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Verkeersveiligheid

Gedragsaanpassingen van bestuurders aan snelheids- en roodlichtcamera’s

Vervolgonderzoek: effectiviteit van roodlichtcamera’s

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Inhoudstafel

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Gebruikte afkortingen

RLC	Roodlichtcamera
SRLC	Snelheids- en roodlichtcamera
SRLCWS	Snelheids- en roodlichtcamera met waarschuwingsbord

Gebruikte afkortingen in bijlage

CI	Confidence Interval
FWO	Flemish Research Foundation
GSCD	Green Signal Countdown Devices
ITE	Institute of Transportation Engineers
Kph	Kilometre per hour
Max	Maximum value
Min	Minimum value
RLC	Red Light Camera
ROI	Regions of Interest
SD	Standard Deviation
SE	Standard Error
SRLC	Combined Speed and Red Light Camera
SRLCWS	Combined Speed and Red Light Camera with a Warning Sign
SWOV	Stichting Wetenschappelijk Onderzoek Verkeersveiligheid
TA	Time to Accident
TTC_{min}	Minimal Time to Collision
VIF	Variance Inflation Factor

Gedragsaanpassingen van bestuurders aan snelheids- en roodlichtcamera's. Vervolgonderzoek: effectiviteit van roodlichtcamera's (beknopte versie van het rapport in het Nederlands)

Samenvatting

Aanleiding: Overdreven snelheid en roodlichtnegatie zijn belangrijke oorzaken van ongevallen op verkeerslichtengeregelde kruispunten. Om dit gedrag te ontmoedigen worden verkeerslichtengeregelde kruispunten uitgerust met snelheids- en roodlichtcamera's. De resultaten van een eerdere effectevaluatiestudie van roodlichtcamera's in Vlaanderen toonden echter aan dat roodlichtcamera's weliswaar het aantal zware ongevallen beduidend doen dalen (-14 tot -18%), maar tegelijkertijd leiden tot een stijging van 44% van één type ongevallen, namelijk (meestal minder ernstige) kop-staartongevallen.

Doelstelling: In dit vervolgonderzoek probeerden we deze effecten te verklaren door het rijgedrag van bestuurders op kruispunten met snelheids- en roodlichtcamera's (SRLC's) te observeren. Doel was om beter te begrijpen welke factoren de gevonden stijging van kop-staartongevallen verklaren en vervolgens mogelijke tegenmaatregelen voor te stellen.

Methode: De analyse van het effect op het gedrag van naderende bestuurders gebeurde door gedragsobservaties te combineren met een rijsimulatoronderzoek. Video-opnames op twee verkeerslichtengeregelde kruispunten werden gebruikt om het bestuurdersgedrag voor de plaatsing van de snelheids- en roodlichtcamera (SRLC) te vergelijken met het bestuurdersgedrag na de plaatsing. Daarnaast werd één van deze twee kruispunten nagebouwd in de rijsimulator van het Instituut voor Mobiliteit (Universiteit Hasselt) met als doel om het rij- en kijkgedrag van bestuurders te evalueren. 63 deelnemers naderden het kruispunt in verschillende condities: controle conditie (geen SRLC), conditie met snelheids- en roodlichtcamera (SRLC) en de conditie met snelheids- en roodlichtcamera en waarschuwingsbord (SRLCWS). De data van de 63 deelnemers werden vervolgens gebruikt om de kans op kop-staartbotsingen te schatten via een Monte Carlo simulatie.

Resultaten: De resultaten van de videogebaseerde gedragsobservaties tonen aan dat SRLC's zorgen voor een daling van het aantal snelheidsovertredingen, een daling van de V_{85}-snelheid en een verandering van het keuzegedrag in de dilemmazone (vaker stoppen bij oranje). De resultaten van het rijsimulatoronderzoek geven ook aan dat de kans op een kop-staartbotsing hoger is in de SRLC (6.42) en de SRLCWS conditie (4.01) in vergelijking met de controle conditie (1.00).

