (1998) showed that many factors can mediate the effect of speed limits on traffic safety; in particular, the driver's chosen speed is important. In turn, this choice is influenced by different elements, such as socio-economic factors, personal risk perception and the extent of enforcement. In addition, road conditions and the vehicle have an effect. When a speed limit is not in accordance with the road conditions, this limit will not be obeyed or it will barely be obeyed.

4.1.3 DATA

4.1.3.1 TREATED AND COMPARISON GROUP

The treated group included all road sections that had a reduction in the speed limit from 90 km/h to 70 km/h during 2001 and 2002 located in the province of Limburg, one of the five provinces in Flanders. Road sections on which other measures were performed during the research period that could have had an effect on travel speeds or traffic safety, were excluded. Therefore, local authorities were asked to report whether, in addition to lowering the speed limit, other measures were implemented during the research period. Examples of possible other treatments are changes to traffic regulations such as the right-of-way rules and changes in the infrastructure, such as narrowing or broadening roads. Locations that only had some small changes in the infrastructure, such as repair and maintenance works, were not excluded. Eventually, 61 road sections were included with a total length of 116 km, located in 16 different municipalities in the province of Limburg. The length of the sections ranged from 0.1 to 6.04 km. For most of the road sections a speed limit restriction was applied in 2002, 13 had an adaptation in 2001. The comparison group consisted of 19 sections, with a total length of 53 km. Furthermore, the comparison locations were all located in the province of Limburg. As shown in Table 4-1, most of the road sections (80%) are situated at local roads, 15% are secondary roads that connect, collect and distribute at the local and intercity level, 5% are primary roads, which have the function of connection, collection and distribution at the Flemish level. The majority of the road sections are situated outside the urban area (72%), and have 2x1 lanes (92%). Figure 4-1 shows examples of roads that were adapted.

Table 4-1 Main characteristics of the treated and comparison locations (Agency of Roads and Traffic, Ministry of Mobility and Public Works, 2012)

	Treated group	Comparison group
	Number of locations (%)	
Road category		
- Primary	3 (5%)	1 (5%)
- Secondary	9 (15%)	5 (26%)
- Local	49 (80%)	13 (68%)
Urban area		
- Inside	17 (28%)	2 (10%)
- Outside	44 (72%)	17 (90%)
Number of lanes		
- 2x1	56 (92%)	16 (84%)
- 2x2	4 (7%)	0 (0%)
- 3x1	1 (2%)	3 (16%)

Figure 4-1 Examples of roads at which the speed limit was restricted from 90 km/h to 70 km/h (Source: Google Street View)

The odds ratios are calculated for the total comparison group for the years before the speed limit restriction (see paragraph 2.1.2.1). The results of these calculations are shown in Table 4-2. The odds ratios for the injury crashes show that the comparison group is comparable to the treated group. A subdivision between crashes that occurred at intersections and at road sections, shows a slightly better comparability for crashes that occurred at intersections compared to road sections. The ORs for fatal and serious injury crashes are less comparable, with an odds ratio more different from 1, and standard deviations that exceed 0.20. This can be explained by the low number of crashes, where small fluctuations result in higher relative changes. However, on average, the odds ratios are near to one, and the use of the total comparison group can be considered as comparable with the treated group.

Table 4-2 Odds ratios (OR) and standard deviations (s) for all injury crashes and severe crashes for all years before the implementation of the measure

	Injury crashes		
	Total OR (s)	Intersections OR (s)	Road sections OR (s)
96-97	1.39 (0.20)	0.95 (0.28)	2.05 (0.29)
97-98	0.92 (0.20)	1.00 (0.27)	0.84 (0.29)
98-99	0.93 (0.18)	0.94 (0.25)	0.90 (0.26)
99-00	0.95 (0.18)	1.25 (0.26)	0.76 (0.24)
Average	1.05 (0.19)	1.03 (0.27)	1.14 (0.27)
	Fatal and serious injury crashes		
	Total OR (s)	Intersections OR (s)	Road sections OR (s)
96-97	1.62 (0.32)	1.07 (0.51)	2.23 (0.42)
97-98	0.96 (0.34)	0.75 (0.49)	1.23 (0.49)
98-99	0.70 (0.32)	0.85 (0.44)	0.56 (0.47)
99-00	0.81 (0.29)	1.15 (0.45)	0.64 (0.39)
Average	1.02 (0.32)	0.96 (0.47)	1.16 (0.45)

The qualitative characteristics, as shown in Table 4-1 can also be compared. Therefore, a comparison is made for the classification and urbanization of roads. The following equation is used to examine this:

$$\frac{\frac{\text{length of roads in research group with a certain characteristic}}{\text{total length of roads in research group}}}{\frac{\text{length of roads in comparison group with a certain characteristic}}{\text{total length of roads in comparison group}}} \qquad \text{(Eq. 4-1)}$$

Five equations were calculated: three for the functional classification of roads (local, secondary and primary), and two for the level of urbanization (inside or outside built-up areas). In order to analyse whether differences are significant, the Fisher's Exact Test is calculated. The comparison group is more or less comparable with the treated group for local roads (1.12; p=0.6707); secondary roads (0.83; p=0.2619) are slightly underrepresented in the treated group, in common with primary roads (0.74; p=0.4262). Roads outside urban areas are comparable (0.92; p=0.1708), roads inside urban areas are overrepresented in the treated group (1.50; p=0.3579). However, none of these differences were significant. Regarding the results of those analyses and the calculated odds ratios, we consider the comparison group to be acceptable.

4.1.3.2 Crash data

At the time of the study, crash data for Belgium were available up until 2009 (Federal Public Service Economy, Statistics Department, 2012). However, geo-coded crash data were required, in order to select the crashes at the treated locations. These data was available from 1996 until 2007 (Ministry of Mobility and Public Works, Agency of Roads and Traffic, 2012). Subsequently, the before period starts from 1996 to 2000/2001, the after period from 2002/2003 to 2007. Two groups of crash data were used: (1) injury crashes and (2) severe injury crashes. The spatial analysis programme ArcGIS version 9.3 was used to select the crashes. A buffer of 10 m was applied to make sure all crashes at the selected locations were included. Furthermore, a distinction was made according to the location the crashes occurred: road section and intersection. On average, 322 injury crashes per annum occurred at the treated locations. Fifty-five percent took place at intersections, 45% at road sections. The comparison group consisted of 64 injury crashes per year, with an occurrence of 44% at

intersections. In the case of severe crashes, an average of 74 crashes per annum was found for the treated group, with a proportion of 48% at intersections. On average, the comparison group comprised 21 severe crashes, with 37% occurring at intersections. An initial view is given by Figure 4-2, which shows the mean crash rates per km, for both all injury crashes and the more severe crashes in the treated and comparison group. A decrease can be observed for all groups and in the case of severe crashes in particular, this is stronger in the treated group, when compared to the comparison group.
No data was available in relation to traffic volumes or travel speeds at the treated and comparison locations.

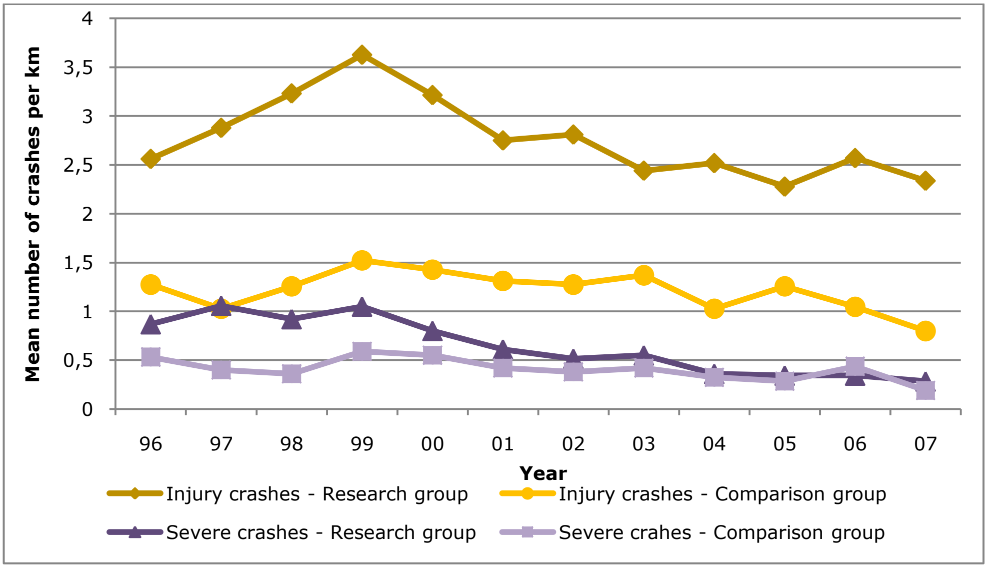


Figure 4-2 Mean crash numbers per km in the treated and comparison group from 1996 to 2007, both for injury crashes and more severe crashes

4.1.4 Method

In this study a before-and-after comparison of the crash rates was applied with control for general trend effects. A control for the RTM phenomenon was not possible since no traffic volume data were available and thus it was impossible to apply an SPF (see paragraph 2.1.3). Hauer et al. (2002) indicate that the RTM phenomenon can be controlled through an estimate of the crash counts of the treated location and the crash frequency expected at similar entities.

However, it was not possible to select a suitable comparison group. As can be seen from Table 4-2, the crash rates at the treated locations are systematically higher compared to the comparison locations, both for the period before and after the measure. This is an important remark, which has consequences for the evaluation method. Table 4-2 shows considerable differences between the mean numbers of crashes in the treated group and the comparison group throughout the full period 1996-2000. These differences seem to be rather structural, as the speed limit reduction was only introduced starting from 2001. Consequently, an EB estimation of crash rates in the period before implementation of the measure, based on this comparison group, would result in a biased (in the present case: an unreasonably low) estimated number of crashes compared to the recorded crash rates. It was not possible to select another comparison group, as there were no other locations within the province of Limburg with an unchanged speed limit of 90 km/h and no information could be obtained from locations elsewhere. As a result, no attempt could be made to correct any RTM-bias and the evaluation was continued as a before-and-after study with a comparison group to account for trend effects.

The problem of zero crashes was solved using a factor of 0.5, which is added to each of the four variables of Eq. 2-3 when one of this equals zero.

4.1.5 **RESULTS**

The results of the analyses are shown in Table 4-3. The decrease of the speed limit from 90 km/h to 70 km/h resulted in a decrease in injury crashes at 62% of the locations. Furthermore, a separate analysis is carried out for crashes that occurred at intersections and at road sections. There was a decrease in crash rates at 43% of the intersections. At road sections, a decrease is found at 70% of the locations. In the case of the fatal and serious injury crashes, a decrease is found at 67% of the locations. A distinction between road sections and intersections showed a decrease in severe crashes at 49% and 67% of the locations, respectively. At the road sections, seven locations (12%) also had an index equal to one.

The meta-analysis for the total number of injury crashes showed a decrease in crash rates of 5% after lowering the speed limit, which was however not significant at the 5% level. For crashes that occurred at intersections, an increase of 11% is found, significant at the 10% level. On the contrary, an analysis of crashes at road sections resulted in a significant decrease of 11%. A meta-analysis for the more severe crashes showed a significant decrease of 33% at all treated locations. This strong decrease was mainly found for crashes that occurred at road sections, for which a significant decrease of 36% was found. The severe crashes at intersections showed a decrease of 6%, which was not significant. These results clearly show more effects for the severe crashes, compared to the total number of injury crashes. In addition, a higher effectiveness is found for the occurrence of crashes at road sections compared to intersections.

Table 4-3 Results of the before-and-after study with correction for trend effects

Analysis per location						
	Total		Intersections		Road sections	
	# eff < 1	# eff >1	# eff < 1	# eff >1	# eff < 1	# eff >1
Injury crashes	38 (62%)	23 (38%)	26 (43%)	35 (57%)	43 (70%)	18 (30%)
Severe crashes	41 (67%)	20 (33%)	30 (49%)	31 (51%)	41 (67%)	13 (21%)

Meta-analysis			
	Total	Intersections	Road sections
	Eff [95% CI]	Eff [95% CI]	Eff [95% CI]
Injury crashes	0.95 [0.88; 1.03]	1.11 [1.00; 1.23]	0.89 [0.80; 0.99]*
Severe crashes	0.67 [0.57; 0.79]*	0.94 [0.73; 1.20]	0.64 [0.52; 0.73]*

* Significant at the 5% level

4.1.6 **DISCUSSION**

Ideally, a traffic safety measure should be evaluated using the EB method (Elvik, 2002; Hauer, 1997). Since the crash rates are much lower in the comparison group compared to the treated group and no traffic volume data were available, this method was not applicable here, as it would lead to biased estimations. One possible explanation for this discrepancy between the treated and comparison group arises from the criteria that were used to select the road sections for reducing the speed limits. One criterion was roads that are located outside urban areas, but still have a high building density. Locations in the comparison group, on the other hand, are mainly situated at rural roads, where traffic volumes may be lower compared to the treated locations. It was not possible to select another comparison group and therefore, it was not feasible to use the EB method to its full extent and to control for RTM. However, roads that had a speed limit restriction were not mainly selected because of a high crash count. A range of different criteria was used: the absence of cycle paths or paths close to the roadway, presence of obstacles close to roadways or a high number of vulnerable road users. From this it can be expected that the occurrence of RTM is possible, though probably rather limited in size as the registered number of crashes was only one of several criteria for inclusion. Moreover the before period counted 5 to 6 years, which probably considerably reduced the RTM effect.

Traffic volume data were not taken into account, since these data were not available. These volume data could have given an explanation of the low crash rates in the comparison group compared to the treated group. Next to this, it would have been interesting to compare the traffic volumes after the implementation of the speed limit restriction with before, in order to analyse whether the speed limit restriction had an effect on the route choice of the drivers. However, as already explained in paragraph 2.1.1, we can expect this effect was limited, due to the road system structure in Flanders. This structure does only give limited opportunity for drivers to choose alternative roads, as these mainly include local roads with a speed limit of 70 km/h or 50 km/h. The speed limit restriction from 90 km/h to 70 km/h, which was mainly implemented at short road sections at the upper category of roads, will probably have had a limited effect on the rerouting choices of the driver.

Since the traffic volumes were not available, it is assumed the RTM effect is small and no changes in traffic volumes occurred due to the speed limit reduction. However, these can be considered as reasonable assumptions. Therefore, the present results at the meta-level are regarded as the best possible estimation of the results that would be found, if exposure data would have been available.

The analyses clearly showed a higher effects for more severe crashes with serious injuries and fatalities, compared to all injury crashes. This can be ascribed to the fact that speed is directly related to injury severity in a crash. This is different than the probability of being involved in a crash, which is more complex, as the occurrence of crashes can seldom be attributed to a single factor (Transportation Research Board, National Research Council, 1998). The analyses also showed a stronger effectiveness at road sections compared to intersections, both for injury crashes, for which even a contradictory was found, and for the more severe crashes. This is more difficult to explain. Crashes that occur at intersections may be less influenced by speed compared to road stretches, and causation might rather be related to manoeuvres, for example turning left. This explains why no decrease was found, but this does not explain why an increase is found. A possible cause for this increase in the number of crashes is the increase in the variance of travel speeds.

Lowering the speed limit will not automatically lead to a change in travel speeds by all drivers. Factors such as habits, non-acceptance of the new measure or inattentiveness might explain why the actual speed adaptation is lower than the required speed adaptation (McCarthy, 1998). Furthermore, the speed limit change was only communicated by adapting traffic signs. Parker (1997) stated that changing posted speed limits alone, without additional enforcement, educational programmes or other engineering measures, only has a minor effect on driver behaviour. Furthermore, the infrastructure of the road was not adapted, which makes it less appealing for drivers to adapt their behaviour, whereas others will strictly follow the rules. This can lead to an increase in the variance in travel speeds, which is an important risk factor for the occurrence of crashes (Aarts & Van Schagen, 2006).

In turn, changes in speed behaviour will not necessarily result in an equivalent effect on traffic safety. As formulated by Nilsson (2004) and Elvik (2004; 2009; 2013), this relationship can be expressed by power estimations of the differences in speeds. In a back-of-the-envelope calculation, this theory can be compared with the results from the present study, and the power estimations can be applied to observed travel speeds at Flemish roads. For this calculation the power estimations are used that resulted from the study by Elvik (2009), from which we applied the power estimations for rural roads and freeways, as these are also the type of roads that are included in the present study. In 2007 the mean speed at 70 km/h roads was 75 km/h, at roads with a limit of 90 km/h this was 82.5 km/h. The V_{85} was respectively 95.1 km/h and 85.6 km/h (Riguelle, 2009). Using the power estimations on these speeds resulted in an estimated decrease in crash rates between 14% and 35%, as shown in Table 4-4.

Table 4-4 Estimation of effect in number of crashes using power estimations by Elvik (2009) for mean and V_{85} speeds at 90 km/h roads and 70 km/h roads in Flanders in 2007

	Mean speeds 82.5 → 75 km/h	V85 speeds 95.1→85.6 km/h
Fatal injury crashes	-32%	-35%
Serious injury crashes	-22%	-24%
Injury crashes	-14%	-15%

The results from our analyses are less favourable with respect to all injury crashes. In the case of severe crashes, the results are more in line with these theoretically expected results. However, this reasoning lacks validity due to its non-experimental setting. At the least, we would recommend a more detailed analysis of the speed behaviour on the roads in question.

4.1.7 **CONCLUSIONS**

- As a result of the restriction of the speed limit from 90 km/h to 70 km/h on highways in Flanders, the number of injury crashes non-significantly decreased by 5%, the severe crashes decreased significantly by 33%
- Less favourable effects were found for intersections (injury crashes: +11%; severe crashes: -6%) compared to road sections (injury crashes: -11%, severe crashes: -36%). Changes in variances of travel speeds may be a causal factor.

- This study was unable to obtain data on travel speeds. Future research is required to examine the relationship between the speed limit and the travel speeds of the driver, and the effect on traffic volumes.

4.2 DYNAMIC SPEED LIMITS ON MOTORWAYS. A TRAFFIC SAFETY EVALUATION.

Dutch report:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E. & Wets, G. (2014). Dynamic speed limits on motorways. A traffic safety evaluation. Diepenbeek: Steunpunt verkeersveiligheid.

4.2.1 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 result of high traffic volumes or other environmental conditions (Islam, Hadiuzzaman, Fang, Qiu, & El-Basyouny, 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 based on 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, Brandenburg, & Twisk, 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 (Islam et al., 2013; Habtemichael & de Picado Santos, 2013; Lee, Hellinga, & Saccomanno, 2004). DSLs are sometimes used in order to reduce vehicle emissions and road noise (Papageorgiou, Kosmatopoulos, & Papamichail, 2008).

DSL systems are also applied on Flemish motorways. The speed limit is denoted by electronic signs that are housed within gantries situated above motorway lanes. DSL systems in Flanders are compulsory and have three main objectives:

(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 speeds and to 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 speeds: at moments with a high traffic flow, speed limits will be reduced, which will lead to a more homogeneous traffic flow and to fewer 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 from automatic incident detection cameras at that location. Data on speed and occupancy are used to set the appropriate DSLs. When the loops and cameras detect a high occupancy together with low speeds, 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.

4.2.2 **PREVIOUS STUDIES**

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 reduces the crash potential. The greatest reduction occurred at the location with high traffic turbulence. Abdel-Aty, Dilmore and Dhindsa (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, Dilmore, & Hsia, 2006). In a later study, they 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 (Abdel-Aty, Cunningham, Gayah, & Hsia, 2008). Habtemichael and de Picado Santos (2013) found 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 give however no indication about the impact of this measure. 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 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 DSLs 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, Harms, Hoogendoorn, & Brookhuis (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. 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. Kwon, Brannan, Shouman, Isackson and Arseneau (2007) studied the effect of DSLs at a work zone in Minnesota.

No peer reviewed empirical studies were found that analysed the impact on traffic safety. Therefore, the present study analysed the traffic safety effect of DSL systems in Flanders, based on an empirical analysis of observed crash data.

4.2.3 **DATA**

In 2003, the first DSL systems were installed on 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 were included, which cover a total distance of 59.54 km. These five segments are located at access roads to the ring road of Antwerp, which is one of the two busiest ring roads in Belgium.

Table 4-5 gives an overview of the characteristics of the treated locations; Figure 4-3 gives a geographical overview of the locations. Every dot indicates a gantry that shows variable speed limits per lane. 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 4-5 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	2
4	E313 Geel-Ranst	31.80	2009	2
5	E34/E313 Ranst-Antwerp	10.00	2003	2

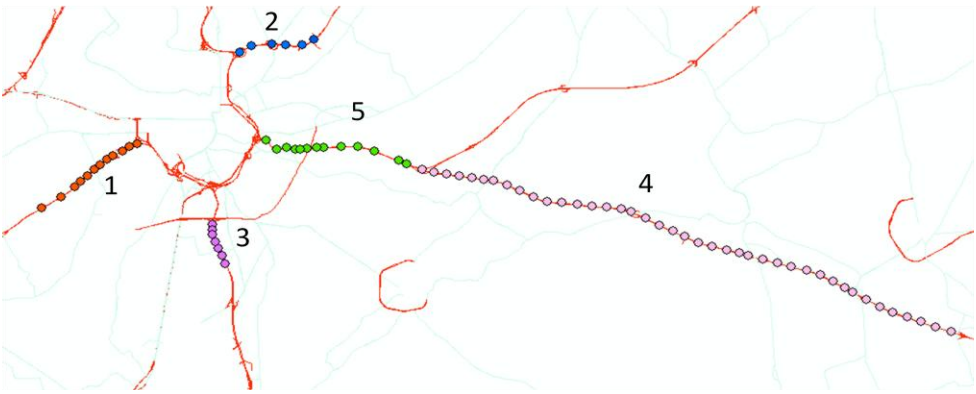


Figure 4-3 Geographic location of the treated segments

All crashes from 1999 up to 2011 were selected. 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 at the ring road of Antwerp, to which all 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 DSL systems were 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 and fatally injured persons (see 2.1.6 for more information).

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 4-6 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 4-6 Average number of crashes/year that occurred at the treated locations during the before and the after period

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

4.2.4 **METHOD**

The traffic safety effect was estimated through a before-and-after comparison of crashes, with control for RTM and the general trend effect. The effect was calculated as described in Eq. 2-9.

To calculate the average number of crashes at similar entities ($E[\kappa]$), see Eq. 2-4, an SPF is used that has been developed for the crash occurrence of injury crashes at Flemish motorways. This study developed an SPF per motorway segment, and included several variables: traffic volume, length of road segment, type of road segment and number of lanes. The type of road segment included two main categories: (1) road segments at entries/exits and interchanges and

(2) 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.

$$E[\kappa] = e^{\alpha} * L^{\beta} V^{\gamma} e^{\sum_{i=1}^{n} \delta_i x_i} \quad \text{(Eq. 4-2)}$$

with $E[\kappa]$= 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..5)

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 in 2008, 381 in 2009 and 544 in 2010. The road segments included in the SPF have an average length of 2448 m (st. dev. 2726 m) and an average traffic volume of 36,047 vehicles/24h (st. dev. 20,045). Table 4-7 displays the results of the SPFs for the injury crashes and the severe crashes. The segment type and the number of lanes were however not significant for both models.

Table 4-7 Results of the SPFs

	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)***
Overdispersion	0.313 (SE:0.031)	0.325 (SE:0.070)
Elvik index of goodness-of-fit	0.822	0.824
Likelihood ratio test statistic (χ^2)	1013.5***	500.6***

*** $p<0.001$

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 DSL systems 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 on the motorways during the before period to the annual average number of crashes that occurred in 2008-2010.

No separate model was available for side crashes and single-vehicle crashes, for which it was subsequently not possible to control the RTM effect.

Since the treated locations are long (smallest section=4.44 km), the problem of zero crashes did not occur, and thus it was not necessary to control for this.

A meta-analysis of the five locations was carried out, through the use of Eq. 2-25 through Eq. 2-28; which results in one overall effect estimate and in more statistically reliable outcomes (Fleiss, 1981).

4.2.5 **RESULTS**

A meta-analysis of the injury crashes showed a significant decrease of 18% after the implementation of DSLs (see Table 4-8). 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 4-8, 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 at the 5% level, but was significant at the 10% level [0.67; 0.97]. 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.

Table 4-8 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	0.97 [0.71; 1.34]

* Significant at 5% level

4.2.6 **DISCUSSION**

The study showed that DSL systems have 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%.

Since favourable effects were found for the number of injury crashes, but no effect was found for the severe crashes, this means that this measure mainly has an effect on the crashes with slight injuries. This can probably be ascribed to the circumstances under which this measure is active. This measure will mainly be active at busy moments. Possibly speeds are already lower, and crashes that occur at these moments are rather related to manoeuvres between vehicles, instead of high driving speeds. The main purpose of dynamic speed limits is to lead the traffic to a more homogeneous traffic flow and to fewer manoeuvres. Furthermore, the headway is smaller, through which the available space is used more efficiently and the chance on the occurrence of traffic jams is subsequently lower.

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 using an observed number of crashes. Furthermore, the effects of such a traffic safety system are largely dependent on the traffic situation where the DSL systems are installed and thus no systems can be considered as identical.

A limitation of the present study is that the RTM phenomenon could only be controlled for in the analyses of the injury and severe crashes since an SPF was only available for these types of crashes. Subsequently RTM was not controlled for in the analyses with the different crash types (i.e. rear-end crashes, side crashes, single-vehicle crashes). However, it can be expected that the RTM phenomenon was not present at the treated locations, since the installation of DSL systems is not based on the occurrence of crashes, but on mobility factors, such as traffic flows. An analysis of the injury and severe crashes with and without control for RTM confirms this assumption, as it showed similar results.

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). In future research 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.

4.2.7 CONCLUSIONS

- The installation of DSL systems had a favourable effect on the number of injury crashes (-18%), but no effect was found on the number of severe crashes.
- This favourable effect was mainly attributable to a decrease in the number of rear-end crashes.
- In order to get a clear view on the relation between DSLs and crashes, the effect on the driving speed should be analysed.

CHAPTER 5

SPEED AND RED LIGHT RUNNING ENFORCEMENT ON HIGHWAY

5.1 AN EVALUATION OF THE TRAFFIC SAFETY EFFECT OF FIXED SPEED CAMERAS

This chapter is based on:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). An evaluation of the traffic safety effect of fixed speed cameras. Safety Science, 62, 168–174. doi: 10.1016/j.ssci.2013.07.028

Dutch report:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2012). *Effectevaluatie van snelheids- en roodlichtcamera's op gewestwegen in Vlaanderen* (RA-2012-01). Diepenbeek: Steunpunt Verkeersveiligheid.

Proceedings:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013a). Afremmen of versnellen? Effecten van roodlicht- en snelheidscamera's in Vlaanderen. In *Jaarboek Verkeersveiligheid 2013*. Paper presented at the Flemish traffic safety conference, Antwerp.

5.1.1 INTRODUCTION

Driving speed influences both the chance to be involved in a crash and the severity of the injuries when a crash occurs (Elvik et al., 2004; Mountain, Hirst, & Maher, 2004). Nevertheless, many drivers exceed the speed limits. A study of different countries around the world showed that on average 40% to 50% of the drivers drive faster than the posted speed limit (OECD, 2006). Nilsson (2004) and Elvik et al. (2004) described the relationship between speed and crashes as a power function, which indicates the crash risk increases more than proportionally with higher speeds. A measure that is often implemented to tackle this problem, is the installation of speed cameras. In Flanders, Belgium, which covers about 5000 km of highways (roughly the upper category of roads, motorways excluded), more than 250 speed cameras were installed since 2002. All of these cameras are placed along road sections. The speed cameras installed at signalized intersections in Flanders also detect red light running, and are discussed in the next chapter (see chapter 5.2). The traffic safety effects of speed cameras on motorways were analysed separately (see chapter 6.2 and 6.3). The decision to install a camera is based on the number and severity of the crashes during the last five years and the presence of black spots in a distance of one kilometre. The fine includes €50 up to a speeding level of 10 km/h. Inside the built-up area, 30 km/h zones, school and residential areas €10 is added for every km/h above the initial level of 10 km/h. At a speeding level from 30 km/h or more drivers are brought to court, they receive a fine between €55 and €2750 and a driving ban for 8 days to 5 years. For other roads, the rules are less strict: there is an additional €5 for every km/h above the initial 10 km/h and drivers are brought to court at speeding levels from 40 km/h. 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 present study analyses the traffic safety effects of fixed speed cameras on highways in Flanders.

5.1.2 **PREVIOUS STUDIES**

In order to determine whether speed cameras are an appropriate method to tackle the speeding problem, an evaluation of the safety effect is essential. Elvik et al. (2009) carried out a meta-analysis of studies that analysed the effects of speed cameras on crash numbers and crash severity. Only studies that applied some kind of comparison group were included, as studies that did not applied a comparison group systematically showed larger effects, probably due to a lack of control for confounding factors. Based on several studies, mainly conducted in Europe and Australia, an overall decrease of 16% in the number of injury crashes was found. Furthermore, a favourable effect was found in the number of fatal crashes, for which the overall estimation was a decrease of 39%.

Mountain et al. (2004) studied the effect for separate distance bands in order to analyse to what distance the speed cameras have an effect. Therefore they analysed the effect of 62 speed cameras in the United Kingdom at roads with a speed limit of 30 miles/h (≈48 km/h). The highest effect was found at a distance up to 250 m from the camera, on which a significant decrease of 25% in the number of injury crashes was found. Between 250 m and 500 m this decrease dropped to 15% and between 500 m and 1000 m this was -12%. However, both of these results were non-significant. Also Hess (2004) analysed the effects of speed cameras, but he used cumulative distances of 250 m, 500 m, 1000 m and 2000 m. He found the highest effects in the immediate vicinity of the camera, for which a decrease of 46% was found up to 250 m from the camera. The effects dropped with the distance from the camera, and at a distance of 500 m, 1000 m and 2000 m decreases of respectively 41%, 32% and 21% in the number of injury crashes were found.

5.1.3 **DATA**

5.1.3.1 **TREATED AND COMPARISON GROUP**

In order to perform an effect evaluation, the following information was collected:

- a geographical location of the crashes around the speed cameras;
- crash information (year, involved road users, severity) for both treated locations and comparison group;

- date (year) the camera was installed and operational;
- information about other measures implemented on the treated road section during the research period;
- characteristics of the road section (inside/outside urban area, number of lanes, speed limit)

At the end of 2012, around 230 fixed speed cameras were installed at the Flemish highways. All of these cameras are photo radar units mounted in boxes. Speed can be detected through two systems: either through two inductive loops embedded in the pavement, which calculates the speed of the vehicle based on the time the vehicle needs to pass the two loops and the distance between the loops. Or either through electromagnetic waves, for which the system can detect the speed of a vehicle based on the echo of these waves (Ministry of Mobility and Public Works, Roads and Traffic Agency, 2013).

The Roads and Traffic Agency delivered information of the year during which the camera was installed and the year the camera was operational (i.e. drivers were ticketed). The before period ranged until the year before the camera was installed, the after period ranged from the year after the camera was operational. Subsequently, the years during which the camera was installed until this was operational were not taken into account in this study. This period ranged from one to six years, and is further referred to as the installation period. In most cases the time of installation and the time the camera was operational, was the same year. However, some locations had problems with the inductive loops and subsequently with the registration of the speeds. It took four to six years until the cameras at these locations were operational and drivers were ticketed. We decided to restrict the before period until the year the camera was installed, as we can expect drivers' behaviour change when they see the newly installed camera. On the other hand, the after period started from the time the camera was operational, because it is unclear whether drivers knew that offenders were not ticketed and whether this had an influence on their behaviour.

Furthermore, responsible authorities were asked to provide information about other measures that were implemented during the research period, for example change of the maximum speed limit, changes in the infrastructure for pedestrians or cyclists and resurfacing of the road. Based on this information, it was possible to exclude the traffic safety effects of these measures and to examine the isolated effect of the speed cameras.

Crash data of at the least one year before and after the installation period of the camera is required in order to enable a before-and-after evaluation. Since at the time of the study geo-located crash data for Flanders was available up until 2008, only cameras installed up to and including 2007 could be evaluated. In total, 107 locations were excluded, since these were installed after 2007, or installed before 2008, but operational (i.e. offenders were ticketed) after 2007. In addition, 15 cameras were excluded because the date of installation or commencement was unknown and 11 locations were excluded, as no information was received about other local measures. This information is required in order to make it possible to assess only the effect of speed cameras and to exclude the effect of other measures that were implemented during the research period. Eventually, 97 locations were included in the treated group. For 32 locations the required information was available, but it was not possible to exclude the effect of other traffic safety measures, as these measures were implemented the year during which the camera was installed, or during the year directly before or after. For 65 locations, the isolated effect of the installation of a speed camera could be examined. The flow chart of this selection is shown in Figure 5-1.

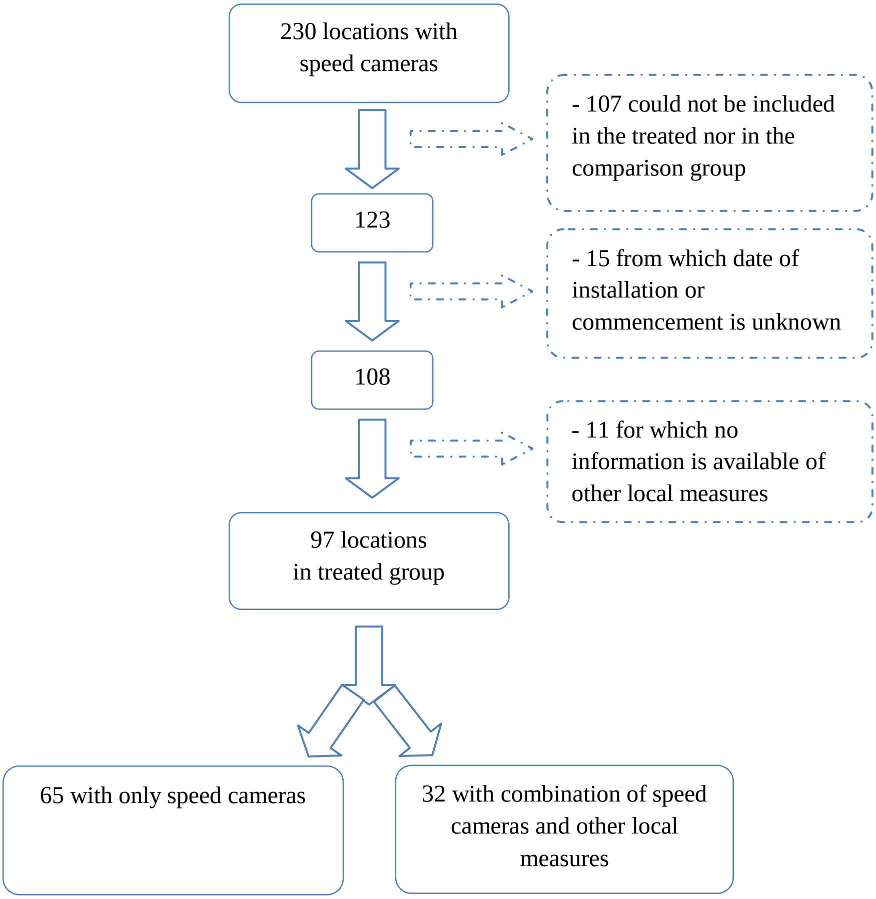


Figure 5-1 Flow chart of the selection of the treated locations of fixed speed cameras on highways

The comparison group comprised all crashes in Flanders, which gives a good estimation of the general trend. To analyse whether this group was comparable with the treated group, the odds ratios for the crash frequencies from the years of the before period were calculated. An overall estimation of the odds ratios showed a score of 1.04, which can be considered as an indication of a good comparability between the treated and the comparison group (Hauer, 1997).

5.1.3.2 Crash data

The present study aims to examine the traffic safety effect of fixed speed cameras in Flanders through a before-and-after comparison of the injury crashes. In a first analysis all injury crashes were included, in a second analysis the fatal and serious injury crashes were studied. All crashes that occurred at a distance of 500 m upstream and downstream from the camera were selected. In addition, the crashes were selected at different distance bands of 250 m, until 1000 m from the camera. Through these different distance bands it was examined whether or not the effect differed according to the distance from the camera. Furthermore, the characteristics of the locations were taken into account and it was analysed whether or not the effectiveness differed according to the location inside or outside the urban area, number of lanes, maximum speed limit and whether or not other speed cameras were located nearby. Next to the crash level, an analysis on the level of casualties was executed, and the effect on each road user type (car occupants, cyclists, moped riders, motorcyclists and pedestrians) was examined.

The research period ran from 2000 until 2008, meaning that, as the first cameras were installed in 2002, for any location at the least two years of data in the before period and one year of data in the after period was available. On average, the before period amounted to 3.88 years, the after period to 2.55 years. Table 5-1 shows the descriptive statistics of the crashes from the treated locations, with a distinction between the before and the after period.

Table 5-1 Descriptive statistics of crashes (per location)

Characteristics		N	Before Mean (st. dev.)	After Mean (st. dev.)
Total			17.12 (18.71)	10.57 (21.05)
Severe			*3.95 (3.67)*	*1.28 (2.81)*
Inside /outside urban area	Inside	26	24.58 (26.14)	18.86 (30.80)
	Outside	39	12.15 (8.77)	4.97 (6.45)
Number of lanes	1	35	11.4 (7.83)	7.31 (9.32)
	2	17	30.06 (25.72)	22.29 (37.04)
Maximum speed limit	50	22	20.59 (22.28)	18.23 (32.99)
	70	32	18.19 (18.17)	7.75 (10.26)
	90	7	8.00 (6.93)	2.57 (2.94)
Other cameras within 1500 m	0 or 1	47	12.94 (13.87)	8.21 (22.42)
	≥2	18	28.06 (24.96)	16.72 (15.88)

5.1.4 METHOD

It was not possible to control for the RTM phenomenon, as no traffic volume data were available and thus no SPF could be calculated (see paragraph 2.1.3). It was furthermore not possible to use the comparison group to control for the RTM effect. The comparison group that is used in the present study only included total crash numbers for Flanders, for which it was impossible to calculate the variance, which is needed to estimate the overdispersion factor.
In order to control for the zero counts, an EB estimation was executed, based on the crash frequencies in the treated group. This was applied for both the before and the after period. Subsequently, Eq. 2-23 was applied.

The trend effect and thus the implementation of other traffic safety measures on a wider scale, is taken into account through the use of a comparison group. This formula does however not control for more locally implemented measures. In order to exclude the effect of these measures, the research period of each location was adapted. When the measures were implemented before the camera was installed, the before period started from the year after the measures were completed. When a measure was implemented after the installation period, the after period was shortened until the year before the measure was implemented. It was however not possible to exclude the effects of these treatments for all locations. This was the case when the measure was implemented during the same year(s) of the installation period of the camera, or during the year before or after this installation period. These locations were included in a separate meta-analysis, and the overall effect of all the measures together was examined.

5.1.5 RESULTS

5.1.5.1 OVERALL EFFECT

Table 5-2 shows the results of the meta-analyses of the 65 locations for which the effect of the speed cameras was analysed and of the 32 locations for which the combined effect of speed cameras and other measures was studied. An analysis of the isolated effect of speed cameras showed a non-significant decrease in the number of injury crashes of 8%. The fatal and serious injury crashes significantly decreased by 29% from before to after. These results are found when crashes at a distance of 500 m from the camera were selected. Next to this, the effects on separate distance bands were analysed, that is 0-250 m, 250-500 m, 500-750 m, 750-1000 m. In the case of all injury crashes, a non-significant decrease of 1% was found at a distance of 250 m from the camera, and a non-significant decrease of 8% was found at a distance between 250-500 m. An analysis of the injury crashes at the distances of 500-750 m and 750-1000 m from the camera showed a slight increase of 2% and 8% respectively. However, none of these results was significant. In the case of the severe crashes, a clear decrease is found at a distance of 0-250 m (-27%) and at 250-500 m (-23%). At a distance of 500-750 m an increase was found (+14%), which was even higher at 750-1000 m from the camera (+27%). These results were however not significant.

For 32 locations it was not possible to analyse the isolated effect of the implementation of speed cameras, as other traffic safety measures were implemented during or shortly before or after the installation period of the camera. The majority of these measures included a decrease in the legally imposed speed limit of 20 km/h, which was implemented at 23 locations. Nine road sections were resurfaced, and at six locations changes in the infrastructure for cyclists or pedestrians were implemented. The locations that had a combination of measures showed a decrease of 10% for all injury crashes, and of 23% for the severe crashes. Both results were however not significant.

Table 5-2 Results of the meta-analyses (index of effectiveness [95%CI]) of fixed speed cameras on highways

	All injury crashes	Severe crashes
Speed cameras (65 locations; 0-500 m)	0.92 [0.82; 1.02]	0.71 [0.54; 0.92]**
0-250 m	0.99 [0.85; 1.14]	0.73 [0.50; 1.06]
250-500 m	0.92 [0.79; 1.06]	0.77 [0.53; 1.11]
500-750 m	1.08 [0.93; 1.27]	1.14 [0.81; 1.62]
750-1000 m	1.02 [0.88; 1.19]	1.27 [0.86; 1.87]
Speed cameras + other measures (32 locations; 0-500 m)	0.90 [0.76; 1.07]	0.77 [0.46; 1.27]

** Significant at the 5% level

5.1.5.2 Effects according to the characteristics of the locations

Next to the overall result, it was analysed whether differences in the effect could be found according to the characteristics of the location. The effects were calculated for the speed cameras inside and outside the urban area, according to the number of lanes and the maximum speed limit on the main road. The road with the highest road category was selected as the main road. When several roads had the same road category, the road with the highest number of lanes or highest legally imposed speed limit was selected. In addition to this, it was examined whether the presence of other speed cameras had an influence on the effect. In line with the general definition of the Flemish Government, a distinction was made between locations that had no or one other speed camera within a radius of 1500 m on the one hand, and locations with two or more speed cameras on the other hand. Table 5-3 shows the indices of effectiveness, subdivided to the different characteristics of the locations. All crashes at a distance of 500 m from the camera were included.

Table 5-3 Results of the meta-analyses (Index of effectiveness [95% CI]) according to the characteristics of the location

Features		No. of locations	Effectiveness
Inside /outside urban area	Inside	26	0.89 [0.77; 1.02]*
	Outside	39	0.96 [0.81; 1.14]
Number of lanes	1	35	0.87 [0.73; 1.03]
	2	17	0.92 [0.79; 1.07]
Maximum speed limit	50	22	0.77 [0.66; 0.90]**
	70	32	1.07 [0.91; 1.25]
	90	7	1.00 [0.59; 1.61]
Other cameras within 1500 m	0 or 1	47	0.88 [0.76; 1.01]*
	≥2	18	0.97 [0.82; 1.14]

* Significant at the 10 % level

**Significant at the 5% level

Maximum likelihood linear regression models (using SPSS GENLIN procedure) were fitted, in order to analyse the relationship between each of these characteristics and the effectiveness. The effect per location (θ_l) was selected as dependent variable, for which the natural logarithm ln(θ_l) was calculated. The independent variables were the four characteristics. All these variables were dummy coded, and were given a value of 0 or 1, as shown in Table 5-4.

The functional form of the model can be described as:

$$\ln(\theta_l) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \qquad \text{(Eq. 5-1)}$$

With x_1, …, x_n being the independent variables and β_1,…, β_n the estimation parameters.

As the results in Table 5-5 show, no significant parameter could be identified. One parameter was almost significant, that is the speed parameter through which 90 km/h locations are compared with 50 km/h locations. The negative sign of the parameter estimate indicates that the safety performance of cameras was larger at 50 km/h locations than at 90 km/h locations.

Table 5-4 Dummy-coded independent variables

	Description
Built-up area	0= outside built-up area; 1= inside built-up area
Number of lanes	0= 1 lane; 1= 2 lanes
50 km/u vs. 90 km/h	1= 50 km/h; 0=70 km/h; 0=90 km/h
70km/u vs. 90 km/h	0= 50 km/h; 1=70 km/h; 0=90 km/h
Presence of other speed cameras within 1500 m	0= no or 1 speed camera; 1= 2 or more speed cameras

Table 5-5 Results of the regression analysis

Parameter	Parameter estimate	Standard error	Chi-square	Sig.
Intercept	0.54	0.28	3.83	0.050
Built-up area	0.16	0.34	0.23	0.633
Number of lanes	-0.24	0.18	1.70	0.193
50km/u vs 90 km/h	-0.83	0.45	3.50	0.061
70km/u vs 90 km/h	-0.47	0.29	2.68	0.102
Presence of other speed cameras within 1500 m	-0.07	0.18	0.14	0.706

Deviance =13.978; Df=44.

5.1.5.3 Effect on casualty level

In addition to the analyses of the crash frequencies, analyses on the level of casualties were performed. Table 5-6 shows the mean number of injured road users per year per location, both for the treated group and for the comparison group (i.e. all traffic injuries in Flanders). The rightmost column shows the odds ratio, which is the relative change of the number of injured road users in the treated group, compared to the relative change in the comparison group. The analyses showed for all types of road users that the decrease in the number of injured road users was higher in the treated group compared to the comparison group. Truck drivers were not included, as the number of injured truck drivers was too low (only 0 to 2 injuries per year in the total treated group). The highest decrease was found for motorcyclists and pedestrians, for which the number of casualties decreased by 37%. The number of injured moped riders decreased by 16%. A decrease of 12% was found for cyclists and the number of injured car occupants decreased by 9% from before to after the installation of speed cameras.

Table 5-6 Before-and-after comparison of casualties

	Mean number of injured road users per year per location						Odds ratio
	Treated group			Comparison group			
	Before	After	Difference (%)	Before	After	Difference (%)	
Car occupants	2.68	2.09	-22	11230.57	9687.76	-14	**0.91**
Moped riders	0.86	0.56	-36	2253.04	1721.62	-24	**0.84**
Cyclists	0.79	0.79	-0.20	2379.97	2698.98	+13	**0.88**
Motorcyclists	0.37	0.23	-37	1075.40	1070.75	-0.4	**0.63**
Pedestrians	0.36	0.27	-27	737.43	858.25	+16	**0.63**

5.1.6 **DISCUSSION**

The present study showed a slight, however non-significant, decrease (-8%) in the number of injury crashes after the installation of a speed camera. In the case of the severe crashes, a higher and significant decrease was identified (-29%). A meta-analysis of Elvik et al. (2009), showed a significant decrease of 16% in the number of injury crashes and 39% in the number of fatal crashes. The present study found a stronger effect on the severe crashes compared to all injury crashes, similar to earlier results of Elvik et al. (2009). This higher effect on the severe crashes compared to all injury crashes may be ascribed to the dual effect of lower driving speeds, namely a lower risk to be involved in a crash and less severe consequences if a crash occurs (Aarts & Van Schagen, 2006).

An analysis of the crashes up to 500 m from the camera showed the cameras work well, in particular for the severe crashes. A more detailed analysis at different distance bands from the camera showed that the effect on the total number of injury crashes up to 500 m is mainly due to the effect at a distance of 250-500 m (-8%), since at the distance of 0-250 m only a limited effect was found (-1%). These results are slightly different from previous research. Mountain et al. (2004) found the highest effect up to 250 m from the camera (-25%), which dropped at a distance between 250 m and 500 m (-12%). Also Hess (2004) found higher effects in the immediate vicinity of the camera. The corresponding figures for the cumulative distances of 250 m, 500 m and 1000 m were reductions in the number of injury crashes of 46%, 41% and 32% respectively. It is however difficult to draw any conclusions from the results at the different distance bands in the present study, as the effects on the injury crashes are limited and not significant. This is not the case for the severe crashes. Whereas a limited effect was found for all injury crashes, the severe crashes showed a clear decrease at a distance of 250 m from the camera. At a longer distance, that is 500-1000 m from the camera, the favourable effect vanishes and both for the injury crashes as the more severe crashes a tendency to an increase in crash rates appears. The kangaroo effect may give a possible explanation: drivers compensate the lower driving speed at the speed camera through a higher speed from about 500 m after the camera. However, this is a hypothesis that should be analysed in future research.

An analysis of the effects according to the characteristics of the locations, showed one almost significant parameter. Locations with a speed limit of 50 km/h performed better compared to locations with a speed limit of 90 km/h. This may be explained by the driving speeds. Previous research in Flanders found a speeding rate of 63% at roads with a speed limit of 50 km/h whereas a speeding rate of 19% was found at 90 km/h roads (Riguelle, 2012a). From this it can be expected that the installation of a speed camera, which will lead drivers to follow the legally imposed speed limits, will have an effect on roads with lower speed limits (e.g. 50 km/h) in particular. Furthermore, these roads are often located in an environment with many vulnerable road users, which are often severely injured in a crash.

Though it was not possible to determine whether these results were significant, a strong decrease is found for each of the road user categories. The decrease was the highest for motorcyclists and pedestrians. This high effect can be linked to the more favourable effect that was found for the severe crashes, as motorcyclists and pedestrians are often severely injured when involved in a crash.

It is remarkable that similar results are found at locations for which the isolated effect of a speed camera was studied (injury crashes: -8%; severe crashes: -29%) and at locations for which the combined effect of the installation of speed cameras together with other measures was analysed (injury crashes: -10%; severe crashes: -23%). At the majority of the locations, these other measures included a decrease in the legally imposed speed limit. This may indicate that the installation of a speed camera in particular had a favourable influence on driving speeds and subsequently on traffic safety, rather than the decrease of the legally imposed speed limits. However, to be sure, driving speeds should be analysed.

A few limitations have to be mentioned. At first, it was not possible to control for the RTM effect. In order to control for this effect, crash frequencies at similar entities are required (Elvik, 2008b; Hauer et al., 2002). The comparison group that comprised all crashes in Flanders is not feasible for this, as it only counts the total frequencies and no subdivision can be made into different units. Furthermore, no traffic volumes were available, and thus it was not possible to apply a crash prediction model.

The comparison group also included crashes from the treated locations. This could have led to an underestimation of the effectiveness, as the trend encompasses the effect of the cameras. However, only 1.4% of the total number of crashes in Flanders occurred at the treated locations (3652 crashes at a distance of 500 m from the speed cameras compared to 261,273 crashes in Flanders for the total research period 2000-2008). It can be expected that the inclusion of these crashes had no substantial influence on the results.

A possible limitation is that the after period was quite short (on average 2.6 years). This is a consequence of the fact that the majority of the cameras were installed or operational in 2007, and geo-located crash data were available until 2008. In addition to this, the before and the after period was shortened for several locations, in order to exclude the influence of other locally implemented measures. A longer after period could reveal whether similar results are found, and could lead to more statistically significant results.

The 65 treated locations were scattered over more than 5000 km of highways around Flanders. However, inevitably other speed cameras were installed near those treated locations. This was mainly the case for cities or main roads to or from these cities. For this reason, we compared the effect of speed cameras that had no or one other speed camera within 1500 m and the speed cameras that had two or more cameras within 1500 m. This is based on a definition of the Flemish Government, which describes cameras as clustered when two or more cameras are within 1500 m from each other. The number of locations that had two or more cameras within 1500 m was limited (18 of 65 locations). Furthermore, no significant differences were found between the clustered and the single locations. The regression model showed that the presence of other speed cameras within 1500 m is not a significant parameter, which is a clear indication of a low interdependence of the cameras. It can however be argued that 1500 m is quite a small distance. Nevertheless, we believe that speed cameras that are installed at a longer distance, for example 5000 m, will only have limited influence. This is due to the Flemish road infrastructure, which is not homogenous, but often changes only after a few kilometres. This can be attributed to the high building density alternated with rural environments. Apart from these assumptions, we cannot be sure about the interdependence of the speed cameras at a longer distance.

Another limitation, and possible reason for not finding significant results, is that crashes in both directions were selected. Nevertheless, at the majority of the locations (94%) only a camera in one direction is installed. This could have had the consequence that the effect in the present study was underestimated, as it can be expected that speed cameras will have a limited or no effect in the direction where no camera is installed. It was not possible to analyse both directions separately, as the direction of the crash is not systematically reported.

Furthermore, it would have been interesting to have information on the frequency and duration of operation of the cameras. This could reveal whether there was a correlation between the intensity of use and the effectiveness. For example, road users could be asked how high they think the chance is they are detected when passing a speed camera, and to what extent this differs according to the location.

5.1.7 **CONCLUSIONS**

- The installation of speed cameras on highways in Flanders resulted in a non-significant decrease of 8% in the number of injury crashes at a distance up to 500 m from the camera. This effect was mainly found at a distance of 250-500 m from the camera, whereas no effect was found at 0-250 m from the camera.
- At a distance up to 500 m, the number of severe crashes significantly decreased by 29%.

- There are no clear differences according to the characteristics of the location where the camera is installed, but it seems that cameras at locations with a lower speed limit generate greater effects. Furthermore, a favourable effect was found for all road user categories.
- It can be concluded that speed cameras are an effective measure to improve traffic safety at locations with a high number of speed violations.

5.2 TO BRAKE OR TO ACCELERATE? SAFETY EFFECTS OF COMBINED SPEED AND RED LIGHT CAMERAS

This chapter is based on:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). To brake or to accelerate? Safety effects of combined speed and red light cameras*. Journal of Safety Research, 50*, 59–65. doi: 10.1016/j.jsr.2014.03.011

Dutch report:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2012). *Effectevaluatie van snelheids- en roodlichtcamera's op gewestwegen in Vlaanderen* (No. RA-2012-01). Diepenbeek: Steunpunt Verkeersveiligheid.

Proceedings:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2012). The effect of red light cameras on safety. Paper presented at ICTCT 2012 workshop, Hasselt.

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). The effect of combined speed and red light cameras on safety. In *TRB 92nd Annual Meeting Compendium of Papers*. Paper presented at the Transportation Research Board, Washington DC.

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). Afremmen of versnellen? Effecten van roodlicht- en snelheidscamera's in Vlaanderen. In *Jaarboek Verkeersveiligheid 2013*. Paper presented at the Flemish traffic safety conference, Antwerp.

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). The traffic safety effect of combined speed and red light cameras. Paper presented at the Transport Research Arena, Paris.

5.2.1 **INTRODUCTION**

Many signalized intersections in several countries, are equipped with enforcement cameras in order to tackle red light running. Red light running is a substantive problem that has led to numerous crashes. These violations are typically associated with side impacts, which often lead to severe injuries (Garber, Miller, Abel, Eslambolchi, & Korukonda, 2007). The red light cameras detect vehicles through two closely spaced inductive loops, embedded in the pavement at the limit line. The system compares the information on the vehicle speed at the stop line with the signal phase, in order to analyse red light running. When a car runs the red light, two photographs are taken: one when the vehicle is crossing the stopping line and one to determine whether the vehicle crossing the intersection. Furthermore, red light cameras sometimes determine driving speeds, through the calculation of the time that the vehicle needs to pass the two loops. Speeding is stated as the most important contributor to fatalities (Elvik et al., 2004). Driving speed both influences the chance to be involved in a crash and the severity of the injuries in case a crash occurs (Elvik et al., 2004; Mountain et al., 2004).

In Flanders, which covers about 5000 km of highways (motorways excluded), more than 400 intersections were equipped with one or more fixed combined speed and red light camera (SRLC) since 2002 (Ministry of Mobility and Public Works, Roads and Traffic Agency, 2013). These cameras are all photo radar units mounted in boxes.

The present study analyses the traffic safety effects of combined speed and red light cameras. This research was carried out at the same time that the effects of the fixed speed cameras were studied (see chapter 5.1).

5.2.2 **PREVIOUS STUDIES**

Previous studies mainly analysed the effect of cameras that only determine red light running but not excessive speed. Although results can differ, it is found that red light cameras reduce the frequency of side crashes and increase the number of rear-end crashes. A meta-analysis of Høye (2013), including several studies mainly from the United States that controlled for RTM, showed a non-significant decrease of 12% in the number of injury crashes. An analysis according to the crash type showed an increase of 19% in the number of rear-end crashes and a decrease of 33% in right-angle crashes. However, the majority of the included studies only analysed the effect of cameras that detect red light running, whereas the focus in the present study is on cameras that both detect red light running and speeding behaviour. A recent study that analysed the effect of the latter type is from Budd, Scully and Newstead (2011). They studied the effect of SRLCs with accompanying warning signs at 77 locations in Victoria, Australia. The results showed a decrease in casualty crashes of 26% at the treated intersections. A distinction according to the crash type resulted in a significant decrease of 44% in right-angle and right-turn crashes, but no change in the rear-end crashes. Vanlaar, Robertson and Marcoux (2014) studied the Winnipeg's photo enforcement safety programme and analysed the effect on red light running violations and speeding on the one hand and the crash effects related to these behaviours on the other hand. They found that there were significantly fewer red light running violations after the installation of the cameras compared to before. This favourable effect was also found in previous studies. A meta-analysis of Elvik et al. (2009) found a reduction in the number of red light running violations of between 20% and 80%. Furthermore, the photo enforcement in Winnipeg was found to be effective in preventing speeding violations in general (at least 1 km/h over the speed limit), but less effective in preventing serious speeding violations (more than 13 km/h over the speed limit) (Vanlaar et al., 2014). For the analysis of crashes related to red light running, a distinction was made between right-angle and rear-end crashes, for which respectively a decrease of 46% and an increase of 42% was found. An analysis of crashes related to speeding showed no effects, not for injury crashes, nor for PDO crashes.

5.2.3 **Data**

5.2.3.1 **Treated and comparison group**

The Roads and Traffic Agency delivered information on the years during which the cameras were installed and became operational. The before and the after period was selected for each intersection separately. The before period ranged until the year before the camera was installed, the after period ranged from the year after the camera became operational. Subsequently, the year(s) during which the camera was installed and became operational were not taken into account in this study. In most cases, this period counted one to two years.

In order to examine the single effect of the SRLCs, it was analysed whether other measures were implemented throughout the research period. Examples of those measures are: installation of traffic signals, changes in turn lanes, changes in the infrastructure for pedestrians or cyclists, resurfacing of the road, conversion to conflict free traffic signals and reduction of the maximum speed limit.

The unit of evaluation is the intersection with SRLCs. The number of the SRLCs at these intersections varies along the intersections. From the total number of 408 SRLC equipped intersections, 253 were eventually included in this research. Sixty intersections were excluded since cameras were installed after 2007. At the time of the present study, geo-located crash data was available up to and including 2008. In order to enable a before-and-after study, only cameras installed up to and including 2007 could be evaluated. Furthermore, four intersections were excluded, as no date of installation of the cameras was available. In addition to this, the cameras at eight intersections were put out of use before 2008, mainly due to problems with the inductive loops; and from six locations no information was received in relation to local measures. It was not possible to exclude the effect of other traffic safety measures for 77 intersections, because these measures were implemented during the same year the SRLC was installed or during the year right before or after the installation. Finally 253 intersections were selected, for which the isolated effect of the installation of SRLCs could be examined.

The database with all crashes in Flanders was selected as the comparison group, as this gives a good estimation of the general trend. This comparison group can be considered as comparable to the treated group as the average odds ratio was 0.99.

5.2.3.2 Crash data

At the time the study was carried out, geo-located crash data were available from 1996 until 2008 (Ministry of Mobility and Public Works, Roads and Traffic Agency). All crashes within a radius of 50 m from the intersection centre were included in the present study. No data was available in relation to traffic volumes at the treated locations.

Two groups of crash data were included: all injury crashes and severe injury crashes. Furthermore, two types of crashes were differentiated: side and rear-end crashes. All crashes from 2000 until 2008 were included, meaning that, as the first cameras were installed in 2002, for any location at least two years of data in the before period and one year of data in the after period were available. The before period amounted on average to 3.1 years, the after period to 3.7 years.

The injury crashes in the treated group decreased from 800 in 2000 to 618 in 2008, with an average of 713 crashes per year. The severe crashes had a range from 144 in 2000 to 58 in 2008, with an average number of 90. The crash numbers in Flanders, which are selected in order to control for the general trend effects, decreased throughout 2000-2008 from 33,023 to 27,057, with an average of 29,030 crashes per year. The severe crashes had an average of 4532, with a range from 6017 in 2000, to 3905 in 2008. Next tables show the descriptive statistics of the crashes from the treated locations, with a distinction between the before and the after period and subdivided to the characteristics of the locations. Furthermore a distinction was made between side crashes (Table 5-7) and rear-end crashes (Table 5-8).