Conclusie: Snelheids- en roodlichtcamera's beïnvloeden het bestuurdersgedrag. SRLC's zorgen voor een daling van het aantal snelheidsovertredingen, een daling van de V_{85}-snelheid en een verandering van het keuzegedrag in de dilemmazone (vaker stoppen bij oranje). Daarnaast leiden SRLC's ook tot ongewenste neveneffecten in de vorm van bruuskere remmanoeuvres en een verhoogd risico op kop-staartaanrijdingen. Aangezien waarschuwingsborden de neveneffecten lijken te nuanceren wordt aanbevolen om de bestuurders goed te informeren dat ze een SRLC-kruispunt naderen.

1 Inleiding

Meer dan 400 kruispunten in Vlaanderen zijn uitgerust met roodlichtcamera’s die zowel roodlichtnegatie als een te hoge snelheid detecteren. De resultaten van een eerdere effectevaluatiestudie van roodlichtcamera’s in Vlaanderen (De Pauw, Daniels, Brijs, Hermans, & Wets, 2012) toonden aan dat roodlichtcamera’s weliswaar het aantal zware ongevallen beduidend doen dalen (-14 tot -18%), maar tegelijkertijd leiden tot een stijging van 44% van één type ongevallen, namelijk (meestal minder ernstige) kop-staartongevallen.

In een vervolgonderzoek probeerden we deze effecten te verklaren door het rijgedrag van bestuurders op kruispunten met snelheids- en roodlichtcamera’s te observeren. Doel was om beter te begrijpen welke factoren de gevonden stijging van kop-staartongevallen verklaren en vervolgens mogelijke tegenmaatregelen voor te stellen.

2 Methode

De analyse van het effect op het gedrag van naderende bestuurders gebeurde door gedragsobservaties te combineren met een rijsimulatoronderzoek. Het bestuurdersgedrag werd op twee verkeerslichtengeregelde kruispunten voor de plaatsing van de snelheids- en roodlichtcamera (SRLC) vergeleken met het bestuurdersgedrag na de plaatsing. Bij een dergelijke vergelijking blijft de locatie voor en na de plaatsing van de SRLC identiek (met uitzondering van de SRLC) en wordt verzekerd dat de gevonden effecten te wijten zijn aan de aan- of afwezigheid van de SRLC. Deze vergelijking gebeurde op basis van videobeelden. De videocamera’s registreerden de voertuigen terwijl ze het kruispunt vanuit één kruispunttak naderden. Beide kruispunten werden gedurende twee weken voor en na de plaatsing van de SRLC’s geobserveerd. De video-observaties voor de na-periode startten 6 weken na de plaatsing van de SRLC’s zodat er een zekere gewenningsperiode bestond. Voor beide kruispunten werd 24u beeldmateriaal voor en na de plaatsing van de SRLC geselecteerd voor verdere analyse. Deze 24u werd verspreid over verschillende weekdagen om dagspecifieke toevalsfactoren uit te sluiten. De geselecteerde videobeelden werden vervolgens geanalyseerd om zo het effect van SRLC’s op voertuigsnelheden, het naderingsgedrag bij oranje en kop-staartconflicten vast te stellen.


(a) (b)

Figuur 1. Studielocaties Kapellen (a) en Mechelen (b)

De kruispunten waarop de observaties werden uitgevoerd liggen in stedelijk gebied. Het eerste kruispunt in Kapellen is een viertakskruispunt met een snelheidslimiet van 50km/u, 2x1 rijstroken en een afzonderlijke rijstrook voor links afslaand verkeer. Het kruispunt in Mechelen is een drietakskruispunt met een snelheidslimiet van 70km/u, 2x1 rijstroken en een afzonderlijke rijstrook voor links afslaand verkeer.

Het kruispunt in Kapellen werd ook nagebouwd in de rijsimulator van het Instituut voor Mobiliteit (Universiteit Hasselt) met als doel om het rij- en kijkgedrag van bestuurders te evalueren. 63 deelnemers naderden het kruispunt in verschillende condities: controle conditie (geen SRLC), conditie met snelheids- en roodlichtcamera (SRLC) en de conditie met snelheids- en roodlichtcamera en waarschuwingsbord (SRLCWS). Deze condities verschenen in een willekeurige volgorde. Bij het naderen van het kruispunt werden de deelnemers altijd geconfronteerd met een voorligger (op 65 m) en een achterligger (op 25 m). Het verkeerslicht veranderde van groen naar oranje wanneer de deelnemers zich op 2.5 sec. van de stoplijn bevonden (d.w.z. volgtijd van 2.5 sec.). Hierdoor had elke deelnemer evenveel tijd om te reageren op de faseverandering. De deelnemers kregen de instructie om te rijden zoals ze normaal zouden rijden met hun eigen auto en de verkeersregels toe te passen zoals ze deze dagelijks toepassen.

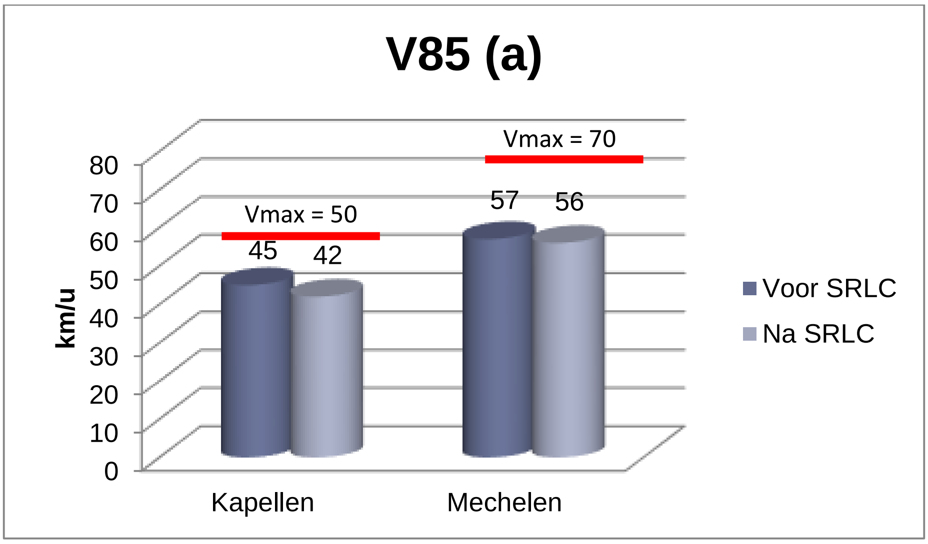
Figuur 2. Werkelijke situatie versus situatie in rijsimulator

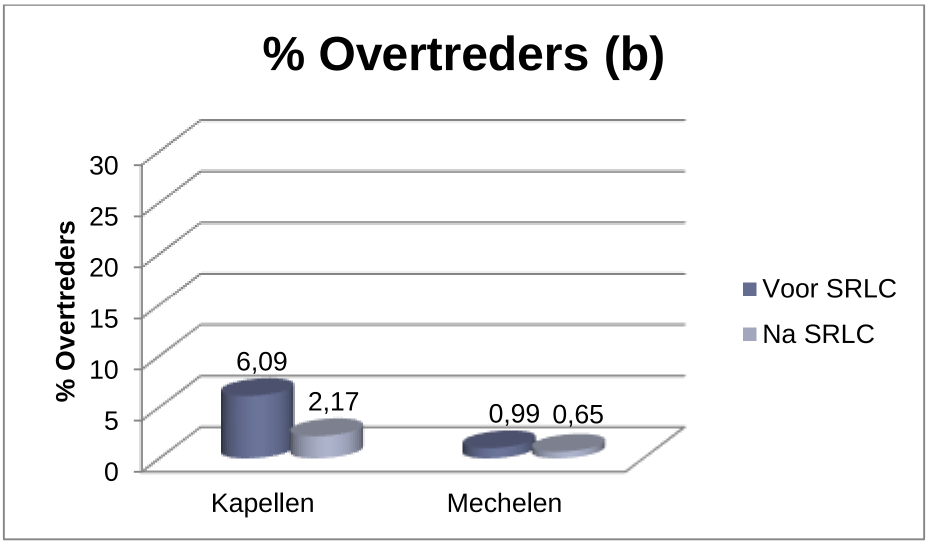
3 Resultaten

3.1 Effect op bestuurdersgedrag

3.1.1 Snelheidsgedrag

De plaatsing van de SRLC toonde op beide kruispunten een gunstig effect op voertuigsnelheden en snelheidsovertredingen. De V_{85}-snelheid daalde in Kapellen (-3 km/u) en Mechelen (-1 km/u); het aantal snelheidsovertredingen daalde van 6.09% naar 2.17% in Kapellen en van 0.99% naar 0.65% in Mechelen. Deze resultaten bevatten ook de voertuigsnelheden van de bestuurders die gestopt zijn bij het rode en oranje verkeerslicht.