Table 5-7 Descriptive statistics of side crashes (per location)

Characteristics		N	Before Mean (st. dev.)	After Mean (st. dev.)
Total		253	4.57 (4.66)	3.71 (4.80)
Severe crashes		*253*	*0.79 (1.08)*	*0.39 (0.81)*
Inside /outside urban area	Inside	95	4.47 (3.90)	3.00 (2.95)
	Outside	158	4.73 (5.73)	4.89 (6.70)
Number of lanes	1	71	3.58 (3.50)	2.66 (2.58)
	2	153	5.15 (5.04)	4.25 (5.53)
Maximum speed limit	50	68	3.90 (4.78)	4.50 (7.34)
	70	85	5.06 (5.39)	3.53 (3.76)
	90	94	4.74 (3.87)	3.24 (2.97)
Other intersections within 1500 m	0 or 1	152	4.17 (3.80)	3.01 (3.09)
	≥2	101	5.17 (5.68)	4.76 (6.46)

Table 5-8 Descriptive statistics of rear-end crashes (per location)

Characteristics		N	Before Mean (st. dev.)	After Mean (st. dev.)
Total		253	2.36 (3.19)	3.49 (4.04)
Severe		*253*	*0.44 (0.77)*	*0.15 (0.44)*
Urban area	Inside	95	1.53 (1.88)	3.11 (3.19)
	Outside	158	2.86 (3.68)	3.73 (4.47)
Number of lanes	1	71	1.07 (1.30)	1.92 (2.15)
	2	153	2.84 (3.06)	4.09 (4.41)
Maximum speed limit	50	68	1.19 (1.68)	2.62 (2.95)
	70	85	2.44 (2.95)	3.13 (3.50)
	90	94	3.17 (3.96)	4.38 (4.96)
Other intersections within 1500 m	0 or 1	152	2.43 (3.64)	3.53 (4.21)
	≥2	101	2.25 (2.37)	3.45 (3.80)

5.2.4 **METHOD**

As in the study of speed cameras on highways (see chapter 5.1), it was not possible to control for the RTM phenomenon, because no traffic volume data were available and thus an SPF could not be applied (see paragraph 2.1.3). RTM could neither be controlled with the comparison group. In order to control for this effect, the mean crash rates and the overdispersion at those comparable locations are required. Since the comparison group consists of all crashes in Flanders, the overdispersion could not be calculated.

In order to control for the zero counts, an EB estimation was executed, based on the crash frequencies in the treated group. This was applied for both the before and the after period. Subsequently Eq. 2-23 was applied.

The trend effect and subsequently the implementation of other traffic safety measures on a wider scale is taken into account through the use of a comparison group. However, this formula does not control for more locally implemented measures. In order to exclude the effects of these measures, the research period of each location was adapted, similar as was done in the study of the fixed speed cameras. When the measures were implemented before the camera was installed, the before period started from the year after the measure was completed. When a measure was implemented after the installation, the after period was shortened until the year before the measure was implemented. It was however not possible to exclude these other treatments for all intersections. This was the case when the measure was implemented during the same year the SRLC was installed or during the year right before or after the installation. These locations were included in a separate meta-analysis, and the overall effect of all these measures together was examined.

5.2.5 **RESULTS**

The best estimate of the overall effect on injury crashes of the 253 intersections, for which the isolated effect of SRLCs could be evaluated (i.e. all the locations for which the confounding effect of other measures could be eliminated), is a non-significant increase of 5% (see Table 5-9). An analysis of the fatal and serious injury crashes showed a decrease of 14%, non-significant at the 5%

level, but upper limit close to one. The number of side crashes, which often occur in crashes with red-light running, decreased non-significantly with 6%. The reduction in severe side crashes was 24%, significant at the 5% level. Rear-end crashes on the other hand, showed a significant increase of 44% in the number of injury crashes. An analysis of the severe rear-end crashes was not possible, as the number of crashes in the treated group was too low, with an average of 12 crashes per year.

It was not possible to analyse the isolated effect of SRLCs for 77 intersections, as other measures were implemented during the same year the camera was installed, or shortly before or after the installation period of the camera. The majority of these measures included a reduction of the speed limit and a resurfacing of the road. The intersections with multiple measures showed a significant decrease in the number of injury crashes of 28%. In the case of the severe crashes, a non-significant decrease of 12% was found.

Table 5-9 Results of the meta-analyses (index of effectiveness [95% CI])

	All injury crashes	Severe crashes
SRLCs (253 intersections)		
All crash types	1.05 [0.98; 1.12]	0.86 [0.73; 1.02]
Side crashes	0.94 [0.85; 1.03]	0.76 [0.59; 0.98]*
Rear-end crashes	1.44 [1.29; 1.62]*	
SRLCs + other measures (77 intersections)		
All crash types	0.72 [0.63; 0.81]*	0.88 [0.64; 1.21]

* Significant at the 5% level

Table 5-10 shows the different effects according to the characteristics of the intersection, for which the location inside or outside the urban area, the number of lanes on the main road and the maximum speed limit on the main road were taken into account. The road with the highest road category was selected as the main road. When several roads had the same road category, the road with the highest number of lanes or the highest legally imposed speed limit was selected. In addition to this, it was examined whether the presence of other intersections with SRLCs had an influence on the effect. In line with a definition by the Flemish Government, two groups were selected: (1) intersections that have no or one other SRLC equipped intersection within a radius of 1500 m and (2) intersections with two or more equipped intersections at that distance. Because of the contrast in effects between side and rear-end crashes, those were separately analysed.

Table 5-10 Results of the meta-analyses (index of effectiveness [95% CI]) according to the characteristics of the intersection

Characteristic			Side crashes	Rear-end crashes
Inside /outside urban area	Inside	95	1.14 [0.98; 1.33]	1.70 [1.39; 2.08]*
	Outside	158	0.82 [0.72; 0.93]*	1.33 [1.16; 1.53]*
Number of lanes	1	71	0.89 [0.73; 1.08]	1.42 [1.10; 1.84]*
	2	153	0.93 [0.83; 1.05]	1.44 [1.26; 1.66]*
Maximum speed limit	50	68	1.06 [0.87; 1.28]	1.57 [1.22; 2.02]*
	70	85	0.97 [0.83; 1.14]	1.44 [1.19; 1.76]*
	90	94	0.83 [0.71; 0.97]*	1.38 [1.16; 1.64]*
Presence of other intersections with SRLCs within 1500 m	0 or 1	152	0.82 [0.72; 0.93]*	1.34 [1.16; 1.55]
	≥2	101	1.11 [0.96; 1.29]	1.61 [1.35; 1.93]*

* Significant at the 5% level

Maximum likelihood linear regression models (using SPSS GENLIN procedure) were fitted, in order to analyse the relationship between each of these characteristics and the effectiveness. The effect per intersection (θ_l) was selected as dependent variable, for which the natural logarithm $\ln(\theta_l)$ was calculated. The different characteristics were selected as independent variables. All these variables were dummy coded, and were given a value of 0 or 1.

The functional form of the model can be described as:

$$\ln(\theta_l) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \qquad \text{(Eq. 5-2)}$$

Where x_1, …, x_n are the independent variables and β_1,…, β_n the estimation parameters.

In a first regression-analysis, the effects on side crashes were taken into account and the four independent variables were included. The correlation matrix of the estimation parameters showed a high correlation (ρ>0.60) between the built-up variable and the first speed variable (50 km/h vs. 90 km/h) and between the built-up variable and the second speed variable (50 km/h vs. 90 km/h). The variable with the smallest contribution to the model fit was eliminated, which were the two speed variables. The results of this new model, without the speed parameters, are shown in Table 5-11. This calculation showed only one almost significant variable (parameter estimate= 0.21; p=0.065): the presence of other intersections with SRLCs. The positive sign of the estimation parameter indicates that the decrease in the number of crashes was smaller at the intersections with two or more SRLC equipped intersections within 1500 m, compared to intersections with no or only one SRLC equipped intersection within 1500 m. As shown in Table 5-11, no other significant parameters could be identified.

Secondly, a regression-analysis was applied with the effect on rear-end crashes as dependent variable. Again the correlation matrix showed a high correlation (ρ>0.60) between the built-up variable and each of the two dummy-coded speed variables. Since the speed variables had the smallest contribution to the model fit, these were eliminated. However, no significant parameters could be found in the new model (see Table 5-11).

Table 5-11 Results of the regression analyses for side crashes and rear-end crashes

Parameter	Side crashes				Rear-end crashes			
	Parameter estimate	Standard error	Chi-square	Sig.	Parameter estimate	Standard error	Chi-square	Sig.
Intercept	-0.22	0.11	4.26	0.039	0.26	0.11	5.49	0.019
Built-up area	0.19	0.12	2.66	0.103	0.17	0.12	1.93	0.165
Number of lanes	-0.01	0.12	0.02	0.902	0.02	0.12	0.04	0.848
Presence of other intersections with SRLCs within 1500 m	0.21	0.11	3.41	0.065	-0.04	0.12	0.11	0.745

Side crashes: Deviance=125.27; Df=220

Rear-end crashes: Deviance=139.47; Df=220.

In addition to the effect estimates of the crash level, an analysis on the level of casualties was carried out. Table 5-12 shows the mean number of injured road users per year, both for the treated group, and for the comparison group that includes all injured road users in Flanders. The rightmost column shows the odds ratios, which is the relative change of the number of injured road users in the treated group, compared to the relative change in the comparison group. These odds ratios show a result lower than one only for cyclists, which indicates that a higher decrease was found in the treated group compared to the comparison group. The relative change was close to, but slightly higher than one for all other road users (car occupants, moped riders, motorcyclists, pedestrians). The number of injured truck drivers was too low to analyse (on average 11.4 injured/ year).

Table 5-12 Before-and-after comparison of casualties

Type of road user	Mean number of injured road users per year						Relative change
	Treated group			Comparison group			
	Before	*After*	*Difference (%)*	*Before*	*After*	*Difference (%)*	
Car occupants	2.37	2.00	-16	11577.81	9602.86	-17	1.02
Moped riders	0.33	0.27	-18	2313.05	1766.19	-24	1.08
Cyclists	0.40	0.36	-9	2284.70	2659.22	+16	0.78
Motorcyclists	0.14	0.14	+7	1062.51	1065.20	+0.003	1.07
Pedestrians	0.09	0.11	+23	701.59	831.02	+18	1.04

5.2.6 DISCUSSION

As a result of the installation of combined SRLCs, the number of side injury crashes non-significantly decreased, but the number of rear-end injury crashes strongly increased. In addition to this, the present study examined the effect on fatal and serious injury crashes, for which an almost significant decrease of 14% was found. This can mainly be ascribed to a decrease in severe side crashes. Furthermore it was found that the installation of a SRLC together with other measures, for example the reduction of the maximum speed limit or the resurfacing of the road, resulted in a greater effect on injury crashes, compared to the isolated effect of the installation of SRLCs.

An analysis of the relation between the characteristics of a location and the effect estimation, showed no significant parameter for the rear-end crashes and only one almost significant parameter for the side crashes. The effects on side crashes were less favourable when other intersections with SRLCs were nearby. One possible explanation is that this effect correlates with other unknown variables, such as traffic volume and infrastructural characteristics, which were not taken into account in the analyses.

An effect estimation on the level of casualties showed a decrease in the number of injuries only for cyclists, whereas for the other road users (car occupants, moped riders, motor cyclists, pedestrians) a slight increase was found. The different effects on side and rear-end crashes can be a possible explanation for this result. The increasing effect on rear-end crashes may counteract the decreasing effect on side crashes. As the increase in the number of rear-end crashes mainly appears between drivers of a motorized vehicle, this can explain why for these types of road users generally no effects were found. This cannot explain why no favourable effect is found for the number of injured pedestrians. However, as can seen from Table 5-12, the number of involved pedestrians is much lower compared to the other road user categories and thus SRLCs possibly did not had any effect on the number of injured pedestrians.

The method in the present study has its limitations. It was not possible to properly control for the RTM effect since the comparison group included all crashes in Flanders and subsequently the overdispersion and thus the weight could not be calculated. No other suitable comparison group with separate locations could be selected. Subsequently the treated group was used, which might be affected by the biased selection of the SRLC intersections that could have caused RTM. Another possible option for a comparison group was the selection of the crashes that occurred at intersections, instead of using all crashes in Flanders. However, in order to select crashes that occurred at intersections in Flanders, a different selection method needs to be used, compared to the selection method for crashes in the treated group. The selection of the crashes in the treated group is based on geographical located data, for which all crashes in a radius of 50 m from the intersection centre were selected. In order to select the crashes at intersections in Flanders, geo-located data cannot be used, as there is no data layer with the geo-location of all intersections in Flanders. Therefore, the crash reporting form by the police should be used to determine whether a crash occurred at an intersection. However, we previously experienced that these different ways of selection introduce a systematic bias. A second possible option was to select the crashes at the intersections where after 2008 a SRLC was installed. It could be expected that these locations are similar to the treated locations. However, at these locations an increase could be observed in the number of crashes from 2002 to 2007, whereas the general crash trend in Flanders decreased during these years.

As the comparison group included all crashes in Flanders, subsequently also the crashes that occurred at the treated locations were included. This could have led to an underestimation of the effect, as the comparison group was partially influenced by the installation of the cameras. However, only 3.06% of all crashes in Flanders were included in the treated group. It can be expected that the inclusion of these crashes had no substantial influence on the results.

Furthermore, spillover effects were not taken into account. The installation of SRLCs could have had an effect at the nearby intersections without SRLCs. As the comparison group comprised all crashes in Flanders, spillover effects could have led to an underestimation of the effect. In a meta-analysis of Høye (2013) spillover effects were found, mainly on right-angle crashes. It was however found that the study result were not affected by the control for spillover effects. For other crash types no spillover effects were found. Vanlaar et al. (2014), who examined the effects of combined SRLCs did not found any spillover effects for right-angle crashes, but did found spillover effects for rear-end crashes. However, it should be mentioned that this was found in the first study. No significant spillover effects were found for the second, third and fourth sets of cameras in that study.

Because no data was available in relation to the frequency and duration of the operation of the cameras, it was not possible to study the relationship between the intensity of use and the effectiveness. A more in-depth research of this relationship could be interesting. Road users could for example be asked how high they think the chance is that they are controlled when passing an intersection with a SRLC, and to what extent this differs according to the intersection.

The present study analysed the effects of cameras that both detect speeding and red light running behaviour. It was however not possible to analyse whether the decrease in side crashes was mainly due to a decrease in red light running or to a reduction of the driving speed. A recent study found no effects on crashes related to speeding, but found a decrease of 46% in the number of right-angle crashes and an increase of 42% in the number of rear-end crashes, which were defined as related to red light running (Vanlaar et al., 2014). It can be stated that red light cameras (only detecting red light running) and SRLCs (detecting speeding and red light running) are two different measures. Despite the fact that for both camera types generally similar results are found (decrease in side crashes, increase in rear-end crashes), it would be interesting for future research to analyse in a more detailed manner whether there are differences between these two measures in the effects on driving behaviours and crashes.

In line with previous studies high increases were found in the number of rear-end crashes (+44%). Though these bring about less severe consequences (Garber et al., 2007), future research can help to develop measures in order to tackle this unintended effect. E.g. measures could be assessed that are intended to harmonize drivers behaviour at intersections in a way that avoids rear-end crashes. Elements that could play a role in explaining the effects on rear-end crashes are travel speed before the crash and the phase of the traffic light at the time of the crash. The hypothesis is that most rear-end crashes occur at orange phase and it causes some drivers to brake abruptly and unexpectedly. An analysis of the psychological processes that play a role in the behaviour of road users at the time they are subjected to unmanned camera surveillance could give more information. Furthermore, it could be examined to what extent the detection of travel speed has an influence on the occurrence of rear-end crashes.

5.2.7 **CONCLUSIONS**

- The installation of SRLCs generated a slight increase in the number of injury crashes. This can mainly be attributed to an increase in the number of rear-end crashes (+44%). The circumstances of this increase should be examined in future research.
- The fatal and serious injury crashes showed a favourable effect (-14%), that was largely the result of a decrease in the severe side crashes (-24%).
- A favourable effect was only found for the number of injured cyclists.

CHAPTER 6

SPEED ENFORCEMENT ON MOTORWAYS

6.1 AUTOMATED SECTION SPEED CONTROL ON MOTORWAYS: AN EVALUATION OF THE EFFECT ON DRIVING SPEED

This chapter is based on:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). Automated section speed control on motorways: An evaluation of the effect on driving speed. *Accident Analysis and Prevention, 73, 313-322*.
doi: 10.1016/j.aap.2014.09.005

Dutch report:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014).
Snelheidscamera's en trajectcontrole op Vlaamse autosnelwegen. Evaluatie van het effect op snelheidsgedrag en verkeersveiligheid. Diepenbeek:
Instituut voor Mobiliteit.

6.1.1 INTRODUCTION

Excessive and inappropriate speed is the major road safety problem in many countries (OECD, 2006). Speed limits, which provide information to the drivers about the safe speed to travel in average conditions, are often exceeded. Excessive speed is a widespread social problem, which affects the entire road network: urban roads, rural roads, main highways and motorways. Speeding concerns all types of motor vehicles and all groups of road users (OECD, 2006). According to the SARTRE 3 survey, which provides information on self-reported speeding behaviour of drivers in Europe, the highest numbers of speed violations occur on motorways. Twenty-eight 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). In Flanders, Belgium, the crash risk on motorways is lower compared to other roads, but the severity of the crashes is the highest on these road types: 25.2 deaths per 1000 injury crashes (Carpentier & Nuyttens, 2013). Belgian drivers are more tolerant of speeding on motorways compared to other roads (Boulanger, Dewil, & Silverans, 2011). The average speed of passenger cars is 117.1 km/h, and the 85^{th} percentile speed is 130 km/h (Riguelle, 2012b). This average speed is the highest compared to other European countries that have a speed limit of 120 km/h (Finland, the Netherlands, Ireland, Switzerland) and is even higher compared to France, which has a speed limit of 130 km/h on motorways (Riguelle, 2012b).

In order to tackle this problem, authorities can decide to apply some kind of automated speed enforcement, which generally includes three types of enforcement: fixed speed cameras, mobile speed cameras and average speed control (Thomas, Srinivasan, Decina, & Staplin, 2008).

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, Watson, & Fleiter, 2013). In addition, the police use this system for the identification of unlicensed or uninsured drivers and tracking of stolen vehicles.

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.

6.1.2 LITERATURE REVIEW

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 (Soole et al., 2013). 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, Punzo, & Montanino, 2012). 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, Sorvillo, & Punzo, 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 further 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 as in 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.

6.1.3 METHOD

6.1.3.1 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.

6.1.3.2 STUDY AND COMPARISON LOCATIONS

At the Flemish motorways, four locations are currently equipped with ASSC. Two are situated 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 that were included in the present study are located at the E40, which runs from the north-west of the country to the southeast 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 seconds 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=4000m. 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 was heavy goods 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, but are however 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.

6.1.3.3 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 control for the general trend effect, two regression models were applied. The effect on the average speed was analysed through a linear regression model; 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 with binomial distribution and logit link function. The formulas that were used in this study can be found in chapter 2.3.

6.1.3.4 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.
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. This 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 6-1 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.

Table 6-1 Average number of vehicles per measurement point, included in this study

		Before	After
Direction of Brussels	Traffic condition A	213,113	2093,29
	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

6.1.3.5 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.

6.1.4 RESULTS

6.1.4.1 FREE-FLOW TO CONDITIONED FLOW (TRAFFIC CONDITION A)

Figure 6-1 to Figure 6-3 display 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. Figure 6-1 and Figure 6-2 show the speeds on the section in each of the two directions, from which 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 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. Furthermore, 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 Figure 6-3) 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 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.

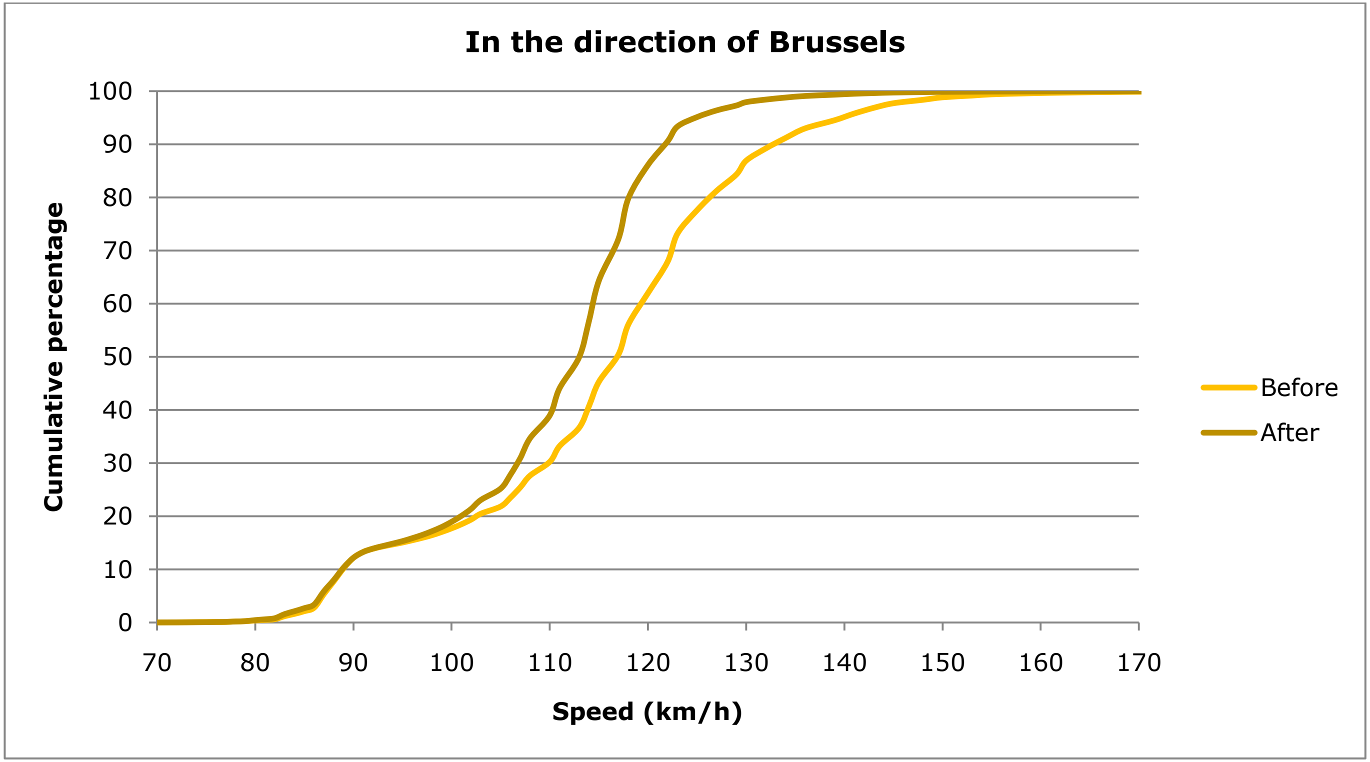


Figure 6-1 Cumulative speed distribution on the ASSC in the direction of Brussels during traffic condition A

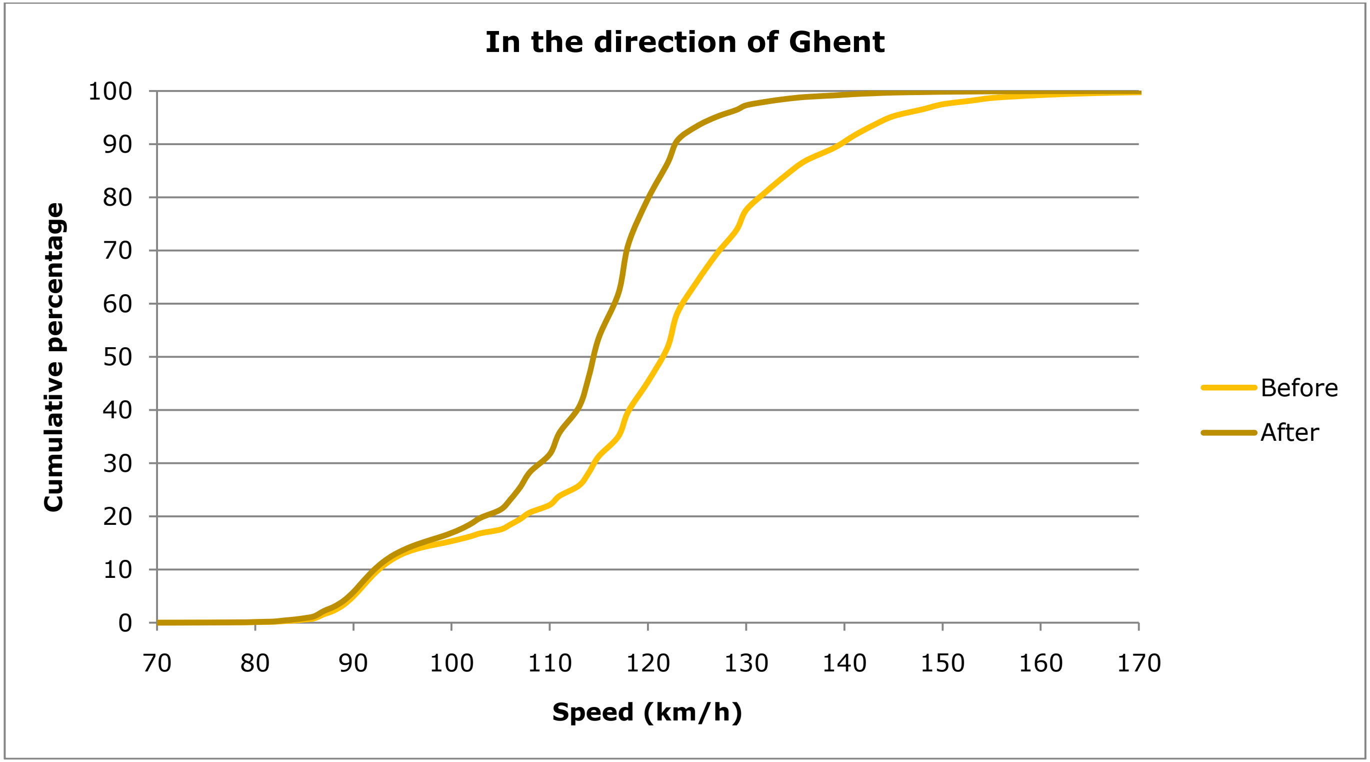


Figure 6-2 Cumulative speed distribution on the ASSC in the direction of Ghent during traffic condition A

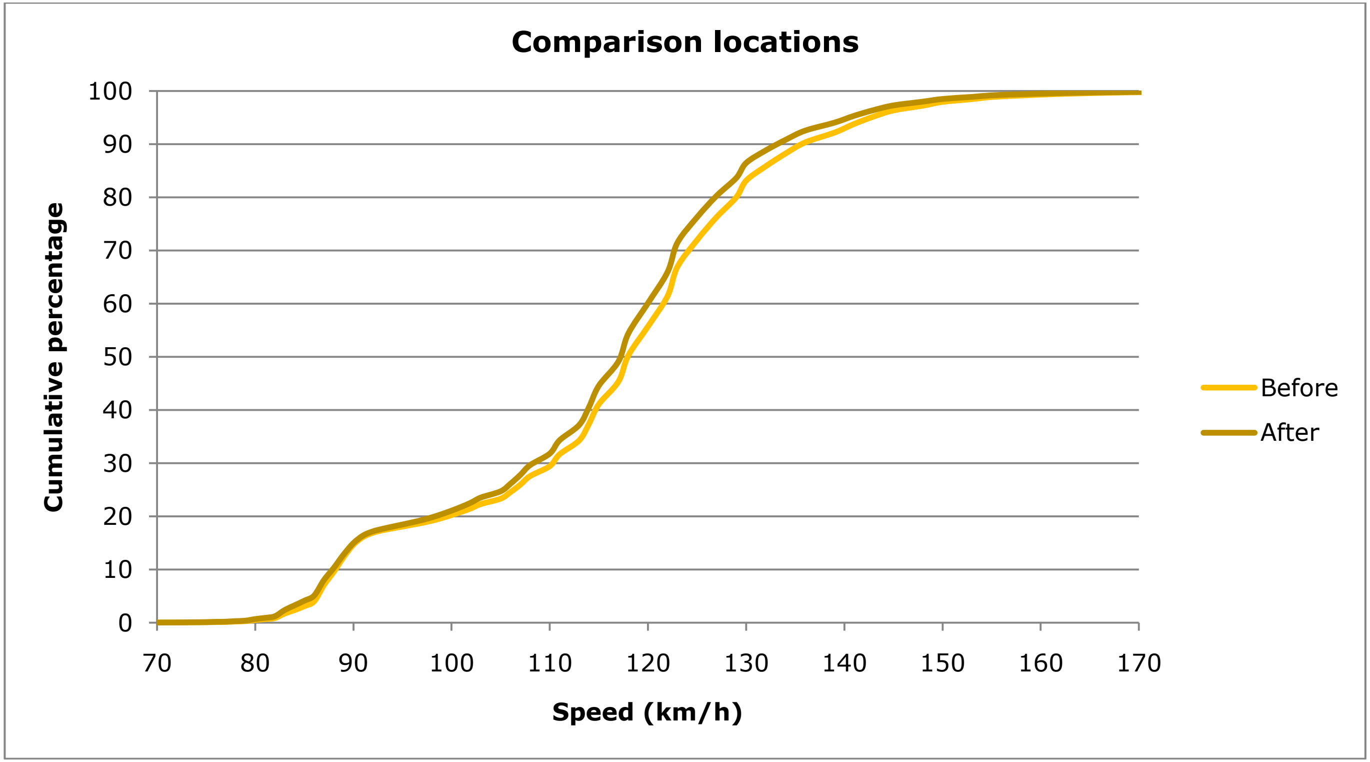


Figure 6-3 Cumulative speed distribution on the comparison locations during traffic condition A

Figure 6-4 and Figure 6-5 show 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 6-2).

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 6-2). At 2.3 km downstream from the exit the speed decreased by 6.59 km/h. Also upstream 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. Also high decreases were found at the locations upstream (-62% and -78%) and downstream (-74%) from the enforced section.

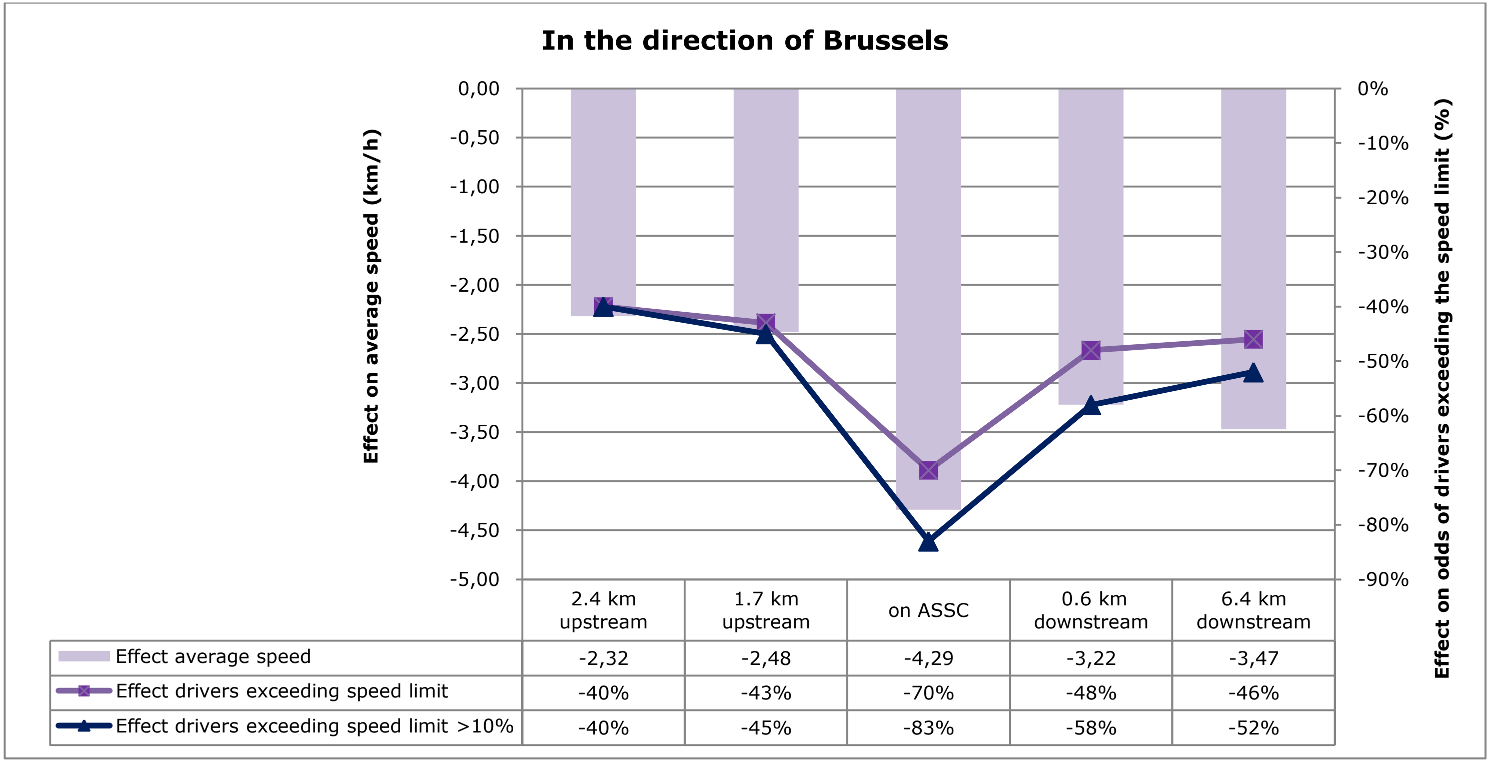


Figure 6-4 Graphical display of the speed effects during traffic condition A at the different measurement points in the direction of Brussels as a result of the installation of ASSC

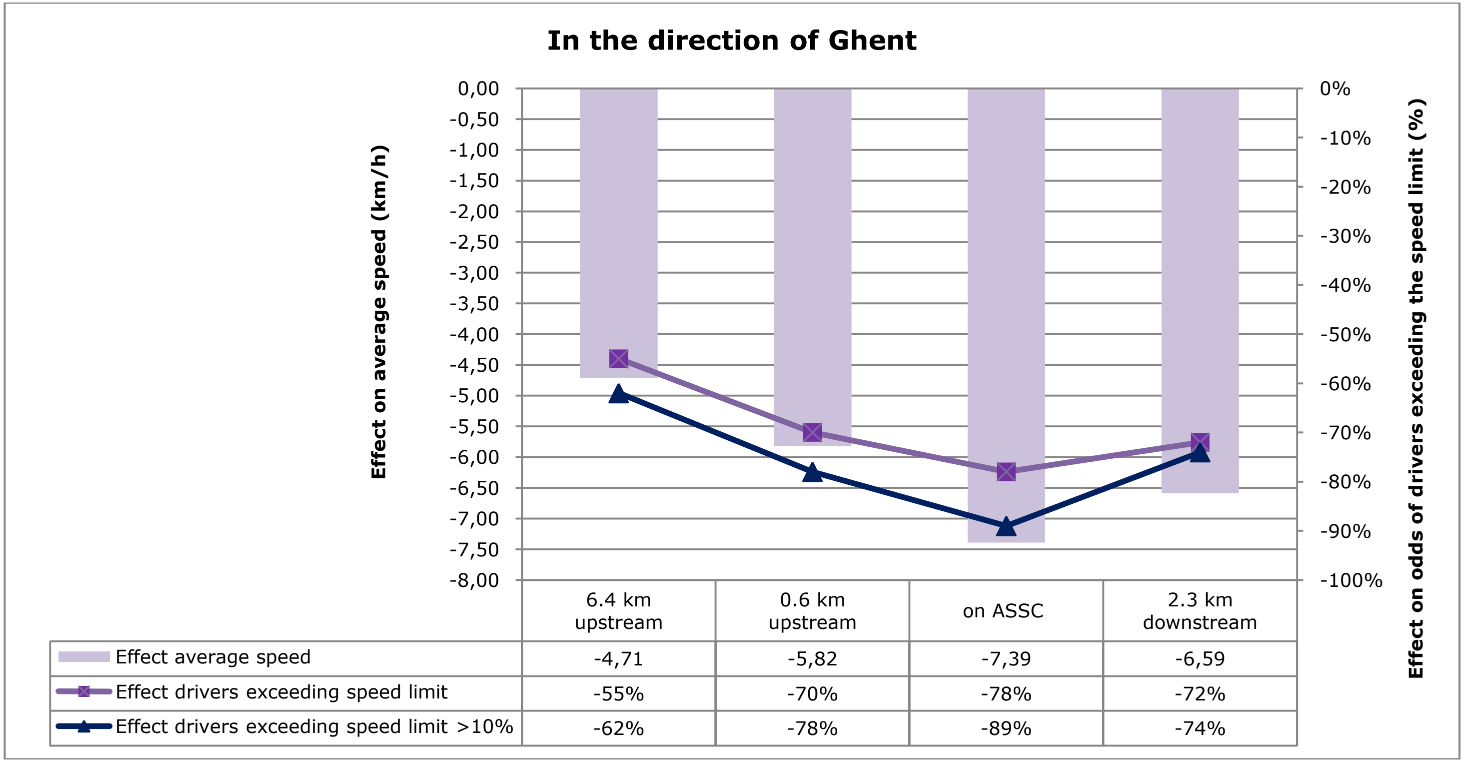


Figure 6-5 Graphical display of the speed effects during traffic condition A at the different measurement points in the direction of Ghent as a result of the installation of ASSC

Table 6-2 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 Effect[a] [95% CI][b]	Effect on odds of drivers exceeding the speed limit Effect[c] [95% CI][d]	Effect on odds of drivers exceeding the speed limit >10% Effect[c] [95% CI]
	In the direction of Brussels		
2.4 km upstream	-2.32 [-2.42; -2.23]*	0.60 [0.59; 0.61]*	0.60 [0.58; 0.61]*
1.7 km upstream	-2.48 [-2.57; -2.38]*	0.57 [0.57; 0.58]*	0.55 [0.54; 0.57]*
On ASSC	-4.29 [-4.38; -4.19]*	0.30 [0.30; 0.31]*	0.17 [0.17; 0.18]*
0.6 km downstream	-3.22 [-3.33; -3.11]*	0.52 [0.51; 0.53]*	0.42 [0.41; 0.43]*
6.4 km downstream	-3.47 [-3.56; -3.37]*	0.54 [0.53; 0.54]*	0.48 [0.47; 0.49]*
	In the direction of Ghent		
6.4 km upstream	-4.71 [-4.80; -4.62]*	0.45 [0.44; 0.46]*	0.38 [0.37; 0.39]*
0.6 km upstream	-5.82 [-5.91; -5.73]*	0.30 [0.29; 0.30]*	0.22 [0.22; 0.23]*
On ASSC	-7.39 [-7.49; -7.29]*	0.22 [0.22; 0.22]*	0.11 [0.11; 0.12]*
2.3 km downstream	-6.59 [-6.69; -6.50]*	0.28 [0.28; 0.29]*	0.26 [0.25; 0.27]*

[a] Calculated through the interaction effect of Eq. 2-29, using SPSS GENLIN models.
[b] Calculated through the Wald confidence intervals (SPSS GENLIN models) with next formula: $\hat{\beta}_j \pm z_{1-\alpha/2}\hat{\sigma}_{\beta_j}$ where z_p is the 100pth percentile of the standard normal distribution (IBM, 2011)
[c] Calculated through the interaction effect of Eq. 2-30, 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: $\exp(\hat{\beta}_j \pm z_{1-\alpha/2}\hat{\sigma}_{\beta_j})$ (IBM, 2011)
* Significant at the 5% level

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 Figure 6-1 and Figure 6-2 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.

6.1.4.2 Conditioned flow to congested flow (traffic condition B)

Table 6-3 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 6-2, 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 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 1.7 km upstream, 8,790 on the ASSC, 8,542 0.6 km downstream and 1,922 6.4 km downstream. These lower absolute rates can subsequently lead to higher relative differences.

Table 6-3 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[a]	Effect on odds of drivers exceeding the speed limit[b]	Effect on odds of drivers exceeding the speed limit >10%[c]
	Effect [95% CI]	Effect [95% CI]	Effect [95% CI]
	In the direction of Brussels		
2.4 km upstream	1.04 [0.68; 1.39]*	0.55 [0.53; 0.57]*	0.58 [0.54; 0.64]*
1.7 km upstream	0.27 [-0.10; 0.64]	0.55 [0.53; 0.57]*	0.55 [0.51; 0.59]*
On ASSC	1.69 [1.36; 2.03]*	0.26 [0.25; 0.27]*	0.14 [0.13; 0.16]*
0.6 km downstream	4.19 [3.70; 4.69]*	0.50 [0.48; 0.52]*	0.45 [0.42; 0.49]*
6.4 km downstream	-17.24 [-17.91; -16.57]*	0.27 [0.26; 0.29]*	0.23 [0.20; 0.26]*
	In the direction of Ghent		
6.4 km upstream	0.40 [-0.17; 0.95]	0.43 [0.41; 0.45]*	0.44 [0.40; 0.49]*
0.6 km upstream	0.43 [0.05; 0.82]*	0.28 [0.27; 0.29]*	0.22 [0.20; 0.24]*
On ASSC	0.30 [-0.05; 0.64]	0.21 [0.20; 0.22]*	0.08 [0.07;0.09]*
2.3 km downstream	2.62 [2.14; 3.10]*	0.89 [0.86; 0.92]*	1.00 [0.94; 1.06]

* Significant at the 5% level

6.1.4.3 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 data were included. As can be seen from Table 6-4, the results are close to the results of the analyses with traffic condition A, but the decreases in the average speed are smaller. 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.

Table 6-4 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	Effect on odds of drivers exceeding the speed limit	Effect on odds of drivers exceeding the speed limit >10%
	Effect [95% CI]	Effect [95% CI]	Effect [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

6.1.5 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 6-5 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. 2-31). With 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.

Table 6-5 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]*

	Direction of Brussels			Direction of Ghent		
	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

6.1.6 EFFECT ON SPEED VARIANCE

Furthermore, also the speed variances were compared from before to after the installation of ASSC. Also for these analyses, data from traffic condition A were selected. Table 6-6 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.

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

	Direction of Brussels	
	Before	After
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	
	Before	After
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	
	Before	After
	13.57	13.15

In Table 6-7 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 periods. Furthermore, no clear differences were found according to the time period.

Table 6-7 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

6.1.7 **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 period 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 odds 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. In addition, 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. However 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 & 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 spots upstream 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, Punzo, & Montanino, 2011; Soole et al., 2013).

A comparison of the effect according to time showed slightly higher effects during the week compared to the weekend, and slightly higher effects during the night compared to the day. The differences are however small. A comparison between off-peak and peak hours showed higher effects during the peak hours.

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 were 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.

It was not possible to analyse the effects on the number of crashes, because of the short after period. Previous research generally found favourable effects for all crash types, especially for the most severe crashes (Soole et al., 2013; Montella, Persaud, D'Apuzzo, & Imbriani, 2012). 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 had an influence on the driving speed. However, in order to control for these confounding variables the comparison locations 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 Figure 6-3, 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 spillover effects, which should be taken into account in the selection of the comparison locations. However, it should be noted that this spillover effect might partly be attributable to the unclear location of the starting and the ending point of the section. In addition, we only found these spillover 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 spillover 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 6-8). These analyses showed that speeds are relatively homogenous 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.

Table 6-8 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 > 10%	9.3%	1.8%	1.3%

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.

6.1.8 **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.

6.2 Behavioural effects of fixed speed cameras on motorways: Overall improved speed compliance or kangaroo jumps?

This chapter is based on:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). Behavioural effects of fixed speed cameras on motorways: Overall improved speed compliance or kangaroo jumps? *Accident Analysis and Prevention, 73*, 132-140. doi: 10.1016/j.aap.2014.08.019

Dutch report:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). *Snelheidscamera's en trajectcontrole op Vlaamse autosnelwegen. Evaluatie van het effect op snelheidsgedrag en verkeersveiligheid*. Diepenbeek: Instituut voor Mobiliteit.

6.2.1 INTRODUCTION

As explained in chapter 6.1, excessive speed is a major traffic safety problem at all road types, also at roads with a higher speed limit, such as motorways. Whereas in chapter 6.1 the behavioural effects of automated section speed control were studied, the effects of the other fixed speed enforcement system, namely speed cameras, are studied in the present chapter. Previous studies mainly analysed the effects at the camera location, but the present study also analysed the effects at the locations at a greater distance upstream and downstream of the camera. The objective hereof was examine whether effects, if present, are merely local (at the spot of the camera) or do extend to a wider area.

6.2.2 LITERATURE REVIEW

An extensive research in Great Britain analysed the effect of 502 fixed speed cameras on both speed and crashes (Gains, Nordstrom, Heydecker, & Shrewsbury, 2005). At roads with a speed limit of 50-70 mph (≈ 80-104 km/h), the installation of speed cameras resulted in an average speed decrease of 5.3 mph (≈ 8.5 km/h). The proportion of drivers breaking the speed limit, decreased by 51%. The proportion of drivers speeding excessively (more than 15 mph) fell by 62%. These authors however applied a simple before-and-after study, without controlling for other factors that could have influenced the driving speed. Makinen (2001) applied a before-and-after study with a comparison group, and analysed the effect of 12 speed cameras at a motorway in the direction of Helsinki, with a speed limit of 80-100 km/h. At the road sections with a speed limit of 80 km/h, the number of drivers exceeding the speed limit decreased by 8% during the first year, with a further decrease of 2% during the second year. At the roads with a speed limit of 100 km/h, the speeding rate decreased by 5% during the first year, with a further decrease of 2% during the second year. Also, Retting, Kyrychenko and McCartt (2008) applied a before-and-after study with a comparison group and examined the effect of six speed cameras at a motorway in a 9-month pilot programme. Those speed cameras were sited on an 8-mile stretch of a freeway in Arizona with a speed limit of 65 mph (≈ 105 km/h). The average speed decreased from 70 mph (≈ 113km/h) before the installation of the cameras to 63 mph (≈ 101 km/h) six weeks after the installation, and 65 mph (≈ 105 km/h) five months after the installation. The odds of drivers that exceeded the speed limit by more than 10 mph decreased by 88%. Liu, Zhang, Wang and Xu (2011) examined the effect of speed cameras at different distances from these cameras. They included seven locations in Nanjing, China. The results showed no effect at 1 km upstream and downstream of the camera. They found that drivers suddenly braked at about 400-300 m before the camera and accelerated again from about 300-400 m after the camera.

6.2.3 METHOD

6.2.3.1 DESIGN

In order to analyse the speed effect of speed cameras, a quasi-experiment was set up. Two locations on motorways were selected at which the government planned to install a speed camera. Speed data were recorded during the research period of the present study. The recorded speed data during the before period were compared with the speed data during the after period, i.e. the period after the installation of the camera. 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 to the treated locations on traffic volume and types of passing vehicles but differed in that there were no speed cameras.

6.2.3.2 STUDY AND COMPARISON LOCATIONS

Two locations on motorways were selected (a definition of motorways can be found in chapter 6.1). Eligible locations were: (1) E19 at Brasschaat in the direction of Antwerp, which is a two-lane motorway, and (2) E40 at Boutersem in the direction of Liège, a three-lane motorway. The posted speed limit at both locations is 120 km/h. The cameras were installed in November 2011. Speed data were collected 13 months before (October 2010) and 10 months after the installation (September 2012) at the Brasschaat site, and 11 months before (December 2010) and 18 months after the installation (May 2013) at the

Boutersem site. Speed data were collected for one week during the before period and one week during the after period.

At each of the motorways, speed data were collected at five locations. These measurement points were for both roads located at similar distances from the camera:

- 3 km upstream (Brasschaat site) – 2.5 km upstream (Boutersem site)
- at the information sign (0.25 km upstream [Brasschaat site] and 0.70 km upstream [Boutersem site])
- at the speed camera
- 1 km downstream
- 3.3 km downstream (Brasschaat site) – 3.8 km downstream (Boutersem site)

For the first and last measurement point, it was not possible to select the same distance from the camera for both motorways, as there were certain restrictions on the locations where the TIRTL devices could be installed (for more information on the TIRTL devices, see 6.2.3.3). It was for example impossible to install these devices close to entry or exit lanes.

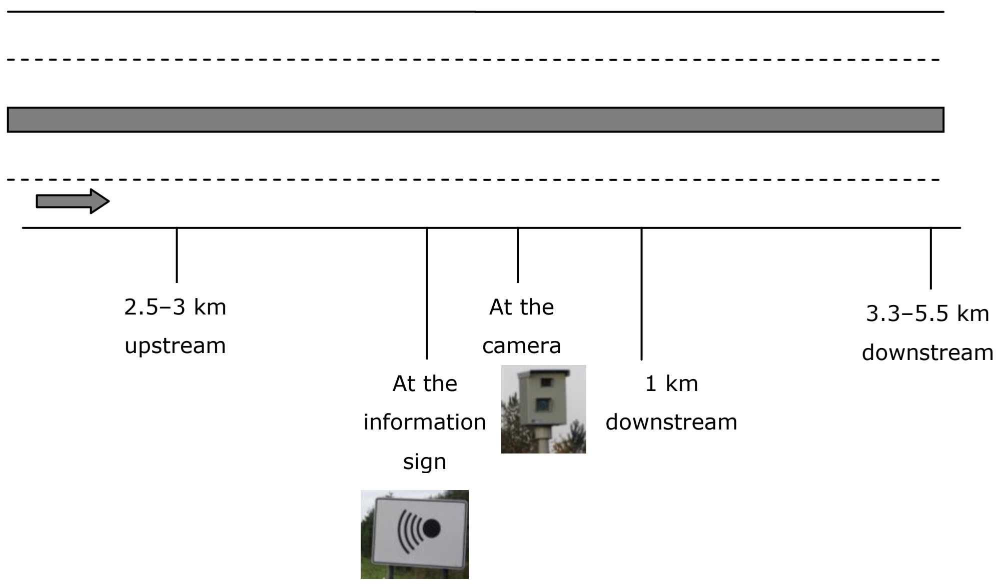


Figure 6-6 Measurement points at different distances from the camera

Next to the treated locations, comparison locations were selected in order to control for other factors that could have had an effect on the driving speed, such as weather and seasonal factors and other more general implemented traffic safety measures. For the Brasschaat site, two comparison locations were selected: one on the same road but in the other direction and about 25 km away from the speed camera and one on a road that also leads to the city of Antwerp (motorway E17). For the Boutersem site, one comparison location was selected on the same road, 15 km away from the speed camera.

6.2.3.3 Data collection

Speed data were gathered through the Infra-Red Traffic Logger (TIRTL). The TIRTL consists of a receiver unit and a transmitter unit placed on opposite sides of the road. The transmitter sends two beams of infrared light parallel to the surface of the road, perpendicular to the direction of the traffic and below the vehicle body. Speed is determined by measuring the time taken to break or re-form each of the two parallel beams and using the known beam separation. It can be stated that drivers' behaviour was not influenced by the presence of the TIRTL, as this equipment was installed at the roadside and was largely invisible because of the high grass. In the central reservation, the installation was somewhat visible.

At the comparison location for the Boutersem site, problems occurred during the data collection in the after period and these data could not be used. However, in order to control for weather conditions, it was necessary to gather data at the comparison locations during the same period as the data gathering at the treated locations. Therefore another device was used in order to gather speed data, namely double inductive loops embedded in the pavement (see also chapter 6.1). These loops are present on slopes and at interchanges between motorways. The loops are managed by a government agency, and the data measured by these loops are frequently controlled. A comparison of the outcomes of the TIRTL with the outcomes of the inductive loops showed equal results, which proved the accuracy of both methods. Both installations gathered speed information per vehicle. As an extra control, a second comparison group was selected for the Brasschaat site, at which speed data were collected through the loops.

6.2.3.4 Selection of free flow moments

In order to make an accurate evaluation of the effect of speed cameras through a before-and-after comparison, only the moments were included at which drivers were free to choose their speed. For this reason, the moments with busy traffic were excluded. 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 passenger cars per minute and the average speed was higher than 80 km/h were included. This mainly corresponds to an LOS A, B and a small part of C (see Figure 6-7). The majority of the time LOS A and B will have been present. LOS A can be defined as free flow; LOS B represents reasonably free-flow, and free flow speeds are maintained. LOS C can be defined as the speeds that are close to free flow but the freedom to manoeuvre is more limited and requires more attention from the driver (Transportation Research Board, National Research Council, 2010). Despite the fact that the moments we selected were not entirely free flow, it are moments that most drivers could choose their own speeds.

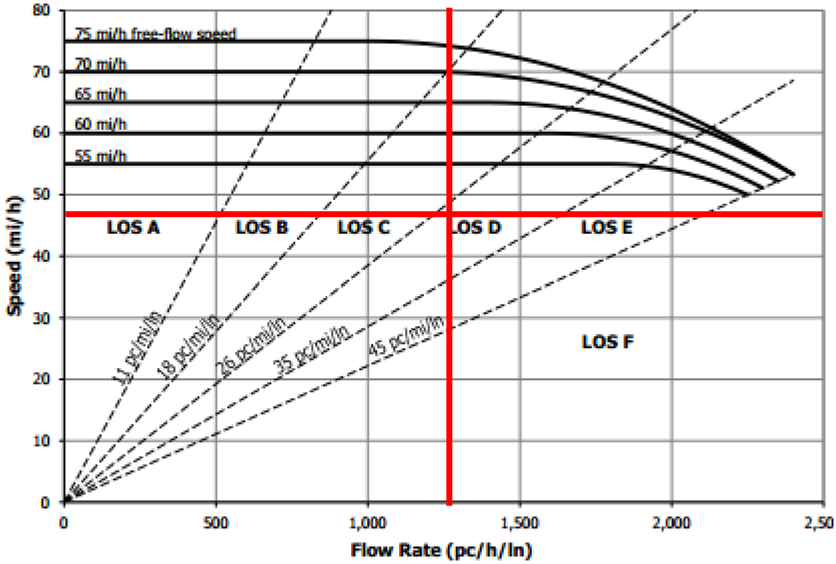


Figure 6-7 Only the vehicles from the upper left corner of the figure were included.

Table 6-9 shows the number of vehicles per location that were included in the research. It should however be mentioned that the camera at the E19 is located close to the ring road of Antwerp. This means that the measurement points at 1 km and 3.5 km downstream from the camera are located on this ring road, which explains why the number of vehicles is clearly higher at these locations compared to the other measurement points. The posted speed limit at all these locations is 120 km/h.

Table 6-9 Number of vehicles included in the study

	E19 Brasschaat		E40 Boutersem	
	Before	After	Before	After
3–2.5 km upstream	138,117	149,571	171,448	178,942
At the information sign	137,348	155,819	168,883	178,178
At the speed camera	147,025	164,184	173,071	179,479
1 km downstream	249,687	314,577	172,151	179,629
3.3–3.8 km downstream	194,240	244,139	134,914	146,860
Comparison location(s)	385,241	386,513	174,856	182,340

6.2.3.5 DATA ANALYSIS

The present study analysed the effect of speed cameras on speed behaviour. Three outcomes were measured:

- Effect on average speed
- Effect on the odds of drivers exceeding the speed limit (> 120 km/h)
- Effect on the odds of drivers exceeding the speed limit by more than 10% (> 132 km/h)

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

Regression models were applied in order to analyze whether the presence of a speed camera (independent variable) had an effect on the driving speed (dependent variable). The formulas that were used in this study are similar to the formulas used in the evaluation of automated section speed control, and can be found in chapter 2.3.

6.2.4 **RESULTS**

6.2.4.1 DESCRIPTIVE STATISTICS

Table 6-10 shows the descriptive statistics of the speeds that were measured at the five measurement points of each of the two locations and at the comparison locations, during both the before period and the after period. At the speed camera at the Brasschaat site the average speed, the standard deviation of speed and the proportion of drivers exceeding the speed limit (i.e. the number of drivers exceeding the speed limit on the total number of drivers) clearly decreased. At the locations upstream and downstream from the camera, an increase in the average speed and the proportion of vehicles exceeding the speed limit could be observed, except for the location at 3.3 km downstream. The standard deviation slightly decreased at all these locations. At the comparison location of the Brasschaat site a slight, however limited, decrease was found from the before to the after period.

At 2.5 km upstream and 3.8 km downstream of the Boutersem site slight increases were found in all the variables. At the other locations, decreases were found, with clear effects at the speed camera location. It should however be noted that an increase is found at the comparison location.

An analysis of the average speeds and proportion of drivers exceeding the speed limit (>10%) during the after period clearly shows the lowest speeds and speed limit violations at the speed camera. At the Brasschaat site, only 3% of the drivers drove faster than 120 km/h, whereas this proportion was 12% at the Boutersem site. Nevertheless, it should be noted that the proportion of drivers exceeding the speed limit before the installation was clearly higher at the

Boutersem site (40%) compared to the Brasschaat site (14%). The proportion of drivers speeding excessively after the installation of the camera reduced to a very low number. At the Brasschaat site, only 642 vehicles exceeded the speed limit of 132 km/h, which is equal to less than one percent of the total number of vehicles that were included in the study. At the Boutersem site, 2% of the drivers exceeded the speed limit of 132 km/h.

Table 6-10 Descriptive statistics (average speed (standard deviation of speed) in km/h; proportion of drivers exceeding the speed limit; proportion of drivers exceeding the speed limit >10%) during the before and the after period

	E19 Brasschaat		E40 Boutersem	
	Before	After	Before	After
3–2.5 km upstream	107.75 (16.81)	110.03 (16.49)	119.6 (16.55)	120.09 (16.52)
	21%	26%	49%	50%
	5%	6%	18%	19%
At the information sign	106.67 (16.09)	109.17 (16.01)	120.59 (17.25)	118.17 (15.80)
	20%	24%	53%	44%
	4%	5%	21%	15%
At the speed camera	105.07 (15.00)	100.21 (12.64)	116.55 (16.37)	110.03 (11.56)
	14%	3%	40%	12%
	3%	0%	14%	2%
1 km downstream	100.51 (14.47)	103.11 (14.10)	114.95 (16.95	114.27 (15.62)
	8%	10%	37%	33%
	2%	2%	13%	10%
3.3–3.8 km downstream	105.87 (13.92)	105.09 (13.76)	117.09 (16.88)	119.02 (17.31)
	14%	12%	42%	47%
	3%	2%	15%	18%
Comparison locations	113.72 (18.83)	113.19 (18.84)	112.37 (16.27)	114.28 (16.45)
	41%	39%	28%	32%
	13%	12%	9%	11%

6.2.4.2 Effect on average speed

The effects on the average speed, i.e. the difference in speed from before to after the installation of speed cameras, taking the general trend effects into account, are graphically displayed in Figure 6-8; more detailed results are shown in Table 6-11. At the speed camera in Brasschaat, decreases were found of 4.33 km/h as a result of the installation of speed cameras. The other locations upstream and downstream showed increases in the average speed, which was 2.81 km/h at 3 km upstream, 3.03 km/h at the information sign and 3.13 km/h at 1 km downstream. No substantial effects were found 3.3 km downstream.
In Boutersem, on the other hand, only decreases were found. These effects became higher when closer to the speed camera. At 2.5 km upstream, a decrease of 1.42 km/h could be assessed. At the information sign, the average speed decreased by 4.33 km/h. At the speed camera, a decrease of 8.44 km/h was found. The speed decreased by 2.60 km/h 1 km after the camera. More than 3 km downstream, no significant effect was found.

In Figure 6-8, a clear V-shape can be observed for both treated roads, with a decrease in the average speed at the speed camera. The decrease in the average speed at the speed camera was more limited in Brasschaat, and an increase was found at the two locations upstream from the camera and at 1 km downstream. A further analysis of the collected speeds during the before period, clearly showed strong differences between the two roads, with higher average speeds at the Boutersem site compared to the Brasschaat site (see Table 6-10). At the speed camera in Brasschaat, the average speed during the before period was 105.07 km/h, while at the Boutersem site, this was 116.55 km/h. Despite the fact that higher decreases were found at the camera in Boutersem, the average speeds in the after period remained higher at this site (100.21 km/h at the Brasschaat site compared to 110.03 km/h at the Boutersem site). The same phenomenon can be found at the measurement points upstream and downstream from the camera.

Furthermore, high differences in the average speed could be observed between the speed camera location and the locations near to the speed camera. This was the case for both motorways and was clearly higher during the after period compared to the before period. At the Brasschaat site, there was a difference of

8.96 km/h between the speeds that were measured at the information sign (which is located at 0.25 km upstream from the camera) and at the speed camera. Furthermore, a difference of 2.9 km/h was found between the speed camera location and the measurement point 1 km downstream (see Table 6-10). For the Boutersem site, these differences were respectively 8.14 km/h and 4.24 km/h.