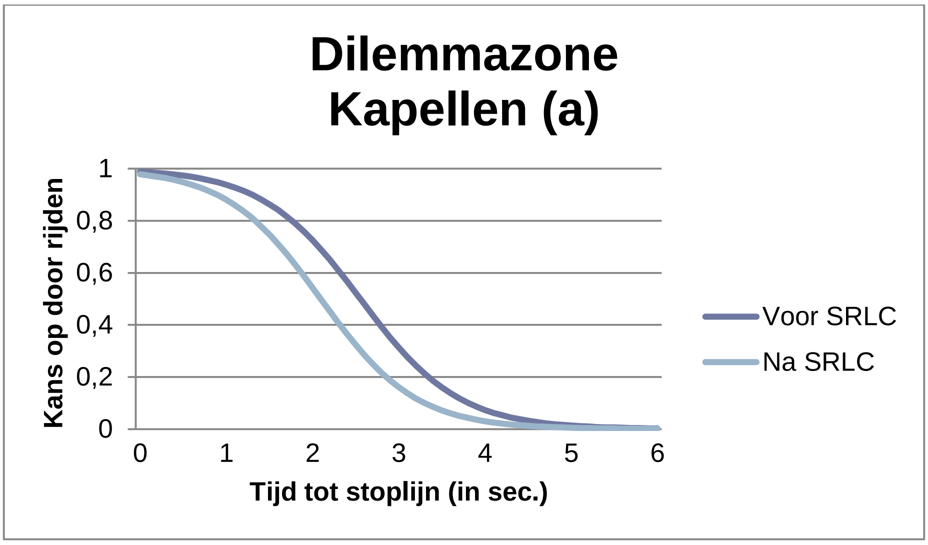


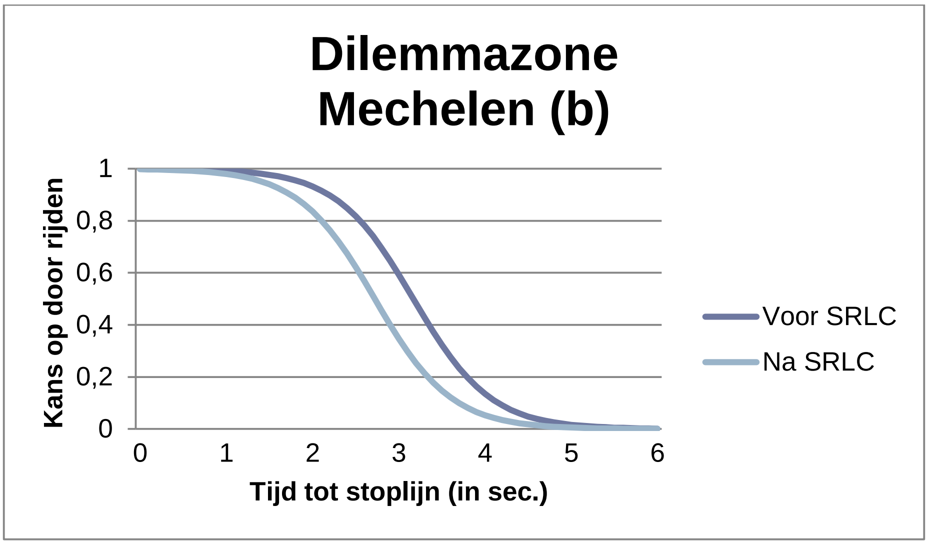


Figuur 3. Effect op snelheidsgedrag: V85 (a) en snelheidsovertredingen (b)