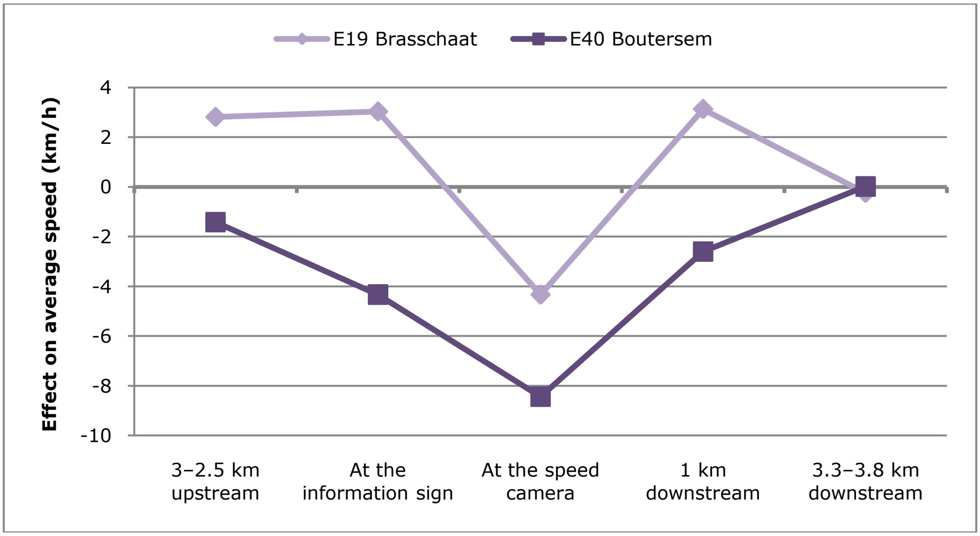


Figure 6-8 Effects on the average speed (in km/h)

Table 6-11 Detailed results of the effects on the average speed

	E19 Brasschaat Effect (km/h) [95% CI]	E40 Boutersem Effect (km/h) [95% CI]	Average effect for Brasschaat and Boutersem (km/h)
3–2.5 km upstream	+2.81 [2.66; 2.97]*	-1.42 [-1.58; -1.27]*	+0.70
At the information sign	+3.03 [2.88; 3.19]*	-4.33 [-4.49; -4.18]*	-0.65
At the speed camera	-4.33 [-4.47; -4.18]*	-8.44 [-8.58; -8.29]*	-6.39
1 km downstream	+3.13 [3.02; 3.25]*	-2.60 [-2.75; -2.45]*	+0.27
3.3–3.8 km downstream	-0.24 [-0.37;-0.12]*	+0.02 [-0.15; 0.18]	-0.11

* Significant at the 5% level

6.2.4.3 Effect on the odds of drivers exceeding the speed limit

Figure 6-9 and Table 6-12 show the effect on the odds of drivers exceeding the speed limit of 120 km/h. At the speed camera in Brasschaat, the odds of drivers that exceeded the speed limit decreased by 77% (see Table 6-12). Furthermore, 3.3 km downstream a small decrease was found (-8%). The odds of drivers exceeding the speed limit increased at the three other locations. At 3 km upstream and at the information sign, these increases were 39% and 34% respectively. At 1 km downstream, this was +33%.

At the Boutersem site a clear decrease was found at the speed camera (-83%). Also at the other measurement points decreases were found: from 15% 2.5 km upstream, over 41% at the information sign, to 32% 1 km downstream. No significant difference was found 3.8 km downstream. Consequently, also in this case a clear V-shaped profile was found.

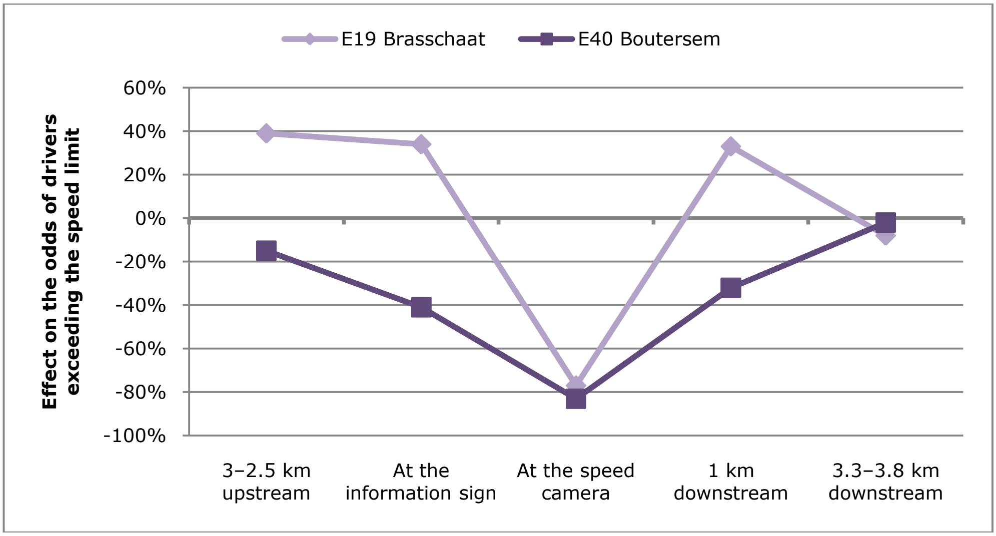


Figure 6-9 Effect on the odds of drivers exceeding the speed limit

Table 6-12 Detailed results of the effects on the odds of drivers exceeding the speed limit

	E19 Brasschaat Effect [95% CI]	E40 Boutersem Effect [95% CI]	Average effect Braschaat and Boutersem
3–2.5 km upstream	1.39 [1.36; 1.42]*	0.85 [0.84; 0.87]*	1.12
At the information sign	1.34 [1.31; 1.37]*	0.59 [0.58; 0.60]*	0.97
At the speed camera	0.23 [0.22; 0.23]*	0.17 [0.165; 0.17]*	0.20
1 km downstream	1.33 [1.31; 1.36]*	0.68 [0.67; 0.70]*	1.01
3.3–3.8 km downstream	0.92 [0.91; 0.94]*	0.98 [0.96; 1.00]	0.95

* Significant at the 5% level

6.2.4.4 Effect on the odds of drivers exceeding the speed limit by more than 10%

The effect on the odds of drivers exceeding the speed limit by more than 10% is shown in Figure 6-10 and Table 6-13. At the speed camera in Brasschaat, the odds of drivers exceeding the speed limit of 132 km/h decreased by 85%. Also at 3.3 km downstream, a decrease was found, which was however limited (-8%). At the other locations, an increase was found.

At the Boutersem site, only decreases were found, except at 3.8 km downstream, where a slight increase could be analysed (+6%). At 2.5 km upstream, the odds of drivers exceeding the speed limit of 132 km/h decreased by 12%. At the information sign, this decrease was -44%. At the speed camera, the highest decrease was found (-88%). A more limited effect was found 1 km downstream (-35%). Again, a clear V-profile could be observed in the effect over the different measurement points.

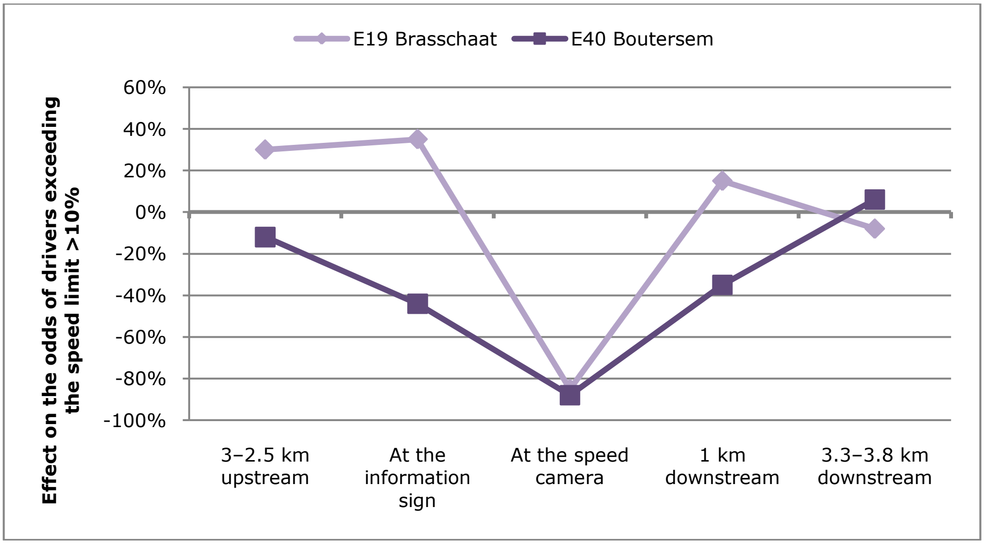


Figure 6-10 Effects on the odds of drivers exceeding the speed limit by more than 10%

Table 6-13 Detailed results of the effects on the odds of drivers exceeding the speed limit by more than 10%

	E19 Brasschaat Effect [95% CI]	E40 Boutersem Effect [95% CI]	Average effect Braschaat and Boutersem
3–2.5 km upstream	1.30 [1.25; 1.34]*	0.88 [0.86; 0.90]*	1.09
At the information sign	1.35 [1.30; 1.40]*	0.56 [0.54; 0.57]*	0.96
At the speed camera	0.15 [0.14; 0.16]*	0.12 [0.11; 0.12]*	0.14
1 km downstream	1.15 [1.10; 1.20]*	0.65 [0.63; 0.67]*	0.90
3.3–3.8 km downstream	0.92 [0.88; 0.96]*	1.06 [1.03; 1.09]*	0.99

* Significant at the 5% level

6.2.4.5 Comparison according to time

Table 6-14 shows the results of the effects according to the time of the week (week/weekend) and the time of the day (day/night; peak/off-peak). Columns 2, 3, 5 and 6 show the difference in the average speed and in the odds of drivers exceeding the speeds of 120 km/h and 132 km/h. Columns 4 and 7 show the results of the regression model in which the time variable was included as the third independent variable, and a three-way interaction model was applied (see Eq. 2-31). 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 this comparison, only the speed data that were measured at the speed camera locations were used.

A comparison of week and weekend showed for all outcomes (average speed, drivers exceeding the speed limit of 120 km/h and 132 km/h) higher effects during the week, compared to the weekend. Only for the average speed at the Brasschaat site the effects were higher during the weekend. The differences were however small. A comparison of the effect during the day and the night generally showed higher effects during the day. At the Boutersem site, a difference of 3 km/h in the average speed effect could be found between both moments. The effect on the average speed at the Brasschaat site was however higher during the night, where a difference of 1.80 km/h was found. Furthermore, higher effects were found during peak moments compared to off-peak hours. The differences were smaller again. Also for this comparison, the effect on the average speed at the Brasschaat site was an exception, at which higher effects were found during off-peak hours.

Table 6-14 Effect according to time of the week (week/weekend) and time of the day (day/night and off-peak/peak) (effect [95% confidence interval])

	E19 Brasschaat			E40 Boutersem		
	Week	Weekend	Week vs. weekend	Week	Weekend	Week vs. weekend
Average speed	-3.66 [-3.85; -3.48]*	-5.09 [-5.31; -4.87]*	-1.43 [-1.74; -1.12]*	-8.65 [-8.82; -8.48]*	-7.79 [-8.05; -7.52]*	0.86 [0.54; 1.19]*
Drivers exceeding speed limit	0.19 [0.18; 0.20]*	0.26 [0.25; 0.27]*	1.35 [1.27; 1.44]*	0.14 [0.14; 0.15]*	0.24 [0.23; 0.25]*	1.68 [1.60; 1.76]*
Drivers exceeding speed limit > 10%	0.12 [0.10; 0.13]*	0.19 [0.17; 0.21]*	1.62 [1.37; 1.93]*	0.09 [0.08; 0.09]*	0.19 [0.18; 0.21]*	2.25 [2.06; 2.45]*
	Day	Night	Day vs. night	Day	Night	Day vs. night
Average speed	-3.98 [-4.14; -3.82]*	-5.78 [-6.18; -5.38]*	-1.80 [-2.21; -1.40]*	-8.76 [-8.90; -8.61]*	-5.73 [-6.21; -5.24]*	3.03 [2.56; 3.49]*
Drivers exceeding speed limit	0.21 [0.20; 0.22]*	0.29 [0.27; 0.31]*	1.41 [1.31; 1.52]*	0.16 [0.15; 0.16]*	0.31 [0.29; 0.33]*	1.94 [1.80; 2.08]*
Drivers exceeding speed limit > 10%	0.11 [0.10; 0.13]*	0.24 [0.21; 0.27]*	2.09 [1.76; 2.48]*	0.11 [0.10; 0.11]*	0.21 [0.19; 0.23]*	1.93 [1.71; 2.18]*
	Off-peak	Peak	Off-peak vs. peak	Off-peak	Peak	Off-peak vs. peak
Average speed	-4.31 [-4.47; 4.16]*	-3.20 [-3.62; -2.77]*	1.12 [0.66; 1.58]*	-8.35 [-8.51; -8.18]*	-8.84 [-9.14; -8.55]*	-0.50 [-0.85; -0.15]*
Drivers exceeding speed limit	0.24 [0.23; 0.25]*	0.14 [0.13; 0.16]*	0.59 [0.52; 0.68]*	0.18 [0.18; 0.19]*	0.11 [0.11; 0.12]*	0.62 [0.59; 0.66]*
Drivers exceeding speed limit > 10%	0.16 [0.15; 0.18]*	0.06 [0.04; 0.10]*	0.39 [0.25; 0.61]*	0.13 [0.13; 0.14]*	0.05 [0.04; 0.06]*	0.38 [0.33; 0.44]*

* Significant at the 5% level

6.2.5 DISCUSSION

The present study analysed the effects of on motorways installed fixed speed cameras on the driving speed. At the camera location, strong effects were found: The average speed decreased by 6.4 km/h after the installation of a speed camera; the odds of drivers exceeding the speed limit decreased by 80%; and the odds of drivers exceeding the speed limit by more than 10% decreased by 86%. At the locations upstream and downstream from the camera, no clear effects were found. At 3–2.5 km upstream from the camera, the average speed and the odds of drivers exceeding the speed limit slightly increased (average speed: +0.70 km/h; odds of drivers exceeding the speed limit: +12%; odds of drivers exceeding the speed limit by more than 10%: +9%); at the information sign, slight decreases were found (-0.65 km/h; -3% and -4%). Downstream from the camera, no strong effects were found, not at a distance of 1 km downstream nor at 3.3–3.8 km downstream.

It is difficult to compare the results of the present study with the results of the existing literature. The roads in the present research are not always comparable to the treated roads in other studies, and for example the speed limit or the type of road may differ. However, generally it can be concluded that the results in the present study are more limited for the effect on the average speed but are still well in line with previous studies regarding the effect on the number of speed limit violations (Makinen, 2001; Retting et al., 2008). Nevertheless, we believe that these results, the braking and accelerating behaviour of drivers, can be generalized to other motorways, national and international. This effect should be confirmed by future research in other countries.

Liu et al. (2011) analysed the effect of a speed camera 1 km upstream and downstream of the camera. They found no effects at these locations, and they observed that drivers started to brake at about 400 m to 300 m upstream and returned to their initial speed 300 m to 400 m downstream. The present study found distinct results regarding the effect of speed cameras at a greater distance. At the Brasschaat site, an increase was found at the two locations upstream and at 1 km downstream, whereas at the Boutersem site a decrease was found at these locations. At 3.3-3.8 km downstream, generally no effects were found. The average speed and the proportion of drivers speeding (excessively) during the before period was higher at the Boutersem site, which may explain why higher decreases were found for these locations. The differences in the speeding behaviour before the installation of the camera can probably be ascribed to the characteristics of these locations. The speed camera in Brasschaat is sited at a two-lane motorway, about two kilometres before the start of the ring road of Antwerp. This ring road is one of the two busiest roads in Belgium, and is even the second most congested road in the world (INRIX, 2013). The Boutersem site on the other hand is localised at a three-lane road, more than 30 km away from a busy ring road. Subsequently, the two locations are very different.

It can be concluded that the present study is an extensive study that included a large amount of vehicles. Despite the fact that already a great deal of research has been done about speed cameras, only a limited number of studies have examined the speed effects of speed cameras at a greater distance from these cameras. The present study clearly showed a V-profile with the highest effects at the speed camera, but smaller and even unfavourable effects at the locations upstream and downstream from the camera. However, confirmation from other studies is necessary as the study only included two locations in one country. It was not possible to analyse more than two locations with speed cameras as there were only two eligible locations (as we needed measurements with the same equipment and on the same locations both in the before- and the after period) available in Flanders. Furthermore, the data gathering includes a time and money consuming effort.

Speed data were only gathered at one moment during the after period which was due to several practical reasons (e.g. shortly after the speed camera was installed at the Boutersem location road works were applied at a distance up to the first measurement point, which took several months). Subsequently it was impossible to analyse whether there was a difference in the effect directly after the installation of the camera and a longer time after the installation. This would be an interesting case for future research.

An analysis of the speed profiles before and beyond the cameras showed high differences in the average speed and the proportion of drivers exceeding the speed limit at short distances. Between the location with the information sign (250 m downstream from the camera) and the speed camera location in Brasschaat, speed differences of almost 9 km/h could be observed; in Boutersem, the speed decreased by 8 km/h at a distance of 700 m. At a distance of 1 km downstream from the camera, the average speed and the proportion of drivers exceeding the speed limit increased again at both locations.

The effects on speed might have been influenced by the interaction between vehicles. It can be expected that as a result of the installation of a speed camera, the interaction between vehicles increases, which subsequently influences the driving speed. This can be studied through an analysis of the headways, which were not available in the present study, but which could be an interesting case for future research.

On the basis of these results it is unclear what effects should be expected on the occurrence of crashes. Despite the fact that high decreases were found at the speed camera, more limited decreases and even increases were found at the locations upstream and downstream from the camera. Between the speed camera location and the locations close before and after the speed camera, high differences in the average speed during the after period were found. This can be defined as the so-called kangaroo effect: drivers do slow down in the neighbourhood of the camera and accelerate again after the camera. This sudden braking might affect the resulting effect on safety negatively. In order to get a clear view on the crash effects, these were studied separately, from which the results are described in chapter 6.3.

6.2.6 CONCLUSIONS

- The installation of fixed speed cameras has had a clear effect on the speed behaviour of road users at the two investigated camera locations. The driving speed reduced on average by 6.4 km/h, the odds of drivers exceeding the speed limit reduced on average by 80% and the odds of drivers exceeding the speed limit by more than 10% reduced by 86%.
- The effects at the locations upstream and downstream of the camera are smaller and even speed increases are found.

- A clear V-profile is found in the spatial speed distribution for both locations. Drivers slow down quite abruptly in the last few hundred metres before the camera and speed up again after passing the camera to regain their original speed after not more than 1 km beyond the camera location.

6.3 Safety effects of fixed speed cameras on motorways in Flanders, Belgium: Empirical results

Dutch report:

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). *Snelheidscamera's en trajectcontrole op Vlaamse autosnelwegen. Evaluatie van het effect op snelheidsgedrag en verkeersveiligheid*. Diepenbeek: Instituut voor Mobiliteit.

6.3.1 **Introduction**

Whereas in chapter 6.2 the speed effects of fixed speed cameras on motorways were studied, the effects on crashes are studied in the present chapter. This paper describes the results of a study that analysed the effects of fixed speed cameras on the occurrence of crashes. Whereas most previous studies included speed cameras that were located at different types of highways, the present study specifically targeted motorways. Furthermore, crashes were selected at different distances from the camera, through which separate analyses were applied for the effects upstream from, at, and downstream from the camera.

6.3.2 **Literature review**

Previous studies generally suggest that speed cameras are effective in reducing speed and crashes. Elvik et al. (2009) for example, applied a meta-analysis of several studies that examined the traffic safety effects of fixed speed cameras, mainly from Europe and Australia. The number of crashes of all severities decreased by 16% when the publication bias was controlled for. The number of fatal crashes decreased by 39%. A recent study comes from Li, Graham and Majumdar (2013), who analysed the traffic safety effect of 771 locations with speed cameras in England and found a decrease of 23% in the number of injury crashes. Nevertheless, the estimates of the impact vary considerably (Shin, Washington, & van Schalkwyk, 2009). Road characteristics such as road type, speed limit and the number of minor junctions within site length, are defined as important factors when estimating the safety impact of speed cameras (Li et al., 2013). An evaluation of around 4000 camera sites in the UK showed the most favourable effects for cameras in rural areas compared to urban areas (Gains et al., 2005). Similar results were found by Hess (2004), who studied 49 cameras in the UK and found more favourable effects for cameras at A-roads and trunk roads compared to non-A-roads and urban roads respectively. Elvik (1997) included 64 road sections with speed cameras in Norway and found the highest effects for roads with a speed limit of 70 km/h, followed by 60 km/h roads, for which a decrease of 45% and 27% in the number of injury crashes was found. Roads with a speed limit of 50 km/h and 80 km/h showed less high effects (-15% in the number of injury crashes). Somewhat different results were found in the study that included 65 fixed speed cameras at Flemish highways (motorways excluded), which showed that locations with a speed limit of 50 km/h performed better compared to locations with a speed limit of 90 km/h (see chapter 5.1).

The majority of the available studies include cameras on different road types together, which are often defined as highways. However, the number of studies that analysed speed cameras that were installed on motorways is limited. Motorways, also stated as freeways, are defined here as roads for motorized vehicles only with a median barrier and no at-grade junctions (Elvik et al., 2009). Shin et al. (2009) analysed the traffic safety effects of speed cameras on motorways in Arizona. They found a decrease in the number of injury crashes of 48%, the number of PDO crashes decreased by 56%. These are highly favourable results. Furthermore, they analysed the effects on different crash types. For all crashes together the number of single-vehicles crashes decreased by 63%. The number of sideswipe crashes decreased by 48% (significant at the 10% level), and the number of rear-end crashes decreased by 26% (significant at the 20% level). It should be noted that this was a pilot study, with an after period that only included 8 months.

A number of previous studies analysed the effects at different distances from the camera, which mainly found that the reduction in crashes due to the effect of speed cameras, was negatively correlated to the distance from the camera sites (Hess, 2004; Liu et al., 2011; Mountain et al., 2004). Li et al. (2013) for example analysed the crashes at cumulative distances of 200 m, 500 m and 1 km on both sides of the camera, and found decreases in the number of injury crashes of 28%, 26% and 19% respectively. Also Hess (2004) analysed the effects of speed cameras, and he used cumulative distances of 250 m, 500 m, 1000 m and 2000 m. He analysed 38 cameras at major roads, however not necessarily motorways. He found the highest effects in the immediate vicinity of the camera: -55% in the number of injury crashes up to 250 m from the camera. The effects dropped with the distance from the camera: -44% up to 500m; -36% up to 1000 m; -20% up to 2000 m.

6.3.3 DATA

At the time of the study, crash data were available up until 2011. In order to have at least one year of crash data available in the after period, all speed cameras that were installed and operational up until 2010 could be included. Almost all locations with fixed speed cameras on Flemish motorways could be included in the present study, except for three locations at which speed cameras were installed in 2011. In total 26 locations with speed cameras were studied. Per location one camera (located at the left side of the road) or two cameras (located at the left and right side of the road, both in the same direction) were present. All of these cameras are photo radar units mounted in boxes. Speeds are detected through double inductive loops embedded in the pavement, which calculate the speed of the vehicle, based on the time the vehicle needs to pass the two loops and the distance between the loops. The loops are managed by a government agency, and the data gathered by these loops are frequently controlled. The locations were scattered around the Flemish motorways. Table 6-15 shows the characteristics of the locations where the cameras are installed.

Table 6-15 Characteristics of the treated locations

Characteristics		No. of locations
Number of cameras	1	17
	2	9
Year camera was operational	2007	4
	2008	6
	2009	14
	2010	2
Speed limit (km/h)	90	6
	100	3
	120	17
Number of lanes	2	5
	3	18
	4	3

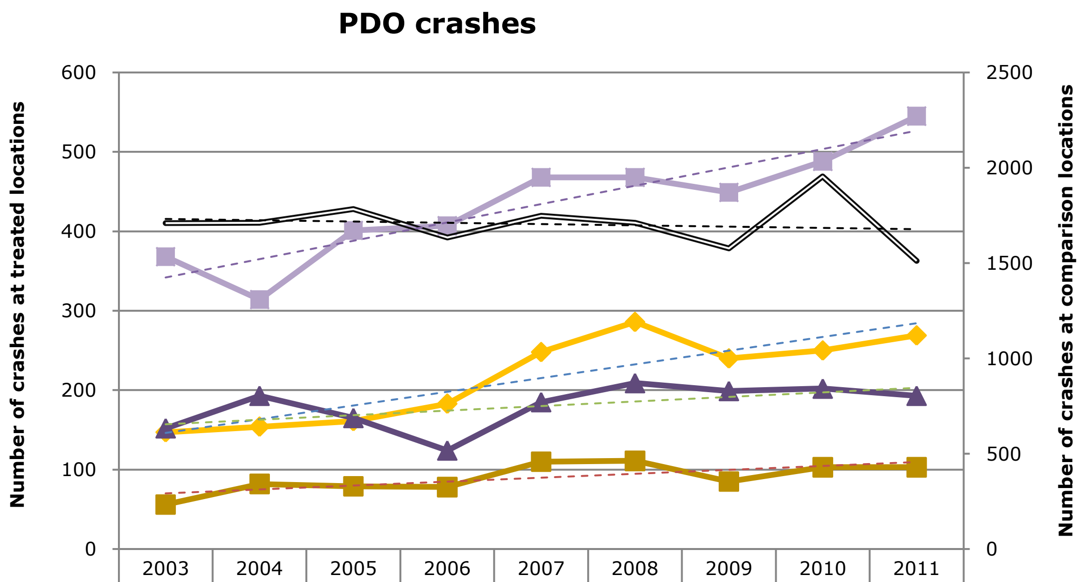
Crashes were selected at different distances from the camera:

- 1200 m up to 200 m upstream from the camera
- 200 m upstream up to 200 m downstream from the camera
- 200 m up to 1200 m downstream from the camera
- 1200 m up to 5000 m downstream from the camera

Only the crashes that occurred in the direction at which the camera is installed were selected. The crashes were subdivided according to their severity: (1) PDO crashes; (2) injury crashes; (3) fatal and serious injury crashes.

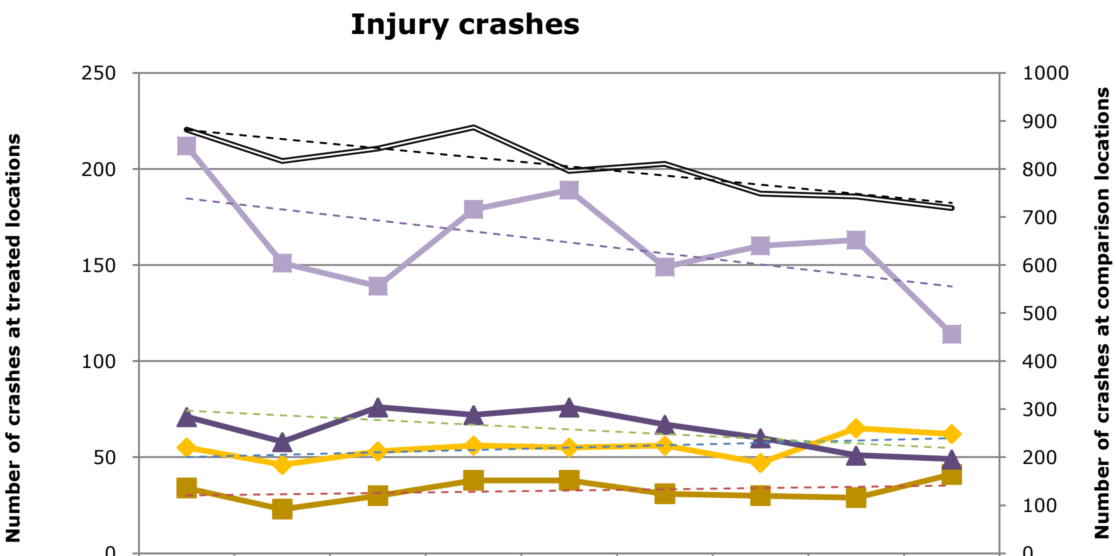
In order to control for general trend effects, a comparison group was selected. This comparison group included all crashes that occurred at Flemish motorways, at least 20 km away from a location with speed cameras. Crashes at entries or exits were not included. In addition, crashes that occurred at the two busiest ring roads in Flanders, namely the ring roads of Brussels and Antwerp, were excluded. Several speed cameras, installed close to each other, are present at these ring roads, which could render the comparison group contaminated by the measure.

Figure 6-11, Figure 6-12 and Figure 6-13 show the number of PDO crashes, injury crashes and severe crashes per year that occurred at the different distances from the camera and at the comparison locations. In order to improve readability, the graphs of the crashes at the treated locations and the graph of the crashes at the comparison locations are set on a different y-axis. The primary vertical axis (left axis) indicates the number of crashes at the treated locations; the secondary vertical axis indicates the number of crashes at the comparison locations.



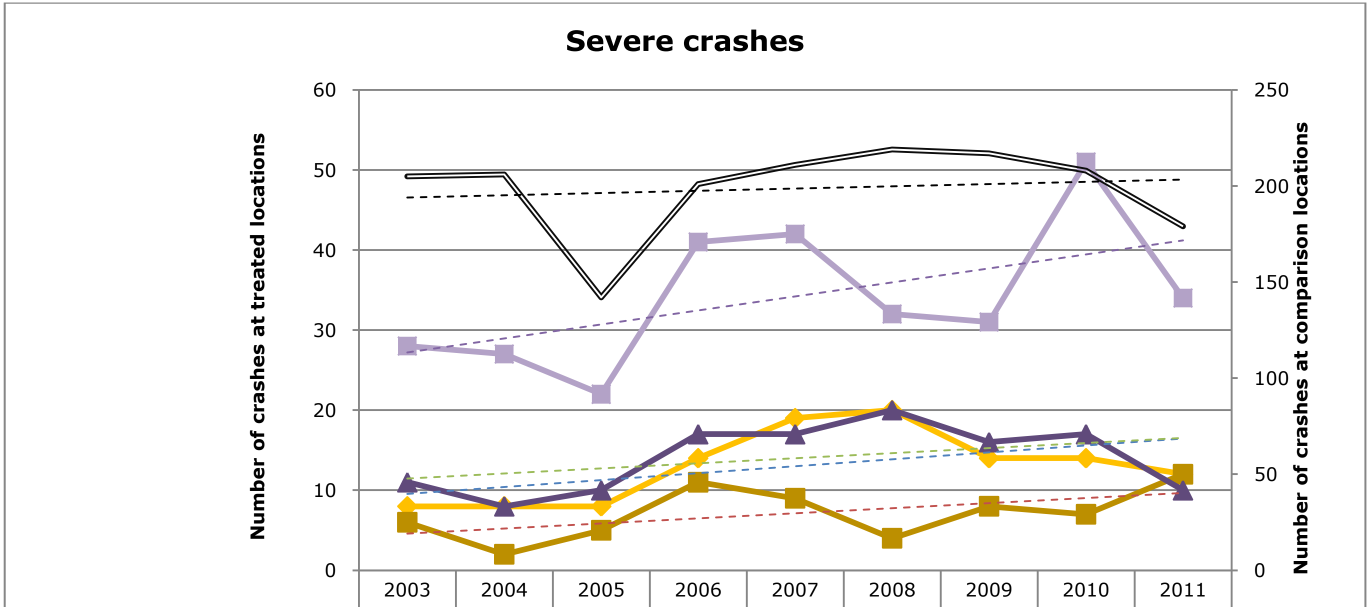
	2003	2004	2005	2006	2007	2008	2009	2010	2011
-1200 m up to -200 m	147	154	161	183	248	286	240	250	269
-200 m up to +200 m	56	82	79	78	110	111	85	103	103
+200 m up to +1200 m	152	193	165	124	185	209	199	202	193
+1200 m up to +5000 m	368	314	401	407	468	468	449	488	545
Comparison group	1709	1711	1783	1635	1749	1711	1577	1954	1512

Figure 6-11 Number of PDO crashes at treated and comparison locations



	2003	2004	2005	2006	2007	2008	2009	2010	2011
-1200 m up to -200 m	55	46	53	56	55	56	47	65	62
-200 m up to +200 m	34	23	30	38	38	31	30	29	41
+200 m up to +1200 m	71	58	76	72	76	67	60	51	49
+1200 m up to +5000 m	212	151	139	179	189	149	160	163	114
Comparison group	882	817	843	887	796	811	749	743	719

Figure 6-12 Number of injury crashes at treated and comparison locations



	2003	2004	2005	2006	2007	2008	2009	2010	2011
-1200 m up to -200m	8	8	8	14	19	20	14	14	12
-200 m up to +200 m	6	2	5	11	9	4	8	7	12
+200 m up to +1200 m	11	8	10	17	17	20	16	17	10
+1200 m up to +5000 m	28	27	22	41	42	32	31	51	34
Comparison group	205	206	142	201	211	219	217	208	179

Figure 6-13 Number of severe crashes at treated and comparison locations

6.3.4 METHOD

In the present study, the EB before-and-after study was used to estimate the effect of speed cameras on traffic safety. The EB method was applied using data from a before period that ranged from 2003 until the year before the camera was installed and an after period that ranged from the year after the camera was operational to 2011. In line with the studies of the speed cameras and the combined speed and red light cameras (see chapter 5), the year(s) during which the camera was installed until this was operational (i.e. violators were ticketed) were not taken into account in this study. For three locations this period included two years, for three other locations this was three years, which was due to technical problems with the inductive loops. All other cameras were installed and became operational during the same year. It was decided to restrict the before period until the year before the camera was installed, as we can expect drivers' behaviour changes when they see the newly installed camera. On the other hand, the after period started from the time the camera was operational and thus excluded the period between the installation of the camera equipment and the formal administrative approval to use them. This was done to making sure that the measured effects applied to a period that represented a similar stage of operation of the investigated camera locations.

In order to control for the RTM phenomenon, an SPF is calculated that has been developed on the basis of the crash occurrence at Flemish motorways. For the injury and the severe crashes, the same SPFs are used as in chapter 4.2 (i.e. the effect evaluation of dynamic speed limits on motorways), for the PDO crashes a new model was developed. An SPF was calculated per motorway segment, based on several variables: traffic volume, length of road segment, type of road segment and number of lanes. The type of road segment included two main categories: (1) road segments at entries/exits and interchanges and (2) road segments between two entries/exits or interchanges. The model has a negative binomial probability distribution with a log link function and is calculated with the SPSS GENLIN procedure. The model can be described as next:

$$E[\kappa] = e^{\alpha} L^{\beta} V^{\gamma} e^{\sum_{i=1}^{n} \delta_i x_i} \quad \text{(Eq. 6-1)}$$

with

$E[\kappa]$= 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..5)

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 traffic volume of 36,047 (st. dev. 20,045). Table 6-16 displays the results of the SPFs for (1) the PDO crashes; (2) the injury crashes; (3) the severe crashes. The segment type and the number of lanes were not significant for the models of the injury crashes and the severe crashes.

Table 6-16 Results of SPFs for the before period

	PDO crashes	Injury crashes	Severe crashes
α	-20.784 (SE:0.803)**	-16.792 (SE:0.623)**	-18.493 (SE: 1.030)**
Length of segment (β)	0.568 (SE: 0.039)**	0.939 (SE:0.029)**	0.951 (SE: 0.047)**
Traffic volume (γ)	1.676 (SE: 0.065)**	1.011 (SE:0.049)**	1.035 (SE: 0.080)**
Segment type (δ_1)	Between entries/exits and interchanges: 0.540 (SE: 0.095)** At entries/exits and interchanges: 0		
Number of lanes (δ_2)	1: 0.110 (SE: 0.085) 2: 0.311 (SE: 0.079)** 3 : 0 4: -0.259 (SE: 0.219) 5: 2.915 (SE: 0.524)**		
Overdispersion	0.755 (SE: 0.047)	0.313 (SE:0.031)	0.325 (SE:0.070)
Elvik index of goodness-of-fit	0.756	0.822	0.824
Likelihood ratio test statistic (χ^2)	888.0**	1013.5**	500.6**

** Significant at 1% level

The model is based on data from 2008-2010. However, the before period in the present study ranged from 2003 up to 2005, 2006, 2007 or 2008, dependent on the moment the camera was installed. It was not possible to calculate a model based on data from these years, since traffic volume data are only available from 2008.

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.

In order to control for the zero counts in the after period, two methods were applied: (1) the empirical continuity correction; (2) the EB estimation. The empirical continuity correction is used as described in Eq. 2-12 – Eq. 2-14.
As a second method the EB approach was applied in the after period, as described in Eq. 2-15. SPFs were calculated based on the treated locations with speed cameras. The calculation of the models was also based on the length of the segment the camera is installed (L) and the traffic volume (I). For each specific after period an SPF was applied. Only the segments with speed cameras (or the segments right before or after the segments with speed cameras, if there were no inductive loops at the segment were the camera is installed) were included. For 2008 and 2009 data from 26 segments were included, for 2010 this amounted to 32 segments and for 2011 this were 37 segments. The average length of the segments in the model is 3845 m (st. dev. 2516) and the average traffic volume is 47,863 (st. dev. 22,228). The results of the models are displayed in Table 6-17. For the severe crashes, it was not possible to calculate a model for the after period of 2010-2011 and 2011, because of the low number of crashes. For the locations with these after periods the model of 2009-2010 was used.

For the results of each of the two methods a fixed effects meta-analysis was calculated.

Table 6-17 Results of SPFs in the after period

		PDO crashes	Injury crashes	Severe crashes
2008-2011	*α*	-19.53 (SE 1.88)**	-16.790 (SE 1.568)**	-20.899 (SE 2.985)**
	Length of segment (*β*)	0.336 (SE 0.091)**	0.579 (SE 0.067)**	0.68 (SE 0.122)**
	Traffic volume (*γ*)	1.805 (SE 0.140)**	1.302 (SE 0.120)**	1.47 (SE 0.226)**
	Overdispersion	0.395 (SE 0.066)	0.101 (SE 0.034)	0.154 (SE 0.094)
	Elvik index of goodness-of-fit	0.806	0.845	0.811
	Likelihood ratio test statistic (χ^2)	117.6**	113.7**	58.5**
2009-2011	*α*	-21.442 (SE 2.226)**	-16.846 (SE 1.784)**	-21.193 (SE 3.467)**
	Length of segment (*β*)	0.382 (SE 0.102)**	0.558 (SE 0.073)**	0.589 (SE 0.134)**
	Traffic volume (*γ*)	1.944 (SE 0.167)**	1.317 (SE 0.138)**	1.561 (SE0.266)**
	Overdispersion	0.402 (SE 0.076)	0.086 (SE 0.036)	0.124 (SE 0.102)
	Elvik index of goodness-of-fit	0.813	0.868	0.846
	Likelihood ratio test statistic (χ^2)	96.9**	90.59**	45.1**

		PDO crashes	Injury crashes	Severe crashes
2010-2011	α	-21.946 (SE 2.693)**	-16.346 (SE 2.184)**	
	Length of segment (β)	0.468 (SE 0.122)**	0.517 (SE 0.085)**	
	Traffic volume (γ)	1.928 (SE 0.202)**	1.301 (SE 0.167)**	
	Overdispersion	0.444 (SE 0.098)	0.100 (0.048)	
	Elvik index of goodness-of-fit	0.792	0.846	
	Likelihood ratio test statistic (χ^2)	64.69**	60.0**	
2011	α	-24.893 (SE 4.60)**	-16.471 (SE 3.156)**	
	Length of segment (β)	0.574 (SE 0.201)**	0.556 (SE 0.122)**	
	Traffic volume (γ)	2.118 (SE 0.341)**	1.278 (SE 0.250)**	
	Overdispersion	0.649 (SE 0.186)	0.120 (SE 0.72)	
	Elvik index of goodness-of-fit	0.745	0.840	
	Likelihood ratio test statistic (χ^2)	29.6**	29.6**	

** Significant at the 1% level

6.3.5 **RESULTS**

6.3.5.1 EFFECTS ACCORDING TO DIFFERENT DISTANCES FROM THE CAMERA

The results according to the different distances from the camera are shown in Table 6-18. Table 6-18a shows the effects that were found when the zero counts were controlled with an empirical continuity correction; Table 6-18b shows the results of the analyses in which the EB estimation is used. A comparison of the results of both methods shows that these are in line with each other, however the increases are slightly higher and the decreases were more limited when the empirical continuity correction was used. As can be seen from Table 6-18 the before- and after evaluation of the PDO crashes resulted in a significant increase at all distances. At the speed camera (-200 m up to +200 m) the number of PDO crashes increased by 51%-59%. Upstream from the speed camera (-1200 m up to -200 m) the number of PDO crashes increased by around 60%. Downstream increases of 19%-28% (+200 m up to +1200 m) and of 28%-30% (+1200 m up to +5000 m) were found. At the total distance, from 1200 m upstream from the camera up to 5000 m downstream, an increase of 33%-34% could be found.

The injury crashes showed a somewhat other effect, with increases in the number of crashes upstream from and at the speed camera location, but decreases downstream from the speed camera. At the speed camera, the number of injury crashes increased by 57%-68%, at 1200 m up to 200 m upstream from the camera this was around +27%. Both results were significant. Downstream from the camera a non-significant decrease of 12%-20% (the last result was almost significant) and a significant decrease of 13%-17% was found. At the total distance the number of injury crashes decreased by 7%-9%.

The effects on the fatal and serious injury crashes should be taken into account with caution, because of the low number of crashes. As can be seen from Figure 6-13, the number of crashes at a distance from 200 m downstream up to 200 m upstream ranged from a minimum of two severe crashes per year up to a maximum of 12 severe crashes per year. At all distances an increase was found.

At 1200 m up to 200 m upstream, the severe crashes increased by 4%-14%. At the camera location (-200 m up to +200 m) the number of crashes were more than double as high as compared to the before period. 200 m up to 1200 m downstream the severe crashes increased by 20%-38%. At 1200 m up to 5000 m downstream the number of crashes increased by 8%-19%. Only the result of the crashes at the camera location was significant, however the 95% CI is very wide, because of the low number of crashes. At the total distance of 1200 m upstream up to 5000 m downstream the number of severe crashes increased by 13%-19%, which was not significant.

Table 6-18a Effects according to the different distances from the camera, with the empirical continuity correction to control for zero counts in the after period

	-1200 m up to -200 m	-200 m up to +200 m	+200 m up to +1200 m	+1200 m up to +5000 m	Total length (-1200 m up to +5000 m)
PDO crashes	1.60 [1.42; 1.80]*	1.59 [1.33; 1.89]*	1.28 [1.14; 1.45]*	1.30 [1.20; 1.40]*	1.34 [1.27; 1.42]*
Injury crashes	1.28 [1.03; 1.60]*	1.68 [1.25; 2.26]*	0.88 [0.70; 1.11]	0.87 [0.76; 1.00]	0.93 [0.85; 1.03]
Severe crashes	1.14 [0.71; 1.83]	2.72 [1.55; 4.79]*	1.38 [0.88; 2.15]	1.19 [0.91; 1.56]	1.19 [0.98; 1.45]

* Significant at the 5% level

Table 6-18b Effects according to the different distances from the camera, with the EB estimation to control for zero counts in the after period

	-1200 m up to -200 m	-200 m up to +200 m	+200 m up to +1200 m	+1200 m up to +5000 m	Total length (-1200 m up to +5000 m)
PDO crashes	1.61 [1.43; 1.81]*	1.51 [1.27; 1.80]*	1.19 [1.05; 1.34]*	1.28 [1.18; 1.39]*	1.33 [1.26; 1.41]*
Injury crashes	1.26 [1.02; 1.57]*	1.57 [1.17; 2.10]*	0.80 [0.64; 1.01]	0.83 [0.72; 0.96]*	0.91 [0.83; 1.01]
Severe crashes	1.04 [0.64; 1.68]	2.35 [1.26; 4.40]*	1.20 [0.77; 1.86]	1.08 [0.83; 1.42]	1.13 [0.93; 1.38]

* Significant at the 5% level

No clear pattern is visible in these differential results. However, generally it could be seen that for all severities increases were found at the distances upstream from the camera and at the camera location. At the locations downstream from the camera the increases are less high for the PDO and severe crashes and decreases were found for the injury crashes. Therefore separate analyses were made for two distances from the camera (see Table 6-19): (1) crashes upstream from and at the camera location (-1200 m up to +200 m) and (2) crashes downstream from the camera (+200 m up to +5000 m). For the PDO crashes, a significant increase of 55% could be found upstream from and at the camera location. This increase was more limited at the locations downstream from the camera (25%-28%). The injury crashes at a distance of 1200 m upstream up to 200 m downstream increased by 31%-33%, whereas a significant decrease could be found downstream from the camera (-17%/21%). Furthermore, a significant increase of 39%-54% and a non-significant increase of 6%-15% was found for the severe crashes.

Table 6-19a Effects according to two distances from the camera: (1) before and at the camera location and (2) downstream from the camera, with the empirical continuity correction to control for zero counts in the after period

	-1200 m up to +200 m	+200 m up to +5000 m
PDO crashes	1.55	1.28
	[1.41; 1.71]*	[1.19; 1.37]*
Injury crashes	1.33	0.83
	[1.12; 1.59]*	[0.74; 0.93]*
Severe crashes	1.54	1.15
	[1.05; 2.26]*	[0.92; 1.45]

* Significant at the 5% level

Table 6-19b Effects according to two distances from the camera: (1) before and at the camera location and (2) downstream from the camera, with the EB method to control for zero counts in the after period

	-1200 m up to +200 m	+200 m up to +5000 m
PDO crashes	1.55	1.25
	[1.41; 1.71]*	[1.17; 1.34]*
Injury crashes	1.31	0.79
	[1.10; 1.56]*	[0.71; 0.90]*
Severe crashes	1.39	1.06
	[0.96; 2.02]	[0.84; 1.33]

* Significant at the 5% level

6.3.5.2 Effects according to crash types

Furthermore, a distinction was made according to the crash type. The three crash types that occur most frequently at Flemish motorways were analysed separately: (1) rear-end crashes; (2) side crashes; (3) crashes against obstacles outside the roadway. For these analyses only the empirical continuity correction was used to control for zero counts in the after period, since it was not possible to calculate an SPF per crash type and thus the EB estimate could not be applied.

In these analyses, all crashes at a distance from 1200 m upstream up to 5000 m downstream were analysed together. PDO crashes showed a significant increase for each of the three crash types (see Table 6-20). The side crashes and the rear-end crashes increased significantly by 29% and 26% respectively, the crashes against obstacles outside the roadway increased by 19%. For the number of injury crashes, no significant difference was found from the before to the after period for the number of rear-end crashes, nor for the number of side crashes. The crashes against obstacles significantly decreased by 28%. The fatal and serious rear-end crashes significantly increased by 55%. On the other hand a decrease, however non-significant, was found in the number of severe crashes against obstacles (-17%). No significant effect was found for the number of severe side crashes. It should be noted again that the results with the severe crashes need to be taken into account with caution, as the number of severe crashes is low.

Table 6-20 Effects according to the crash type

	Rear-end crashes	Side crashes	Crashes against obstacles outside the roadway
PDO crashes	1.26 [1.16; 1.38]*	1.29 [1.14; 1.45]*	1.19 [1.01; 1.40]*
Injury crashes	0.95 [0.83; 1.10]	1.04 [0.80; 1.33]	0.72 [0.58; 0.90]*
Severe crashes	1.55 [1.15; 2.09]*	1.19 [0.70; 2.04]	0.83 [0.56; 1.24]

* Significant at the 5% level

6.3.6 **DISCUSSION**

The present study analysed the traffic safety effects of speed cameras at 26 locations on Flemish motorways. Crashes were selected at different distances from the camera. Based on the found results it can be stated that the speed cameras as introduced on motorways in Flanders have brought about clear increases in crash numbers upstream from and at the camera locations. The effects beyond the cameras are more ambiguous: decreases are found in the number of injury crashes, although still increases in the number of PDO and severe crashes are found. Given their significance, one could tend to consider the effects of the injury crashes as predominant. However, the results for PDO crashes are clearly contradictory and the results for the crashes with serious injuries tend to an increase and should, although not significant, not be neglected. Consequently, no straightforward conclusion can be drawn for the locations beyond the cameras.

It was analysed whether differences could be found according to the characteristics of the location of the camera, for example number of lanes, traffic volume and ring roads vs. other roads. However, no systematic differences could be found, and thus it could be concluded that speed cameras do not lead to other results dependent on the characteristics of the motorway at which the cameras are installed.

The investigated after period was relatively short. At the time the study was applied, crash data were available up until 2011, whereas a lot of cameras were installed in 2009/2010. The after period consisted on average of 2.2 years of crash data. A future replication of the same analyses with data for a longer period could increase the precision of the estimates, which would be particularly useful to assess the effects on the most serious crashes.

As a consequence, the number of crashes at some locations (and especially for the more severe ones) during the after period equals zero. Subsequently it was not possible to calculate the index of effectiveness (see Eq. 2-9) for these locations. No appropriate solution is found yet for this problem. Therefore, two methods were applied: (1) an empirical continuity correction and (2) an EB estimate. The results of both methods were in line with each other and resulted in similar conclusions. Nevertheless, there were differences in the results of both methods, with slightly higher increases, and more limited decreases when the empirical continuity correction was used. Future research is necessary in order to search for the best suitable method.

It is somewhat difficult to compare the results of the present study with previous studies, since the latter often include speed cameras that are located at different road types. Speed cameras on motorways were so far rarely studied separately. Irrespective of the road type, it can be concluded that the results in the present study are not in line with what was already found on the traffic safety effects of speed cameras. A meta-analysis of Elvik et al. (2009), which included studies with speed cameras at different road types, generally found a decrease of 16% in the number of crashes of all severities. The number of fatal crashes decreased significantly by 39%. Shin et al. (2009) included speed cameras on motorways in Arizona and found a decrease of 56% in the number of PDO crashes, and a decrease of 48% in the number of injury crashes.

The results of the present study differ also from the results of a study that analysed the effects of speed cameras at Flemish highways (see chapter 5.1). This study analysed 65 locations with fixed speed cameras at Flemish highways, motorways excluded, and selected injury crashes, and fatal and serious injury crashes at a distance from 500 m upstream up to 500 m downstream from the camera. The analyses showed a non-significant decrease of 8% in the number of injury crashes. In the case of the more severe crashes, a decrease of 29% was found, significant at the 5% level. This indicates that the speed cameras on motorways are less effective, and possibly other elements could have had an influence.

In order to explain the results of the present study, these can be linked with the results of a parallel study, in which the effects on the driving speeds were analysed (chapter 6.2). In this study, the effect on the driving speed was analysed at different distances from two fixed speed cameras at Flemish motorways. At both speed cameras the average speed clearly decreased, but on average no effects were found at the locations upstream and downstream from the camera. In addition, it was found that drivers slow down abruptly right before the camera, and accelerate again behind the camera, defined as the

“kangaroo” effect. This leads to high speed differences at short distances, mainly at the distance upstream from the camera. For example on average there was a difference of 8.6 km/h between the speeds that were measured at the information sign (located at 0.25 km and at 0.70 km before the speed camera) and at the speed camera, and a difference of 3.6 km/h was found between the speed camera location and 1 km downstream.
An analysis of the crashes clearly showed high increases in all crash types from 1200 m upstream up to 200 m downstream from the camera. At the distances downstream from the camera, smaller increases for PDO crashes and decreases for the injury crashes were found. This can be linked with the differences in the driving speed, which were smaller beyond the speed camera compared to before the camera. This supposition is confirmed by the results of the different crash types. These analyses mainly showed increases in rear-end and side crashes, which could be a result of the speed differences and the related manoeuvres. On the other hand, significant decreases were found for the number of crashes against obstacles outside the roadway. These crashes are generally related to high speeds (OECD, 2006; Transportation Research Board, National Research Council, 1998) and thus the favourable results of these crashes can possibly be related to the reduction of the highest speeds.

It should however be noted that the effect is far from what one would expect based on the Power Model (Elvik, 2009; Elvik, 2013; Nilsson, 2004). A comparison of the average speed after with before indicates that the number of crashes would decrease at the speed camera location. At the other locations upstream and downstream from the camera, no real effect could be expected. The main reason why the observed and the expected effect differ, is probably related to the nature of the data that have been used by the two sources. In the present case, a speed distribution is observed that changes across the investigated road stretches (i.e. the V-profile of speeds). Methods such as the Power Model (Elvik, 2009; Elvik, 2013; Nilsson, 2004), make use of an aggregate indicator (typically mean speed) to reflect the speed behaviour for a certain road segment. However, this indicator can be assumed to be based on single point measurements in many or even most cases. In the present case however, not only the mean speed at a single point in space is important, but also the longitudinal speed distribution, i.e. the speed distribution across a certain motorway segment. We believe that the unfavourable effects on the number of crashes can be ascribed to this behaviour (the “kangaroo jumps”). Previous research found that the effects of average speed on crashes are statistically insignificant, but speed variation is an important determinant in predicting segment-based traffic crash rates. An increase of 1% in speed variation would be associated with a 0.3% increase in crash rates (Quddus, 2013). This speed variation is however not taken into account in the Power Model.

6.3.7 **CONCLUSIONS**

The present study evaluated the safety effects of the installation of fixed speed cameras on motorways in Flanders, Belgium. The following conclusions can be drawn:

- Upstream from and nearby the camera locations (-1200 m up to +200 m) significant increases are found in the number of PDO crashes (+55%) and injury crashes (+31%/+33%).
- Downstream from the camera, the results are ambiguous with decreases in the number of injury crashes (-17%/-21%) but still increases in the number of PDO crashes (+25%/+28%).
- The number of side and rear-end crashes generally increases whereas the number of crashes against obstacles outside the roadway (single-vehicle crashes) decreases.
- It is hypothesised that the found effects on crashes can be attributed to the V-shaped spatial speed distribution nearby speed camera sites, with relatively abrupt decelerations before the camera location and accelerations beyond the camera location.

CHAPTER 7

CONCLUSIONS, METHODOLOGICAL ISSUES AND FUTURE CHALLENGES

7.1 OVERVIEW OF THE MAIN CHARACTERISTICS OF THE STUDIES

The purpose of this PhD dissertation was to get a better view on the effects of traffic safety measures, both measures that are already widely implemented, as well as new measures that are gaining popularity. Road safety authorities can use these results as a controlling instrument for the appropriateness of implemented road safety measures and to develop more effective programmes in the future. Information on the effectiveness of different measures that target the same traffic safety problem, can furthermore help to make well-based decisions. In summary, these results can help to improve the effectiveness of a road safety management through well-based decision-making.
Table 7-1 gives an overview of the key characteristics of the different studies that were applied in the present dissertation, together with the main effects of each study. The effects of the different road safety measures are further described in chapter 7.2, together with a description of the policy impacts of these results and the need for further research.

In all the studies, a before-and-after study design is applied, with control for the general trend effect. For the evaluation of crashes, the empirical Bayes method can be defined as the best standard in the evaluation of traffic safety measures. However, some problems occurred during the application of this method, which are described in chapter 7.3.

From the present dissertation it can be concluded that effect estimation is an important part of an effective road safety management. Policies should be encouraged to estimate effects and to apply effect estimation routinely as part of the planning, design and management of roadways. However, before this can be applied effectively, some challenges need to be faced (see chapter 7.4).

Table 7-1 Overview of the key characteristics of the studies

Chapter	Measure	Outcome	Study design	Zero count correction in after period	Comparison group	Main effects	Study limitations
3.1	Black spot treatments	Injury crashes (severity; characteristics of location) Casualties	EB with comparison group	EB estimates with SPF of treated locations	Two groups: black spots treated after the research period and all crashes in Flanders	Injury crashes −24 to −27 % Severe crashes −46 to −57 %	- An analysis according to the crash type was impossible
3.2	Protected left-turn phasing at signalised intersections	Injury crashes (severity; type of crash) Casualties	Before-and-after with lag period and comparison group	EB estimates with average number of crashes at treated locations	Crashes at signalised intersections (without treated locations)	Injury crashes −37% Severe crashes −50 %	- An analysis according to the number of treated legs was impossible - All crashes in a radius of 100 m from the intersection centre were selected
4.1	Reducing the speed limit from 90 to 70 km/h	Injury crashes (severity)	Before-and-after with comparison group	Addition of a factor of 0.5	Crashes at road sections with a speed limit of 90 km/h, located in the same province than the treated locations	Injury crashes −5 % Severe crashes −33 %	- No control for RTM - Small comparison group
4.2	Dynamic speed limits on motorways	Injury crashes (severity; type of crash)	Empirical Bayes with comparison group	Not applied	All crashes on motorways, at least 10 km away from locations with DSLs	Injury crashes −18 % Severe crashes −3 %	

Chapter	Measure	Outcome	Study design	Zero count correction in after period	Comparison group	Main effects	Study limitations
5.1	Fixed speed cameras on highways	Injury crashes (severity; distance from the camera; characteristics of location) Casualties	Before-and-after with comparison group	EB estimates with average number of crashes at treated locations	All crashes in Flanders	Injury crashes −8 % Severe crashes −29 %	- No control for RTM - Quite short after period (2.6 years on average) - Selection of crashes in both directions
5.2	Combined speed and red light cameras	Injury crashes (severity; type of crash; characteristics of location) Casualties	Before-and-after with comparison group	EB estimates with average number of crashes at treated locations	All crashes in Flanders	Injury crashes +5 % Severe crashes −14 %	- No control for RTM - No control for spillover effects
6.1	Automatic section speed control on motorways	Driving speed (average speed; number of speed limit violations)	Before-and-after with comparison group	Not relevant	Two comparison locations, located at a distance of at least 15 km from the treated locations	Clear speed decreases at the section, as well as upstream and downstream from the section	- Analysis of speeds shortly after installation of ASSC, no information on longer term - Impossible to apply an analysis of the crash effects

Chapter	Measure	Outcome	Study design	Zero count correction in after period	Comparison group	Main effects	Study limitations
6.2	Fixed speed cameras on motorways	Driving speed (average speed; number of speed limit violations)	Before-and-after with comparison group	Not relevant	Two comparison locations, located at a distance of 35 km from the treated locations	Kangaroo-effect at the speed camera location	
6.3	Fixed speed cameras on motorways	PDO and injury crashes (severity; distance from camera; type of crash)	Empirical Bayes with comparison group	Empirical continuity correction and EB estimates with SPF of treated locations	All crashes on motorways, at least 20 km away from locations with speed cameras	PDO crashes +55 % at -1200 m up to + 200 m +28% at +200 m up to +5000m Injury crashes +33 % at -1200 m up to + 200 m -17% at +200 m up to +5000m	- Short after period

7.2 WHAT CAN BE LEARNED ABOUT THE EFFECTIVENESS OF THE MEASURES

7.2.1 OVERVIEW OF THE RESULTS

In this PhD dissertation the effects of four engineering measures were studied, with two infrastructural measures and two measures that affect the speed limits. The two infrastructural measures included the treatment of black spots and the installation of left-turn signals. Both of the studies found significant and substantial effects.

As a lot of means are invested in the **black spot treatment programme**, the Flemish government demanded an extensive study on the effects of this measure. As a result of the treatment of the first 134 black spots, a decrease of 24%-27% was found in the number of injury crashes. The number of fatal and serious injury crashes decreased by 46%-57%. The highest effects for the number of injury crashes were found for priority-controlled intersections with changes in the layout (-42%) and at which traffic signals were installed (-35%). The effects at intersections that were already signalized during the before period were less high, however still a decrease of 22% was found for the intersections at which left-turn protection signals were implemented and a decrease of 11% was found for the signalized intersections with changes in the layout. The conversion to roundabouts of both previously priority-controlled and signalized intersections leaded to a decrease of 21% in the number of injury crashes.
Furthermore, a favourable effect was found on the casualty level for each of the road user categories: car occupants, moped riders, cyclists, motorcyclists, pedestrians and truck drivers.

One of the measures from the black spot programme, the **implementation of left-turn protection at signalized intersections**, was analysed in a more in-depth manner, since the number of peer-reviewed studies on this subject is limited. This study found highly favourable results, with a strong decrease in the

total number of injury crashes (-37%). The effect was mainly attributable to a decrease in the number of left-turn crashes (-50%). Despite the results of previous studies, no adverse effects were found on the number of rear-end crashes. Furthermore, the effect on fatal and serious injury crashes was analysed, which showed greater decreases (-59%) than injury crashes.
An analysis of the effect on the number of injured car occupants, cyclists, moped riders and motorcyclists, showed favourable effects for each of these groups.

Moreover, the traffic safety effects were analysed of two engineering measures through which speed limits were reduced.
The first measure included the reduction of fixed speed limits on highways. More specifically the traffic safety effects of the **reduction of speed limits from 90 km/h to 70 km/h** were studied. This measure resulted in a significant decrease of the number of severe crashes (-33%); no significant effect was found for the total number of injury crashes. This difference can be ascribed to the fact that speed is directly related to injury severity in a crash. This is different than the probability of being involved in a crash, which is more complex, as the occurrence of crashes can seldom be attributed to a single factor (Transportation Research Board, National Research Council, 1998). The analyses also showed a stronger effectiveness at road sections compared to intersections, for which even a contradictory result was found in the number of injury crashes (-11% vs. +11%), and for the more severe crashes (-36% vs. -6%). Possibly, crashes that occur at intersections may be less influenced by speed and causation might rather be related to manoeuvres, for example turning left. This explains why no decrease was found, but this does not explain why an increase is found. A possible cause for this increase in the number of injury crashes, is the increase in the variance of travel speeds.