3.1.2 Wel of niet door oranje?

Daarnaast werd het beslissingsgedrag bij oranje op beide kruispunten geanalyseerd. Hierbij is de ‘dilemmazone’ van belang. De dilemmazone is de theoretische locatie op één van de kruispunttakken waar de bestuurder een beslissing (stoppen of doorrijden) dient te nemen bij de faseverandering naar oranje. Voor de bestuurders die geconfronteerd werden met een faseverandering van groen naar oranje werd een verschuiving in de dilemmazone vastgesteld. Deze zone is afgeleid uit de geobserveerde videodata. In dit onderzoek werd de dilemmazone gedefinieerd als het gebied waarin meer dan 10% maar minder dan 90% van de bestuurders besluit te stoppen bij de faseverandering naar oranje. Deze verschuiving in de dilemmazone is zeer gelijklopend voor beide kruispunten. De omvang van de zone blijft na de plaatsing van de SRLC even groot (2.5 sec. voor Kapellen; 2.0 sec. voor Mechelen) maar deze schuift ± 0.5 sec. op naar de stoplijn. Dat wijst erop dat de plaatsing van een SRLC leidt tot een hogere bereidheid tot stoppen tijdens de faseverandering naar oranje, zelfs bij bestuurders die zeer dicht bij de stoplijn genaderd zijn. Terwijl deze hogere stopbereidheid over het algemeen beschouwd kan worden als een gunstig effect, kan deze hogere stopbereidheid bij oranje ook een mogelijke oorzaak zijn van de stijging in kop-staartongevallen.





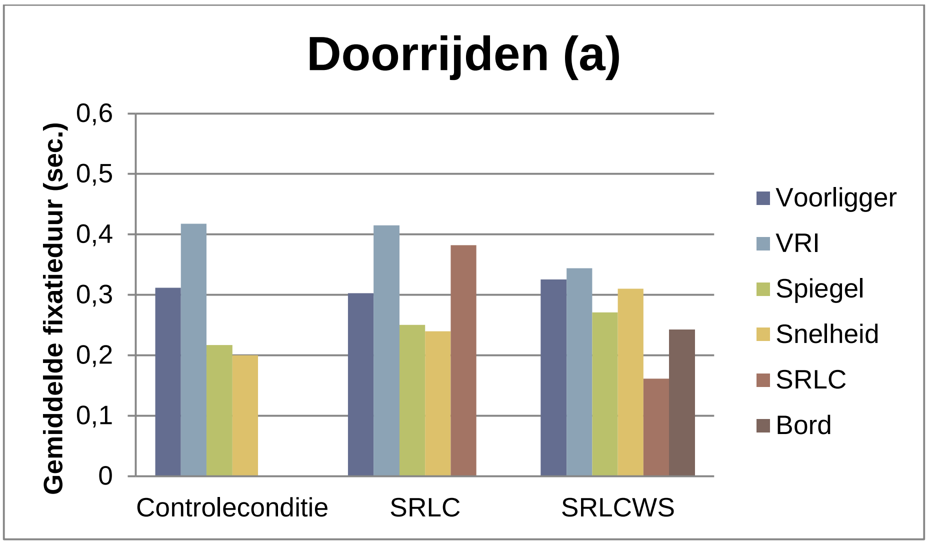
Figuur 4. Verandering keuzegedrag in dilemmazone op kruispunt Kapellen (a) en Mechelen (b)