The second measure included the **dynamic speed limit systems** on motorways. When the inductive loops and cameras detect a high occupancy together with a low speed, the speed limits are reduced. As a result of this measure, a decrease of 18% was found in the number of injury crashes. 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 3%. It is remarkable that this measure has a favourable effect on the number of injury crashes, but no effect was found for the severe crashes. This is different from what was found in the study on the reduction of fixed speed limits and can probably be ascribed to the circumstances this measure is active. This measure will mainly be active at busy moments. Possibly speeds are already lower, and crashes that occur at these moments are rather related to manoeuvres between vehicles, instead of high driving speeds.

Next to the engineering measures, also three enforcement measures were studied: speed cameras, combined speed and red light cameras and average section speed control. For the speed cameras, a distinction was made between highways and motorways.
An evaluation of the effect of 65 **speed cameras** installed on **highways** resulted in a slight, however non-significant decrease (-8%) in the number of injury crashes at a distance up to 500 m from the camera. In the case of the severe crashes, a higher and significant decrease was identified (-29%). This higher effect on the severe crashes compared to all injury crashes may be ascribed to the dual effect of lower driving speeds, namely a lower risk to be involved in a crash and less severe consequences if a crash occurs (Aarts & Van Schagen, 2006). An analysis of the effects at different distances from the camera showed that the effect on the number of injury crashes can mainly be ascribed to the effect at a distance of 250-500 m (-8%), whereas no effect was found at the distance of 0-250 m. These results are not significant, and thus should be taken into account with caution. The severe crashes showed somewhat other results, for which the highest effects were found at a distance of 250 m from the camera. At a longer distance (500-1000 m from the camera), a tendency to an increase in crash rates (both for the injury crashes and the severe crashes) appears. The kangaroo effect may give a possible explanation: drivers compensate the lower driving speed at the speed camera with a higher speed from about 500 m after the camera. The installation of speed cameras furthermore resulted in benefits for all road user categories.

An evaluation of 253 intersections with **combined speed and red light cameras** resulted in a slight, non-significant increase of 5% in the number of injury crashes. This was mainly attributable to an increase in the number of rear-end crashes (+44%). The severe crashes decreased by 14%, which can be ascribed to a decrease in the number of severe side crashes (-24%).
An effect estimation on the level of casualties, showed a decrease in the number of injured cyclists only. The opposite effects on side and rear-end crashes can be a possible explanation for this result. The increasing effect on rear-end crashes may counteract the decreasing effect on side crashes, which will mainly be the case for motorized vehicles.

In addition to the speed cameras and the combined speed and red light cameras on highways, two enforcement measures that tackle the speeding problem on motorways were studied extensively: speed cameras and automated section speed control. Whereas in the previous studies the major focus was on the evaluation of the effect on crashes, in these studies also the effects on the driving speed were analysed.
Automated section speed control is a relatively new measure and the number of studies on the effectiveness are limited. Therefore, a first evaluation of this measure, implemented at the Flemish motorways, was applied. Two locations, at the same road but in opposite direction, each with a section control system over a length of 7.4 km, were analysed. On the enforced sections the speed decreased by 5 km/h, the odds of drivers exceeding the speed limit decreased by 72%, the odds of drivers exceeding the speed limit by more than 10% decreased by 85%. The study found favourable effects up to 6 km before and after the enforced section. These effects ranged from a decrease of minimal 2 km/h to maximal 6 km/h, and from minimal -39% in the odds of speed limit violations to maximal -70%. This might however be ascribed to the unclear location of the starting and the ending point of the section, because the devices are installed at a bridge at the entrance and at the exit of the enforced section. Furthermore the variance of speeds decreased from before the installation of the section control to after.

Next to the average section speed control, also the effects of **speed cameras** installed on **motorways** were studied. Despite the fact that already a great deal of research has been done about speed cameras, only a limited number of studies have examined the speed effects of speed cameras at a greater distance from these cameras. An evaluation of the effect on the driving speeds showed strong effects at the camera location: The average speed decreased by 6.4 km/h after the installation of a speed camera; the odds of drivers exceeding the speed limit decreased by 80%; and the odds of drivers exceeding the speed limit by more than 10% decreased by 86%. At the locations upstream and downstream from the camera, no clear effects were found. At 3–2.5 km upstream from the camera, the average speed and the odds of drivers exceeding the speed limit slightly increased; at the information sign, slight decreases were found. Downstream from the camera, no strong effects were found, not at a distance of 1 km downstream nor at 3.3–3.8 km downstream.
An analysis of the speed profiles before and beyond the cameras shows high differences in the average speed and the proportion of drivers exceeding the speed limit at short distances. Between the location with the information sign (a couple of hundreds of meters upstream from the camera) and the speed camera location, speed differences of on average 8.5 km/h could be observed. At a distance of 1 km downstream from the camera, the average speed and the proportion of drivers exceeding the speed limit increased again at both locations. The presumptions about the braking and accelerating behaviour at speed cameras, as was already stated in the study on the crash effects of speed cameras on highways, were clearly confirmed in this study.

In addition to the speed effects, also the effects on crashes of speed cameras on motorways were examined. In accordance with the analyses of the effects on the driving speed, crashes were selected at different distances from the camera. Based on these analyses it can be stated that the speed cameras as introduced on motorways in Flanders have brought about clear increases in crash numbers before and at the camera locations. From 1200 m upstream up to 200 m downstream from the camera, an increase was found for the PDO and the injury crashes of 55% and 33% respectively. The effects beyond the cameras are more ambiguous: from 200 m up to 5000 m downstream the number of injury crashes decreased (-17%), although still increases in the number of PDO crashes

(+28%) are found. Consequently, no straightforward conclusion can be drawn for the locations beyond the cameras.
The results of this study differ from the results of the study that analysed the effects of speed cameras on highways. This study found more favourable results, which indicates that the speed cameras on motorways are less effective, and possibly other elements could have had an influence.
The effects on the crashes can also be compared with the effects on the driving speed. The increase of the crashes upstream from and at the camera location can be linked to the sudden braking behaviour before and at the camera. Beyond the camera the speed differences were found to be smaller, and in accordance with this finding smaller increases for PDO crashes and decreases for the number of injury crashes were found.
Furthermore, the analyses mainly showed increases in rear-end and side crashes, which could be a result of the speed differences and the related manoeuvres. On the other hand, significant decreases were found for the number of crashes against obstacles outside the roadway. These crashes are generally related to high speeds and thus the favourable results of these crashes can possibly be related to the reduction of the highest speeds.

7.2.2 **POLICY IMPLICATIONS**

All the measures that were studied in this dissertation are implemented in Flanders and some of them were studied in close cooperation with the Flemish government. The outcomes of these studies did have implications for the road safety policy. The main implications are described below.

Favourable effects were found for the **black spot programme** through which the infrastructure of the locations with a high number of crashes was adapted. The largest effects were found for intersections that were previously priority controlled, as these can be strongly modified. However even with some small investments, i.e. implementation of left-turn protection at signalized intersections, large traffic safety benefits were gained. The adaptation of dangerous locations can thus be defined as an effective traffic safety measure.
Nevertheless, the policy makers should not have blind faith in this measure. It is conceivable that on a certain moment the most dangerous spots will have been

handled, and further investment in black spots will not lead to additional benefits in traffic safety. The Dutch Institute for Road Safety Evaluation stated that road safety improvement as a result of several road safety measures also has an effect on high risk locations, and therefore there is less to be gained at those locations by taking new measures (SWOV, 2010). They concluded that the black spot programme can no longer make a substantial contribution to the number of severely and deadly injured in the Netherlands (SWOV, 2010). Furthermore one should try to act preventive instead of curative, and next to an analysis of the number and severity of crashes (the method which is generally used to select black spots), also other methods should be used to detect dangerous locations, for example conflict observation.

For the effect of **combined speed and red light cameras** favourable effects were found in the number of fatal and serious injury crashes, but high increases were found in the number of, less severe, rear-end crashes (+44%). The Minister of Mobility and Traffic Safety therefore asked to apply an extensive research concerning the circumstances of these crashes and to develop measures in order to tackle this unintended effect. In this study, real-world observations and driving simulator-based observations were combined. Elements that were analysed is the travel speed before the crash and the phase of the traffic light at the time of the crash (Polders et al., 2014).

The **speed cameras** at the highways showed to have a favourable effect. As a consequence of this result, the Minister of Mobility and Public Roads kept on going with the installation of new speed cameras. However, these new locations were selected more carefully.

Despite the fact that extra research would be interesting, it can be concluded that **automated section speed control** is more effective than speed cameras. As speed remains an important traffic safety problem for many countries, it can be recommended to apply, if possible, speed enforcement mainly via average speed control instead of speed cameras. One should however not forget to put enough effort in the other domains, i.e. education and engineering. As a consequence of the study on the effects of speed cameras and average section speed control on motorways, the Minister of Mobility and Public Works decided to stop the installation of speed cameras on motorways. They however did not remove the speed cameras that were already implementd, as this could give the impression that drivers are free to speed. On the other hand it was decided to install average section speed control at several new locations. From 2015, 14 new sections will be equipped all around Flanders. In addition to this, it was recommended that the decision to install enforcement systems should be taken into account with caution and should be based both on crash occurrence and driving speeds. In Flanders, and possibly in other countries too, the decision to install a speed camera or an average speed control system is based on the occurrence of a high number of crashes. However, it can be expected that the occurrence of these crashes will not necessarily be related to speed, but also other factors could have had an influence, for example infrastructure. Therefore, it is important to detect both speed and crashes, in order to make a well-founded decision for the appropriate measure.

7.2.3 FURTHER RESEARCH

Based on the results and on the limitations in the different studies, several recommendations for further research can be defined.

The **reduction of the fixed speed limit** was found to be effective for the number of severe crashes, but no effect was found for the number of injury crashes. Lowering the speed limit will however not automatically lead to a change in travel speeds by all drivers. Factors such as habits, non-acceptance of the new measure or inattentiveness might explain why the actual speed adaptation is lower than the required speed adaptation (McCarthy, 1998). In order to get a clear view on the effects of this type of measure, the effects on the speed behaviour should be analysed, which was not possible in the present dissertation.

Furthermore, the analyses showed that the speed limit reduction leaded to a favourable effect on road sections, but at intersections no significant effect was found for the severe crashes and even an increase was found in the number of injury crashes. Crashes that occur at intersections may be less influenced by speed compared to road stretches, and causation might rather be related to manoeuvres, for example turning left. This explains why no decrease was found, but this does not explain why an increase is found. A possible cause for this increase in the number of crashes, might be the increase in the variance of travel speeds. However, further research is necessary, for example through the analysis of the speed behaviour and through conflict observation, in order to observe how drivers behave at the intersections.

The study on the traffic safety effects of a **dynamic speed limit** system was one of the first that applied an empirical study. These results give a first indication, and mainly showed favourable effects on crashes that are related to manoeuvres. However, this study should be extended in future research. Therefore it is recommended to do this type of empirical research again at several road types and in several countries. Furthermore, it would be interesting to analyse the speed limit compliance to the dynamic systems.

Automated section speed control is a relatively new measure that only has been studied in a limited number of cases. The first average speed control systems in Flanders were installed recently, and the effects of these systems were studied shortly after these systems 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. Whereas in the present dissertation the effects up to 6 km were studied, it would be interesting to analyse the effect at larger distances from the section. Moreover, it was not possible to analyse the effects on the number of crashes, because of the short after period. This should also be studied in future research.

The driving speed at **speed cameras** on motorways clearly showed a V-profile, with the highest effects at the speed camera, but smaller and even unfavourable effects at the locations upstream and downstream from the camera. However, confirmation from other studies is necessary as the study in this dissertation only included two locations in one country. Furthermore, speed data were only gathered at one moment during the after period and thus it was impossible to analyse whether there was a difference in the effect directly after the installation of the camera and a longer time after the installation. This would be an interesting case for future research. In addition, the speed effects of cameras on highways should be analysed. It was found that speed cameras on highways lead to more favourable effects on crashes compared to speed cameras on motorways. However, based on the crash effects at the different distances from the camera, probably the kangaroo effect is present at this road too. Because of the lower speeds at the highways, the speed differences might be lower, and thus the unfavourable impact on crashes might be more limited. However, this is a hypothesis that should be analysed in future research.

7.3 METHODOLOGICAL ISSUES

In this dissertation the same methodology was used throughout the different studies, i.e. the before-and-after comparison of traffic crashes or speed behaviour. During the application of this method, several problems occurred, which are described per study. The most important issues, i.e. the ones that occurred in different studies, are discussed here.

7.3.1 CONTROL FOR ZERO CRASHES

One statistical problem that occurred during all studies in which the crash effects were studied, is the occurrence of zero crashes. As explained in paragraph 2.1.4, the effect cannot be estimated when one of the variables (number of crashes in the before or after period of the treated or comparison group) is equal to zero. This problem of zero crashes mainly occurs for the observed number of crashes at the treated location in the after period, since the crash rates during the before period are already corrected by the EB method. A common method to solve this problem is the addition of a factor of 0.5 to each of the four variables when one of these is equal to zero. This method was applied in one of the first studies in this dissertation, namely the effect evaluation of the speed limit reduction from 90 km/h to 70 km/h (see 4.1). However, previous research showed that applying such a continuity factor can lead to deviant results in meta-analyses (Sweeting et al., 2004). No sufficient method is found yet.

In the present dissertation this problem was solved through the application of an EB estimation (for more information on this method, see 2.1.4). Usually the EB method is used to control for the RTM. In that case the expected number of crashes in the before period is lower (e.g. 40), compared to the observed number (e.g. 42), as a result of the control for the RTM phenomenon. This lower number is reached through a weighted estimate of observed number of crashes (e.g. 42) and the predicted number of crashes through a crash prediction model (e.g. 38). For example, for the effect evaluation of speed cameras on motorways (see chapter 6.3) an observed number of 11 injury crashes during the before period at the speed camera, resulted in an expected number of 7.2 crashes.
The same method is used for the after period. However here no similar locations are selected to estimate the expected number of crashes, but data from the treated locations are used. Therefore, two methods are applied:
(1) As for the before period, an SPF was calculated, but this was based on the observed number of crashes at the treated locations during the after period (see chapter 3.1 & 6.3);
(2) The average number of crashes at the treated locations is used (see chapter 3.2, 5.1 & 5.2).

In order to illustrate what the implications of these methods are, Table 7-2 shows the observed number of crashes in the after period, for a subset of 15 speed cameras, as analysed in chapter 6.3. In the fourth column the numbers are displayed, which result from the application of the EB estimate in the after period, using an SPF that is based on the observed crashes in the treated group (method 1). As can be seen from this table, the numbers are lower for locations that have a higher than average number of crashes, and slightly higher at the locations with a lower than average number of crashes. This is in line with the correction that is applied in the before period, however since the SPF is based on the treated locations instead of comparison locations, the difference between the observed number and the estimated number is less high, compared to method as it is applied in the before period.

Table 7-2 Example of the effect on crash numbers in the after period, when using the EB method with an SPF based on the treated locations

Speed camera no.	Number of years in the after period	Observed number in the after period	EB with SPF (based on crashes from treated locations)
1	3	13	9.61
2	3	17	11.32
3	3	0	0.53
4	1	0	0.22
5	2	2	2.95
6	3	0	3.34
7	3	2	1.21
8	1	1	2.24
9	2	6	7.83
10	2	4	4.32
11	2	0	1.71
12	3	1	3.76
13	2	1	0.73
14	2	3	2.74
15	1	0	0.35

Table 7-3 shows the effects when the second method is used, i.e. the average number of crashes at the treated locations. Therefore, the data of a subset of 15 speed and red light cameras are displayed (see chapter 5.2). The differences between the observed and the expected number are very small, and are even smaller compared to the first method.

Table 7-3 Example of the effect on crash numbers in the after period, when using the EB method with the average number of crashes at the treated locations

Speed and red light camera no.	Number of years in the after period	Observed number in the after period	EB with average number of crashes at treated locations
1	1	0	0.62
2	5	15	14.83
3	1	8	6.52
4	1	3	2.73
5	4	13	13.77
6	2	2	2.38
7	1	1	1.58
8	5	30	28.68
9	5	6	6.52
10	5	15	14.83
11	3	8	7.80
12	5	6	6.52
13	5	12	12.06
14	2	7	6.42
15	2	3	3.44

In one of the last studies that were applied in this dissertation, a third method was applied, i.e. the empirical continuity correction. Through this method a continuity factor is calculated which is based on the pooled effect size of all locations without zero events. Future research is necessary to search for the best solution to solve this problem.

7.3.2 LIMITED DATA ON TRAFFIC VOLUMES AVAILABLE

Another methodological problem that occurred with a number studies in which the crash effect was analysed, is the absence of traffic volume data. In the application of an EB before-and-after study, volume data are needed to calculate an SPF (for more information, see paragraph 2.1.3). This SPF estimates the number of crashes based on important factors that explain the variation in the number of crashes at certain locations (e.g. traffic volume, type of intersection, number of lanes) and of the related regression parameters. Traffic volume has in most cases a significant influence on the number of crashes. Therefore

information on these volumes is necessary in order to calculate an SPF and subsequently to control for the RTM phenomenon. However, in Flanders there is only limited data available about the traffic flows and thus it was not possible to control for the RTM phenomenon in three of the included studies, i.e. the effect evaluation of the speed limit reduction from 90 km/h to 70 km/h (chapter 4.1), the effect evaluation of speed cameras on highways (chapter 5.1) and combined speed and red light cameras (chapter 5.2).
For the black spot studies (chapter 3.1), traffic volume data were available. These data were gathered by the contractor that has been assigned to redesign the dangerous intersections and were available for 2000-2003. Based on the traffic volumes of the main and minor road the expected number of crashes per treated intersection could be estimated. Furthermore, also traffic volume data at the Flemish motorways are available, which are registered through double inductive loops in the pavement. In 2008, the government started with the installation of these loops, which is still going on up to now. These data could thus be used in the studies that analysed the crash effects of measures on motorways, i.e. the effect of speed cameras (chapter 6.3) and the effect of dynamic speed limits (chapter 4.2). However, the problem in these studies was that the before period ranged from 2003-2008 for the speed cameras, and 1999-2002 and 2006-2008 for the dynamic speed limits. Since traffic flows are only available from 2008, an adjustment factor was calculated 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 of the years volume data were available.

Next to this, a second problem occured with the absence of traffic volume data, i.e. the impossibility to control for changes in the traffic volume at the treated location. Hauer (1997) stated that in a before-and-after study it is necessary to control for changes in the traffic volumes from the before to the after period. Therefore, one needs to have information on the traffic flows during all years of the research period and one needs to have information about how the expected number of crashes depends on the traffic flow. Since all of the studies in this dissertation included a long research period with several years of crash data in the before and the after period, no sufficient data was available on the traffic flows. It can however be stated that general changes in the traffic volumes are taken into account through the crash data in the comparison group. The changes in the number of crashes in the comparison group include the effects of all factors that had an influence on the number of crashes, including traffic growth (Elvik, 2002). Next to the general trend effects, also the measure itself could have had an effect on the traffic flows. For example, the installation of a speed camera or the restriction of a speed limit at a certain section could have led traffic away from this location, the adaptation of a black intersection could have led to a higher traffic flow on the other hand. Nevertheless, it can be argued that the implementation of the measures that were studied in this dissertation had a limited influence on the traffic flow. The Flemish road structure does only give limited opportunity for drivers to choose alternative roads, as these mainly include local roads with lower speed limits. Since the evaluated measures were implemented at the upper category of roads, this will probably have had a limited effect on the rerouting choices of the driver.

7.3.3 **META-ANALYSIS THROUGH A FIXED EFFECTS MODEL**

In every study of this dissertation, in which the crash effects were analysed, the meta-analysis method was applied in order to get one overall effect estimation of the measure under evaluation.
With this method, at first the effect per location (for example the effect for each intersection with combined speed and red light cameras) was estimated. Subsequently the overall effect of all locations together was calculated, using a fixed effects model. In this overall estimation, every location gets a weight, which is the inverted value of the variance, through which locations with a high number of crashes are given a higher weight.

Other authors (e.g. Hauer, 1997; Persaud & Lyon, 2007) however stated that first the EB estimates, their variances and the observed number of crashes in the after period need to be summed. Afterwards the overall index of effectiveness need to be estimated based on these sums. In this dissertation the preference was given to the weighted method, as this results in more balanced effects compared to the summation method. Greater variation in the effect estimations can be found when these are based on small crash samples compared to larger crash samples (Elvik, 1998). Therefore more weight is given to the effect estimations with a higher number of crashes.

These weights are calculated, based on a fixed effects model. This fixed effects model assumes that there is one true effect size and that there is no systematic variation in effects of the included studies. However, in case of heterogeneity in the effect estimates, a random effects model should be used (e.g. Borenstein, Hedges, & Rothstein, 2007; Elvik et al., 2009). If a fixed effects model is applied on heterogeneous data, too much weight will be assigned to the result with large statistical weights and furthermore the confidence interval of the overall effect will be underestimated. The relative weights assigned under the random effects model otherwise, will be more balanced than those assigned under the fixed effects model. As we move from fixed effects to random effects, extreme studies will lose influence if they are large, and will gain influence if they are small. Furthermore, confidence intervals for the average intervention effect will be wider if the random-effects method is used rather than a fixed effects method, and corresponding claims of statistical significance will be more conservative (Borenstein et al., 2007; Elvik et al., 2009).

The reason that in the present dissertation a fixed effects meta-analysis was used instead of a random effects meta-analysis is that all studies are functionally identical, since all the data of the individual studies were gathered on the same way and the effects were measured in the same manner (Borenstein et al., 2007). However, the heterogeneity of the data should have been studied. This is done for all the studies, through next formula (in accordance with eq. 2-26) (Elvik et al., 2009):

$$\sum_{l=1}^{n} w_l * (\ln(\theta_l))^2 - \frac{(\sum_{l=1}^{n} w_l * \ln(\theta_l))^2}{\sum_{l=1}^{n} w_l} \qquad \text{(Eq. 7-1)}$$

with θ_l = the effect estimate at location l; w_l= weight that is given to location l, which is the inverted value of the variance. The test has a chi² distribution, with g-1 degrees of freedom (with g= the number of estimates of effect that have been combined).

The effect estimates were found to be heterogeneous for the studies in which the effects of speed limit reduction were studied (chapter 4.1 and 4.2), for the analyses of the effects of red light cameras (chapter 5.2), and for the analyses

of speed cameras on motorways. However for all these studies only the effect estimates of the injury crashes, and for the speed cameras also the PDO crashes, were heterogeneous. The results for the severe crashes were homogeneous.
For these five study effects also a random effects model was applied, in order to analyse whether the results are different from the fixed effects meta-analysis. The results of both methods are displayed in table Table 7-4.

Table 7-4 Results of fixed effects vs. random effects model for the results which were found to be heterogeneous

Measure	Results with fixed effects model	Results with random effects model
Reduction of speed limit from 90 km/h to 70 km/h (chapter 4.1)	Injury crashes 0.95 [0.88; 1.03]	Injury crashes 0.93 [0.83; 1.04]
Dynamic speed limits (chapter 4.2)	Injury crashes 0.82 [0.70; 0.96]	Injury crashes 0.85 [0.62; 1.15]
Red light cameras on highways (chapter 5.2)	Injury crashes 1.05 [0.98; 1.12]	Injury crashes 1.04 [0.94; 1.15]
Speed cameras on motorways (chapter 6.3)	PDO crashes 1.34 [1.27; 1.42] Injury crashes 0.93 [0.85; 1.03]	PDO crashes 1.25 [1.09; 1.43] Injury crashes 0.92 [0.80; 1.16]

As can be seen from Table 7-4, the results do not differ much between the two methods. The only difference that can be found, is that the result of the dynamic speed limits is not significant anymore, as the confidence interval becomes wider when the random effects model is used.

7.3.4 INCOMPLETE CRASH REPORTING

One of the challenges for a traffic safety management is the reporting of crash data. Good crash data are essential for the evaluation of traffic safety measures.

Incomplete crash reporting can therefore lead to uncertainty of the estimated effects of traffic safety measures. Hauer & Hakkert (1988) stated that this uncertainty increases, as the level of reported crashes is lower and more variable. More specifically the authors found that the variance of the safety effect of a measure is inversely proportional to the square of the average proportion of crashes reported.

Based on a meta-analysis of 49 studies in 13 countries, Elvik and Mysen (1999) concluded that reporting of injuries in official crash statistics is incomplete at all levels of injury severity. The mean reporting level for deaths within 30 days is 95%, for serious injuries (defined as persons that were admitted to the hospital) this was 70%, for slight injuries (persons treated as outpatients) the reporting level was 25%, for persons with very slight injuries that were treated outside the hospital the reporting level was 10%. The reporting was found to be the highest for car occupants and the lowest for cyclists.

A Belgian study on severely injured persons also showed a high under registration (Nuyttens, 2013). In this study, the data from the hospitals were compared with the data from the police records. According to the police data, a severely injured person is a person that needed more than 24 hours of hospitalization. Based on this definition all patients were selected which stayed at least one night in the hospital as a consequence of a traffic crash. The ratio of the hospital data and the police data was 2.5, which means that the number of severely injured persons was 2.5 times higher according to the hospital data compared to the official police data. This number is probably even an underestimation because of an under registration of the hospital data as not for every patient it is reported that this was a consequence of a traffic crash. However, on the other hand the two definitions not exactly match (at least 24 hours of hospitalization vs. at least one night of hospitalization). Nevertheless this study gives a clear indication of the under registration.

We can however expect that this under registration had no substantial influence on the effect estimation in the present dissertation. As the comparison of the number of crashes after with before came from the same dataset (police records), the ratio was probably similar than when the hospital data would have been used. Furthermore, the general trend effect was taken into account through the use of a comparison group, which also consisted of police data. Nevertheless, this important problem should be handled in the future.

7.4 Evaluation as part of an effective road safety management: Future challenges

The purpose of the present dissertation is not only to present the results of traffic safety measures, but also to emphasize the importance of effect estimation as part of an effective road safety management. However, as explained in this chapter, this can bring several challenges.

7.4.1 Effect estimation remains necessary

A possible barrier for road authorities to evaluate the effects of traffic safety measures, is that this evaluation might prove that important road safety investments had limited or no impact (Hasson et al., 2012). Often evaluation is viewed as an adversarial process and its main use has been to provide a thumbs up or a thumbs down about a programme or project.

Evaluation is however defined as an important, maybe even the most important, contributor to future safety (Porter, 2011). Effect evaluation of traffic safety measures gives information on its contribution to safety, gives the opportunity to researchers to test their predictions on how and why interventions might be effective, it gives policymakers the opportunity to implement the most effective interventions and it gives road safety experts the opportunity to optimize the implementation (Porter, 2011).

According to the OECD there is a need for more training and regular practical usage of effect estimation to support the development of transferable Crash Modification Factors (CMFs). It seems that we are at a turning point, with the prospect of rapid advances and major cost savings through the transfer of results internationally. Currently there is a lack of understanding the value, importance and usage of CMFs in road safety decision making. Policy makers may use CMFs systematically to some extent in their decision-making. However, there are no countries where CMFs are routinely used in a direct manner by practitioners as part of the planning, design and management of roadways (OECD, 2012). This is an important challenge for the future.

7.4.2 Effect estimation as part of a larger efficiency assessment tool

A general term for the tools that can be used to evaluate the effectiveness of traffic safety measures are the 'Efficiency assessment tools' (EATs). These can be defined as "a systematic assessment of the improvement in road safety that can be realised by means of various road safety measures" (Federal Highway Research Institute, 2005) and they comprise cost-effectiveness analyses and cost-benefit analyses.

A cost-effectiveness analysis compares the number of crashes or casualties prevented per unit of cost. A cost-benefit analysis includes an integral efficiency and compares the costs and benefits of different policy alternatives, measured in monetary units. Next to an estimation of the effectiveness, EATs also include an estimate of the costs of each measure and (in case of cost-benefit analyses) a monetary valuation of impacts on safety, environment and travel time. Therefore both costs and benefits need to be assessed and balanced against each other (Federal Highway Research Institute, 2005). The policy aims for the highest possible effects within a certain amount of financial means, or minimal necessary means to reach a certain purpose (Nas, 1996).

The effect estimation can be used to look back to see whether the intended effects are reached, but as explained in chapter 1, it can also be used to look forward and to make the best choices in the different available measures for a certain traffic safety problem. In this context, a third factor can be applied, and next to the effectiveness and costs, the public support need to be taken into account (Elvik, 2008a). Positive public evaluations can, under favourable conditions, lead to an increased willingness to accept a measure and can even lead to an active support. It appears that participation in decision making, knowledge of the contents of plans and perceived effectiveness, positively influence the accomplishment of public support for the treatment of a problem (Goldenbeld, 2002). Public support is considered as an important element, as policymaking acts are considered as a two-way direction in which interaction, transaction and communication with the public are key-elements (Bartels, Nelissen, & Ruelle, 1998). A strong definition of what the term 'support' contains, is absent. However it is often related with acceptability, commitment, legitimacy and participation (Goldenbeld, 2002). It is however difficult to quantify the public support phenomenon. Measuring attitude through surveys is the most common method. An example of this is the SARTRE (Social Attitudes to Road Traffic Risk in Europe)-survey, which examines the attitudes, self-reported behaviour and experiences of European drivers, and of non-drivers.

Subsequently, based on these three dimensions, the best measure to tackle a certain problem can be determined. Intelligent Speed Adaptation systems, for example, may be expected to be both effective and advisable in terms of cost, but lack public support (Elvik, 2008a). Imprisonment for drunk-driving is widely supported, but not (cost)effective (Ross & Klette, 1995). Even if a measure seems promising in terms of effectiveness, also a certain minimum of public acceptance is necessary to introduce a traffic safety measure. When one has a clear view on each of those three elements, one can consequently provide policy-makers with useful and objective information in order to select the most promising measures. Obviously, this has intrinsic strong policy relevance.

7.4.3 TRANSFERABILITY OF RESULTS ACROSS COUNTRIES

A high quality effect analysis is often costly to perform. The growing interest and increasing application of effect estimation of traffic safety measures is therefore an opportunity to increase international cooperation in the development and sharing of CMFs (Hasson et al., 2012).

The question is whether CMFs are transferable to other countries. In an ideal situation, studies would be available from different countries for a long period and all these studies would be of at least adequate and similar methodological quality. However, this will only be available in an exceptional number of cases. Therefore, the transferability of CMFs depends on knowing the circumstances under which different safety measures have been implemented. According to the OECD a study should, next to information on the circumstances, also provide information on the safety estimates by severity of the crash, the standard error of the estimates and some basic information about the methodology (study design, sample, data sources, biases, etc.) (OECD, 2012).

A major deterrent to transferability is the variability in CMF research. This variability can be reduced through proper study design and reporting. Therefore, studies should control for the most important confounding factors related to the analysed measures. Generally, there are two groups of factors that affect the variability of CMFs. The first one is related to the methodology, e.g. sufficient large sample size, control for confounding variables, etc. The other group of factors, i.e. variability of CMFs, is less commonly examined, but also of high importance. The results of an effect estimation largely differs according to the circumstances of crashes and the severity of crashes. This source of variability can be reduced through the application of the CMF as a function of the relevant circumstances. For example, it can be expected that speed cameras have different effects according to the speed limit and the road type. Uncertainty about CMFs can be reduced through a two-pronged strategy with (1) CMF estimates need to be reliable and (2) the dependence of the CMFs on relevant circumstances needs to be established. The OECD (2012) states "(1) If there have been many studies of measure X, not just in country A, but in many other countries, and not just six years ago, but spanning three or four decades; and (2) if these studies obtained highly consistent estimates of the effect of measure X; then (3) it is more reasonable to conclude that the results of these studies can be applied in country B than to conclude the opposite."

Some study results in the present dissertation confirm results that were already found in previous studies, for example the effectiveness of black spot treatment programmes and the effects of combined speed and red light cameras, whereas others counteract the general results that were found in the past, e.g. the traffic safety effects of fixed speed cameras on motorways. Other measures were only studied in a limited number of cases (e.g. automated section speed control and dynamic speed limits) which can initiate further research in different circumstances.

REFERENCES

Aarts, L., & Van Schagen, I. (2006). Driving speed and the risk of road crashes: A review. *Accident Analysis & Prevention*, *38*(2), 215–224. doi:10.1016/j.aap.2005.07.004

Abdel-Aty, M., Cunningham, R. J., Gayah, V. V., & Hsia, L. (2008). Dynamic variable speed limit strategies for real-time crash risk reduction on freeways. *Transportation Research Record: Journal of the Transportation Research Board*, *2078*, 108–116. doi:10.3141/2078-15

Abdel-Aty, M., Dilmore, J., & Dhindsa, A. (2006). Evaluation of variable speed limits for real-time freeway safety improvement. *Accident Analysis & Prevention*, *38*(2), 335–345. doi:10.1016/j.aap.2005.10.010

Abdel-Aty, M., Dilmore, J., & Hsia, L. (2006). Applying variable speed limits and the potential for crash migration. *Transportation Research Record: Journal of the Transportation Research Board*, *1953*, 21–30. doi:10.3141/1953-03

Bartels, G., Nelissen, W., & Ruelle, H. (1998). *De transactionele overheid communicatie als instrument: zes thema's in de overheidsvoorlichting*. Utrecht: Kluwer.

Borenstein, M., Hedges, L., & Rothstein, H. (2007). *Meta-analysis: fixed effect vs. random effects*. Retrieved from www.meta-analysis.com

Boulanger, A., Dewil, N., & Silverans, P. (2011). *Attitudemeting verkeersveiligheid 2009. Deel 3: sociale normen, risicoperceptie en nieuwe thema's* (D/2012/0779/33). Brussel: Belgisch Instituut voor de Verkeersveiligheid.

Budd, L., Scully, J., & Newstead, S. (2011). *Evaluation of the Crash Effects of Victoria's Fixed Digital Speed and Red-light Cameras* (No. 307). Victoria: Monash University, Accident Research Centre.

Bureau of Infrastructure, Transport and Regional Economics (BITRE). (2012). *Evaluation of the national black spot program* (BITRE report 126). Canberra: Department of Infrastructure and Transport.

Cammack, M., Cairney, P., Turner, B., & Steinmetz, L. (2012). *An introductory guide for evaluating effectiveness of road safety treatments* (AP-R421-12). Sydney: Austroads.

Carpentier, A., & Nuyttens, N. (2013). *Jaarrapport verkeersveiligheid 2011: Analyse van de verkeersveiligheidsindicatoren in Vlaanderen tot en met 2011*. Steunpunt Verkeersveiligheid & Belgisch Instituut voor de Verkeersveiligheid.

Cascetta, E., Punzo, V., & Montanino, M. (2011). Empirical analysis of effects of automated section speed enforcement system on traffic flow at freeway bottlenecks. *Transportation Research Record: Journal of the Transportation Research Board*, *2260*, 83–93. doi: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. In *TRB 89th Annual Meeting Compendium of Papers*. Washington, D.C.

De Ceunynck, T., De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2011). *Identification of factors contributing to the occurrence of crashes at high-risk locations* (RA-MOW-2011-027). Diepenbeek: Steunpunt Mobiliteit en Openbare Werken, Spoor Verkeersveiligheid.

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014a). An evaluation of the traffic safety effect of fixed speed cameras. Safety Science, 62, 168–174. doi: 10.1016/j.ssci.2013.07.028

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014b). Automated section speed control on motorways: An evaluation of the effect on driving speed. Accident Analysis and Prevention, 73, 313-322. doi: 10.1016/j.aap.2014.09.005

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014c). Behavioural effects of fixed speed cameras on motorways: Overall improved speed compliance or kangaroo jumps? Accident Analysis and Prevention, 73, 132-140. doi: 10.1016/j.aap.2014.08.019

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014d). Safety effects of an extensive black spot treatment programme in Flanders-Belgium. Accident Analysis & Prevention, 66, 72-79. doi: 10.1016/j.aap.2014.01.019

De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014e). To brake or to accelerate? Safety effects of combined speed and red light cameras. Journal of Safety Research, 50, 59–65. doi: 10.1016/j.jsr.2014.03.011

De Pauw, E., Daniels, S., Thierie, M., & Brijs, T. (2014f). Safety effects of reducing the speed limit from 90 km/h to 70 km/h. Accident Analysis & Prevention, 62, 426–431. doi:10.1016/j.aap.2013.05.003

Elvik, R. (1997). Effects on accidents of automatic speed enforcement in Norway. *Transportation Research Record: Journal of the Transportation Research Board*, *1595*, 14–19. doi:10.3141/1595-03

Elvik, R. (1998). Evaluating the statistical conclusion validity of weighted mean results in meta-analysis by analysing funnel graph diagrams. *Accident*

Analysis & Prevention, *30*(2), 255–266. doi:10.1016/S0001-4575(97)00076-6

Elvik, R. (2002). The importance of confounding in observational before-and-after studies of road safety measures. *Accident Analysis & Prevention*, *34*, 631–635. doi:10.1016/S0001-4575(01)00062-8

Elvik, R. (2007). *State-of-the-art approaches to road accident black spot management and safety analysis of road networks* (TØI report 883/2007). Oslo: Institute of Transport Economics. Norwegian Centre for Transport Research.

Elvik, R. (2008a). Dimensions of road safety problems and their measurement. *Accident Analysis & Prevention*, *40*, 1200–1210. doi:10.1016/j.aap.2008.01.004

Elvik, R. (2008b). The predictive validity of empirical Bayes estimates of road safety. *Accident Analysis & Prevention*, *40*, 1964–1969. doi:10.1016/j.aap.2008.07.007

Elvik, R. (2009). *The Power Model of the relationship between speed and road safety. Update and new analyses.* (TØI Report 1034/2009). Oslo: Institute of Transport Economics. Norwegian Centre for Transport Research.

Elvik, R. (2011). Traffic safety. In: Kutz, M. (Ed.), Handbook of Transportation Engineering. Applications and Technologies, vol. II. New York: McGraw Hill.

Elvik, R. (2012). Analytic choices in road safety evaluation: Exploring second-best approaches. *Accident Analysis & Prevention*, *45*, 173–179. doi:10.1016/j.aap.2011.12.006

Elvik, R. (2013). A re-parameterisation of the Power Model of the relationship between the speed of traffic and the number of accidents and accident victims. *Accident Analysis & Prevention*, *50*, 854–860. doi:10.1016/j.aap.2012.07.012

Elvik, R., Christensen, P., & Amundsen, A. (2004). *Speed and road accidents. An evaluation of the Power Model* (No. 740/2004). Oslo: Institute of Transport Economics. Norwegian Centre for Transport Research.

Elvik, Høye, A., Vaa, T., & Sorensen, M. (2009). *The handbook of road safety measures*. Emerald Group Publishing Limited.

Elvik, R., & Mysen, A. B. (1999). Incomplete accident reporting: meta-analysis of studies made in 13 countries. *Transportation Research Record: Journal of the Transportation Research Board*, *1665*, 133–140. doi:10.3141/1665-18

Elvik, & Vaa, T. (2004). *The handbook of road safety measures*. Elsevier.

European Commission. (2010). *Dynamic speed limits*. Retrieved from ec.europa.eu/transport/road_safety/index_en.htm

Federal Highway Administration, U.S. Department of Transportation. (2013). *Introduction to safety performance functions.* Retrieved from http://safety.fhwa.dot.gov/tools/crf/resources/cmfs/docs/safety_performance_funtions.pdf

Federal Highway Research Institute (2005). *Road safety and environmental benefit-cost and cost-effectiveness analysis for use in decision-making. Recommendations WP5*. Germany: BASt

Fleiss, J. L. (1981). *Statistical Methods for Rates and Proportions. Second Edition*. New York: John Wiley.

Fridstrøm, L., Ifver, J., Ingebrigtsen, S., Kulmala, R., & Thomsen, L. K. (1995). Measuring the contribution of randomness, exposure, weather, and daylight to the variation in road accident counts. *Accident Analysis & Prevention*, *27*(1), 1–20. doi:10.1016/0001-4575(94)E0023-E

Fudala, N. J., & Fontaine, M. D. (2010). Interaction between system design and operations of variable speed limit systems in work zones. *Transportation Research Record: Journal of the Transportation Research Board*, *2169*, 1–10. doi:10.3141/2169-01

Gains, A., Nordstrom, M., Heydecker, B. G., & Shrewsbury, J. (2005). *The national safety camera programme: Four-year evaluation report.* London: PA Consulting Group.

Garber, N. J., Miller, J. S., Abel, R. E., Eslambolchi, S., & Korukonda, S. K. (2007). *The impact of red light cameras (photo-red enforcement) on crashes in Virginia* (FHWA/VTRC 07-R2). Virginia: Virginia Transportation Research Council.

Goldenbeld, C. (2002). *Publiek draagvlak voor verkeersveiligheid en verkeersveiligheidmaatregelen* (D-2002-2). Leidschendam: Stichting Wetenschappelijk Onderzoek Verkeersveiligheid.

Habtemichael, F. G., & de Picado Santos, L. (2013). Safety and operational benefits of variable speed limits under different traffic conditions and driver compliance levels. *Transportation Research Record: Journal of the Transportation Research Board*, *2386*, 7–15. doi:10.3141/2386-02

Hasson, P., Kauppila, J., Assing, K., Yannis, G., & Lassarre, S. (2012). Challenges and opportunities for the assessment of the effectiveness of road safety measures. *Procedia - Social and Behavioral Sciences*, *48*, 3230–3238. doi:10.1016/j.sbspro.2012.06.1289

Hauer, E. (1997). *Observational Before-After Studies in Road Safety*. Oxford: Pergamon.

Hauer, E., & Hakkert, A. S. (1988). Extent and some implications of incomplete accident reporting. *Transportation Research Record*, *1185*, 1–10.

Hauer, E., Harwood, D. W., Council, F. M., & Griffith, M. S. (2002). Estimating safety by the empirical Bayes method: a tutorial. *Transportation Research Record*, *1784*, 126–131. doi:10.3141/1784-16

Hess, S. (2004). Analysis of the effects of speed limit enforcement cameras: Differentiation by road type and catchment area. *Transportation Research Record: Journal of the Transportation Research Board*, *1865*, 28–34. doi:10.3141/1865-05

Hoogendoorn, R. G., Harms, I. M., Hoogendoorn, S. P., & Brookhuis, K. A. (2012). Dynamic Maximum Speed Limits: Perception, Mental Workload, and Compliance. *Transportation Research Record: Journal of the Transportation Research Board*, *2321*, 46–54. doi:10.3141/2321-07

Høye, A. (2013). Still red light for red light cameras? An update. *Accident Analysis & Prevention*, *55*, 77–89. doi:10.1016/j.aap.2013.02.017

IBM. (2011). *IBM SPSS Statistics 20 Algorithms*. Retrieved from www.IBM.com

INRIX. (2013). INRIX National Traffic Scorecard. Retrieved from www.inrix.com/scorecard/

Islam, M. T., Hadiuzzaman, M., Fang, J., Qiu, T. Z., & El-Basyouny, K. (2013). Assessing mobility and safety impacts of a variable speed limit control strategy. *Transportation Research Record: Journal of the Transportation Research Board*, *2364*, 1–11. doi:10.3141/2364-01

Jost, G., & Allsop, R. (2014). *Ranking EU progress on road safety. 8th road safety performance index report*. Brussels: ETSC.

Kwon, E., Brannan, D., Shouman, K., Isackson, C., & Arseneau, B. (2007). Development and field evaluation of variable advisory speed limit system for work zones. *Transportation Research Record: Journal of the Transportation Research Board*, *2015*, 12–18. doi:10.3141/2015-02

Lee, C., & Abdel-Aty, M. (2008). Testing effects of warning messages and variable speed limits on driver behavior using driving simulator. *Transportation Research Record: Journal of the Transportation Research Board*, *2069*, 55–64. doi:10.3141/2069-08

Lee, C., Hellinga, B., & Saccomanno, F. (2004). Assessing safety benefits of variable speed limits. *Transportation Research Record: Journal of the Transportation Research Board*, *1897*, 183–190. doi:10.3141/1897-24

Lee, C., Hellinga, B., & Saccomanno, F. (2006). Evaluation of variable speed limits to improve traffic safety. *Transportation Research Part C*, *14*(3), 213–228. doi:10.1016/j.trc.2006.06.002

Li, H., Graham, D. J., & Majumdar, A. (2013). The impacts of speed cameras on road accidents: An application of propensity score matching methods. *Accident Analysis & Prevention*, *60*, 148–157. doi:10.1016/j.aap.2013.08.003

Liu, P., Zhang, X., Wang, W., & Xu, C. (2011). Driver Response to Automated Speed Enforcement on Rural Highways in China. *Transportation Research Record: Journal of the Transportation Research Board*, *2265*, 109–117. doi:10.3141/2265-12

Lyon, C., Haq, A., Persaud, B., & Kodama, S. T. (2005). Safety performance functions for signalized intersections in large urban areas: Development and application to evaluation of left-turn priority treatment.

Transportation Research Record: Journal of the Transportation Research Board, *1908*, 165–171. doi:10.3141/1908-20

Maher, M., & Mountain, L. (2009). The sensitivity of estimates of regression to the mean. *Accident Analysis & Prevention*, *41*, 861–868. doi:10.1016/j.aap.2009.04.020

Makinen, T. E. (2001). Halo effect of automatic speed enforcement. *Technical Research Centre of Finland*, 341–345.

McCarthy, P. (1998). *Effect of Speed Limits on Speed Distributions and Highway Safety: A survey of literature in Managing speed. Review of current practice for setting and enforcing speed limits* (Special report 254). Indiana: Perdue University, Department of Economics.

McGee, H., Taori, S., & Persaud, B. (2003). *Crash experience warrant for traffic signals* (NCHRP report 194). Washington, D.C.: Transportation Research Board.

Meuleners, L. B., Hendrie, D., Lee, A. H., & Legge, M. (2008). Effectiveness of the black spot programs in Western Australia. *Accident Analysis & Prevention*, *40*, 1211–1216. doi:10.1016/j.aap.2008.01.011

Montella, A., Persaud, B., D'Apuzzo, M., & Imbriani, L. L. (2012). Safety evaluation of automated section speed enforcement system. *Transportation Research Record: Journal of the Transportation Research Board*, *2281*, 16–25. doi:10.3141/2281-03

Montella, A., Punzo, V., & Montanino, M. (2012). Analysis of drivers' compliance to speed limits enforced with an automated section speed enforcement system. In *TRB 91st Annual Meeting Compendium of Papers*. 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 Engineering and Control*, *45*(8), 280–287.

Nas, T. F. (1996). *Cost-benefit analysis: Theory and application*. California: Saga publications.

Nilsson, G. (2004). *Traffic speed dimensions and the power model to describe the effect of speed on safety.* Lund: Lund Institute of Technology.

Nuyttens, N. (2013). *Onderregistratie van verkeersslachtoffers. Vergelijking van de gegevens over zwaar gewonde verkeersslachtoffers in ziekenhuizen met deze in de nationale ongevallenstatistieken.* Brussel: Belgisch Instituut voor de Verkeersveiligheid - Kenniscentrum verkeersveiligheid.

OECD. (2006). *Speed management*. Paris: OECD.

OECD. (2012). *Sharing road safety: Developing an international framework for crash modifications functions.* Paris: OECD.

Ozmen, O., Tian, Z. Z., & Gibby, A. R. (2014). Safety of the Las Vegas left-turn display. *Accident Analysis & Prevention*, *62*, 95–101. doi:10.1016/j.aap.2013.08.006

Papageorgiou, M., Kosmatopoulos, E., & Papamichail, I. (2008). Effects of variable speed limits on motorway traffic flow. *Transportation Research Record: Journal of the Transportation Research Board*, *2047*, 37–48. doi:10.3141/2047-05

Parker, M. R. (1997). *Effect of raising and lowering speed limits on selected roadway sections* (FHWA-RD-92-084). Virginia: U.S Department of Transportation. Federal Highway Administration.

Persaud, B., & Lyon, C. (2007). Empirical Bayes before-after safety studies: Lessons learned from two decades of experience and future directions.

Accident Analysis & Prevention, *39*, 546–555. doi:10.1016/j.aap.2006.09.009

Polders, E., Cornu, J., De Ceunynck, T., Daniels, S., Brijs, K., Brijs, T., Hermans, E. & Wets, G. (2014). Drivers' behavioural responses to combined speed and red light cameras. Manuscript submitted for publication

Porter, B. E. (2011). *Handbook of traffic psychology*. Elsevier.

Quddus, M. (2013). Exploring the relationship between average speed, speed variation, and accident rates using spatial statistical models and GIS. *Journal of Transportation Safety and Security*, *5*, 27–45. doi:10.1080/19439962.2012.705232

Ragnøy, A. (2011). *Automatic section speed control. Results of evaluation.* (No. 2625). Oslo: Directorate of Public Roads.

Retting, R. A., Kyrychenko, S. Y., & McCartt, A. T. (2008). Evaluation of automated speed enforcement on Loop 101 freeway in Scottsdale, Arizona. *Accident Analysis & Prevention*, *40*, 1506–1512. doi:10.1016/j.aap.2008.03.017

Riguelle, F. (2009). *Nationale gedragsmeting snelheid 2003-2007*. Brussel: Belgisch Instituut voor de Verkeersveiligheid - Observatorium voor de verkeersveiligheid.

Riguelle, F. (2012a). *Nationale gedragsmeting Snelheid- 2010*. Brussel: Belgisch Instituut voor de Verkeersveiligheid - Kenniscentrum verkeersveiligheid.

Riguelle, F. (2012b). *Nationale gedragsmeting "snelheid op autosnelwegen" - 2011*. Brussel: Belgisch Instituut voor de Verkeersveiligheid - Kenniscentrum verkeersveiligheid.

Rodegerdts, L., Blogg, M., Wemple, E., Myers, E., Kyte, M., Dixon, M., … Carter, D. (2007). *Roundabouts in the United States* (NCHRP report 572). Washington, D.C.: Transportation Research Board.

Ross, H. L., & Klette, H. (1995). Abandonment of mandatory jail for impaired drivers in Norway and Sweden. *Accident Analysis & Prevention*, *27*, 151–157. doi:10.1016/0001-4575(94)00047-P

SARTRE consortium. (2004). *European drivers and road risk. The SARTRE 3 survey. Part 1 Report on principle analyses*.

SARTRE consortium. (2012). *European road users' risk perception and mobility. The SARTRE 4 survey.*

Schulze, H., & Koßmann, I. (2010). The role of safety research in road safety management. *Safety Science*, *48*(9), 1160–1166. doi:10.1016/j.ssci.2009.12.009

Shinar, D. (2007). *Traffic Safety and Human Behavior*. Oxford: Elsevier.

Shin, K., Washington, S. P., & van Schalkwyk, I. (2009). Evaluation of the Scottsdale Loop 101 automated speed enforcement demonstration program. *Accident Analysis & Prevention*, *41*, 393–403. doi:10.1016/j.aap.2008.12.011

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 Analysis & Prevention*, *54*, 46–56. doi:10.1016/j.aap.2013.01.018

Sørensen, M., & Elvik, R. (2007). *Black Spot Management and Safety Analysis of Road Networks* (No. 119/2007). Oslo: Institute of Transport Economics. Norwegian Centre for Transport Research.

Srinivasan, R., Council, F., Lyon, C., Gross, F., Lefler, N., & Persaud, B. (2008). Safety Effectiveness of Selected Treatments at Urban Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, *2056*, 70–76. doi:10.3141/2056-09

Srinivasan, R., Lyon, C., Persaud, B., Baek, J., Gross, F., Smith, S., & Sundstrom, C. (2012). Crash modification factors for changes to left-turn phasing. *Transportation Research Record: Journal of the Transportation Research Board*, *2279*, 108–117. doi:10.3141/2279-13

Subbiah, M., & Srinivasan, M. R. (2008). Classification of 2×2 sparse data sets with zero cells. *Statistics & Probability Letters*, *78*. doi:10.1016/j.spl.2008.06.023

Sweeting, M. J., Sutton, A. J., & Lambert, P. C. (2004). What to add to nothing? Use and avoidance of continuity corrections in meta-analysis of sparse data. *Statistics in Medicine*, *23*, 1351–1375. doi:10.1002/sim.1761

SWOV. (2010). The high risk locations approach. Retrieved from www.swov.nl/rapport/Factsheets/UK/FS_Blackspots.pdf

Thomas, L. J., Srinivasan, R., Decina, L. E., & Staplin, L. (2008). Safety effects of automated speed enforcement programs: Critical review of international literature. *Transportation Research Record: Journal of the Transportation Research Board*, *2078*, 117–126. doi:10.3141/2078-16

Transportation research board, National Research Council. (1998). *Managing speed. Review of current practice for setting and enforcing speed limits* (Special report 254). Washington, D.C.: National Academy Press.

Transportation research board, National Research Council. (2010). *Highway Capacity Manual 2010*. Washington, D.C.

Vaa, T. (1997). Increased police enforcement: effects on speed. *Accident Analysis & Prevention*, *29*, 373–385. doi:10.1016/S0001-4575(97)00003-1

Vanlaar, W., Robertson, R., & Marcoux, K. (2014). An evaluation of Winnipeg's photo enforcement safety program: Results of time series analyses and an intersection camera experiment. *Accident Analysis & Prevention*, *62*, 238–247. doi:10.1016/j.aap.2013.09.023

Van Nes, N., Brandenburg, S., & Twisk, D. (2010). Improving homogeneity by dynamic speed limit systems. *Accident Analysis & Prevention*, *42*, 944–952. doi:10.1016/j.aap.2009.05.002

Wang, X., & Abdel-Aty, M. (2008a). Analysis of left-turn crash injury severity by conflicting pattern using partial proportional odds models. *Accident Analysis & Prevention*, *40*, 1674–1682. doi:10.1016/j.aap.2008.06.001

Wang, X., & Abdel-Aty, M. (2008b). Modeling left-turn crash occurrence at signalized intersections by conflicting patterns. *Accident Analysis & Prevention*, *40*, 76–88. doi:10.1016/j.aap.2007.04.006

Wegcode. (2013). Retrieved from www.wegcode.be/

CURRICULUM VITAE

Ellen DE PAUW

Personalia

Place of birth	Ghent, Belgium
Date of birth	March 4, 1986
Nationality	Belgian
Address	Hoekstraat 4, 9270 Laarne
E-mail	ellen.depauw@uhasselt.be

Education

2007 – 2009	Master of Science in Health Education and Health Promotion Ghent University, Belgium Degree: magna cum laude
2004 – 2007	Bachelor of Social Nursing Arteveldehogeschool Ghent, Belgium Degree: cum laude

Work experience

Feb 2011 – Feb 2015	Hasselt University, Belgium PhD student Transportation Sciences
Sept 2009 – Feb 2011	Ghent University, Belgium Scientific researcher Health Sciences

Journal publications

• Maes, L., Van Cauwenbergh, E., Van Lippevelde, W., Spittaels, H., De Pauw, E., Oppert, J., Van Lenthe, F., Brug, J., De Bourdeaudhuij I. (2011). Effectiveness of workplace interventions in Europe to promote healthy nutrition: a systematic review. European Journal of Public Health, 22(5), 677-682. doi: 10.1093/eurpub/ckr098

• De Pauw, E., Daniels, S., Thierie, M., & Brijs, T. (2014). Safety effects of reducing the speed limit from 90 km/h to 70 km/h. Accident Analysis & Prevention, 62, 426–431. doi:10.1016/j.aap.2013.05.003

• De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). Safety effects of an extensive black spot treatment programme in Flanders-Belgium. Accident Analysis & Prevention, 66, 72-79. doi:10.1016/j.aap.2014.01.019

• De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). An evaluation of the traffic safety effect of fixed speed cameras. Safety Science, 62, 168–174. doi: 10.1016/j.ssci.2013.07.028

• De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). To brake or to accelerate? Safety effects of combined speed and red light cameras. Journal of Safety Research, 50, 59–65. doi:10.1016/j.jsr.2014.03.011

• De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). Behavioural effects of fixed speed cameras on motorways: Overall improved speed compliance or kangaroo jumps? Accident Analysis and Prevention, 73, 132-140. doi: 10.1016/j.aap.2014.08.019

• De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). Automated section speed control on motorways: An evaluation of the effect on driving speed. Accident Analysis and Prevention, 73, 313-322. doi: 10.1016/j.aap.2014.09.005

Conference publications

- De Pauw, E., Daniels, S., Brijs, T., Hermans, E., Wets, G. (2011). The magnitude of the resgression to the mean effect in traffic crashes. In: Proceedings of the 24th ICTCT workshop. Warsaw, Poland.

- De Pauw, E., Thierie, M., Daniels, S., & Brijs, T. (2012). Safety effects of Restricting the speed limit from 90 to 70 km/h. In TRB 91st Annual Meeting Compendium of Papers DVD. Paper presented at the Transportation Research Board, Washington DC.

- Daniels, S., De Pauw, E., Brijs, T., Hermans, E., & Wets, G. (2012). 10 jaar aanpak van gevaarlijke punten in Vlaanderen. In Jaarboek Verkeersveiligheid 2012. Paper presented at the Flemish traffic safety conference, Ghent.

- De Pauw, E., Thierie, M., Daniels, S., & Brijs, T. (2012). Safety effects of restricting the speed limit from 90 to 70 km/h. Paper presented at the ICTCT 2012 workshop, Hasselt.

- De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2012). The effect of red light cameras on safety. Paper presented at ICTCT 2012 workshop, Hasselt.

- De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). The effect of combined speed and red light cameras on safety. In TRB 92nd Annual Meeting Compendium of Papers. Paper presented at the Transportation Research Board, Washington DC.

- De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). Redesigning black spots in traffic: An effect evaluation. In TRB 92nd Annual Meeting Compendium of Papers. Paper presented at the Transportation Research Board, Washington DC.

- De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). The Magnitude of the regression to the mean effect in traffic crashes. In TRB 92nd Annual Meeting Compendium of Papers. Paper presented at the Transportation Research Board, Washington DC.

- De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). Afremmen of versnellen? Effecten van roodlicht- en snelheidscamera’s in Vlaanderen. In Jaarboek Verkeersveiligheid 2013. Paper presented at the Flemish traffic safety conference, Antwerp.

- De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). The effect of protected left-turn signals on traffic safety. Paper presented at the ICTCT 2013 workshop, Maribor.

- De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). The Traffic safety effect of combined speed and red light cameras. Paper presented at the Transport Research Arena, Paris.

- De Pauw, E., Daniels, S., Thierie, M., & Brijs, T. (2014). Reduction of the Speed limit at highways: An evaluation of the traffic safety effect. Paper presented at the Speed Congress, London.

- De Pauw, E., Van Herck, S., Daniels, S., & Wets, G. (2014). Conflictvrije verkeersregelinstallaties: het effect op de verkeersveiligheid. In Jaarboek verkeersveiligheid 2014. Paper presented at the Flemish road safety conference, Ostend.

Reports

• De Pauw, E., Maes, L., De Bourdeaudhuij, I. (2011). EFeKT. Evalueren Van eFfecten en Kernprocessen van preventieve meThodieken, ontwikkeld binnen de Vlaamse gezondheidsdoelstellingen. (2011/01) Gent: Steunpunt Welzijn, Volksgezondheid en Gezin.

• De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2012). Het programma voor de herinrichting van de gevaarlijke punten op gewestwegen in Vlaanderen: een effectevaluatie. (RA-MOW-2011-021). Diepenbeek: Steunpunt Mobiliteit en Openbare Werken, Spoor Verkeersveiligheid.

• De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2012). Effectevaluatie van snelheids- en roodlichtcamera’s op gewestwegen in Vlaanderen (RA-2012-01). Diepenbeek: Steunpunt Verkeersveiligheid.

• De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). Snelheidscamera’s en trajectcontrole op Vlaamse autosnelwegen. Evaluatie van het effect op snelheidsgedrag en verkeersveiligheid. Diepenbeek: Instituut voor Mobiliteit (IMOB).

• De Pauw, E., Daniels, S., Brijs, T., Hermans, E. & Wets, G. (2014). Dynamic speed limits on motorways. A traffic safety evaluation. Diepenbeek: Steunpunt verkeersveiligheid.

Other publications

- De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). Safety evaluation of a black spot treatment programme in Flanders. The World Road Association (PIARC), 359, 78-83.

- De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). Onderzoek IMOB: trajectcontrole verhoogt veiligheid meer dan flitspaal. Verkeersspecialist 206, 24-25

Supervisor of next master theses:

- Kopmanis, C. (2012). Amenability to treatment of various traffic safety problems. Diepenbeek: Hasselt University

- Van Herck, S. (2013). Conflictvrije verkeersinstallaties: Het effect op de verkeersveiligheid. Diepenbeek: Hasselt University

- Magis, M. (2014). De effectiviteit van dynamische rijstrooksignalisatie in Vlaanderen. Analyse van de gereden snelheid ten opzichte van de maximum snelheid. Diepenbeek: Hasselt University

- Page, N. (2014). Verkeersveiligheid in de Kennedytunnel: Effectiviteit van de snelheidsverlaging van 100 km/u naar 70 km/u. Diepenbeek: Hasselt University

- Bervoets, O. (2014). Introducing the lighting vision: The effects on motorways traffic safety. Diepenbeek: Hasselt University