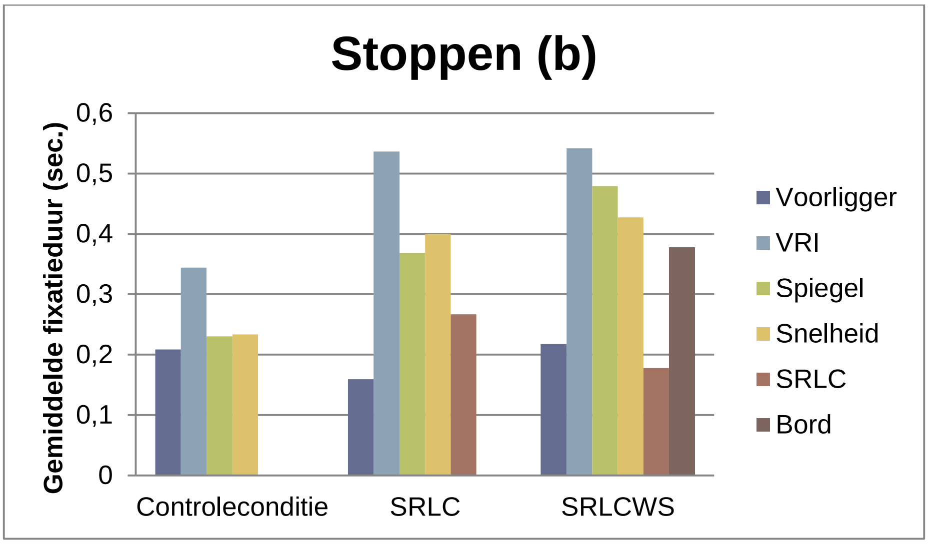
3.1.3 Volggedrag

Het effect van SRLC's op het volggedrag van bestuurders in een voertuig-volgsituatie werd ook onderzocht. Doorgaans wordt een volgtijd van 2 sec. beschouwd als een veilige volgafstand ten opzichte van de voorligger. Na de plaatsing van de SRLC daalde de gemiddelde volgtijd van de voertuigen van 1.92 sec. naar 1.69 sec. in Kapellen en van 2.06 sec. naar 1.64 sec. in Mechelen. SRLC's blijken dus een effect uit te oefenen op de volgtijd. Een mogelijke verklaring hiervoor is de invloed die SRLC's hebben op de voertuigsnelheid. Bestuurders gaan vaak trager rijden op locaties met SRLC's wat leidt tot een kleinere volgtijd.

3.1.4 Kijkgedrag

Een analyse van het kijkgedrag in de rijsimulator toonde aan dat bestuurders die stoppen vaker de SRLC (62% vs. 28%) en SRLCWS (68% vs.51%) hebben waargenomen dan bestuurders die niet stoppen. Hieruit blijkt dat bestuurders meer geneigd zijn om te stoppen als ze een SRLC waarnemen of weten dat ze er één naderen. Vervolgens bleek ook dat de gemiddelde fixatieduur van de bestuurders voor de SRLC langer was in de SRLC-conditie dan in de SRLCWS-conditie. Een mogelijke verklaring hiervoor is dat bestuurders die het waarschuwingsbord hebben opgemerkt niet meer naar de snelheids- en roodlichtcamera kijken.





Figuur 5. Gemiddelde fixatieduur voor 'doorrijden' (a) en 'stoppen' (b)

3.2 Risico op kop-staartaanrijdingen

Behalve het effect op bestuurdersgedrag, werd ook nagegaan welk effect de plaatsing van een SRLC heeft op het risico op kop-staartaanrijdingen. Dit risico werd geschat via een Monte Carlo simulatie gebaseerd op de snelheid/acceleratiedata uit de rijsimulator en de volgtijden geobserveerd op locatie. De stopafstanden werden berekend voor de voor- en achterligger. Een kop-staartaanrijding gebeurde wanneer de som van de stopafstand van de achterligger en de volgafstand groter was dan de stopafstand van de voorligger. Voor elke conditie werden 100.000 iteraties uitgevoerd. De kans op een kop-staartaanrijding lag hoger voor de SRLC (6.42) en de SRLCWS conditie (4.01) in vergelijking met de controle conditie (1.00). Hieruit blijkt dat een SRLC het risico op een kop-staartaanrijding verhoogt. Deze resultaten liggen in lijn met de internationale wetenschappelijke literatuur die eveneens een stijging aangeeft van kop-staartongevallen. De aanwezigheid van een waarschuwingsbord op de toegangswegen naar het kruispunt vermindert het risico op kop-staartconflicten, maar het risico blijft nog steeds hoger dan in situaties waarin geen SRLC aanwezig is. Over het algemeen blijkt de combinatie van een SRLC en waarschuwingsbord de ongunstige effecten (zoals bruuske remmanoeuvres) van SRLC's te verminderen. Dit wordt bevestigd door de resultaten van de rijsimulatorstudie waaruit blijkt dat de gemiddelde deceleratiewaarde voor de SRLCWS conditie (-3.45 m/s²) lager is dan deze voor de SRLC conditie (-4.28 m/s²). De gemiddelde deceleratiewaarde voor de controleconditie bedroeg -2.83 m/s². De remmanoeuvres blijken veel bruusker te zijn in de SRLC conditie en worden min of meer gecompenseerd door de plaatsing van een waarschuwingsbord waarbij ze de normale deceleratiewaarde van -3m/s² benaderen.

4 Aanbevelingen

Het onderzoek toont aan dat snelheids- en roodlichtcamera's (SRLC's) het bestuurdersgedrag beïnvloeden. SRLC's zorgen voor een daling van het aantal snelheidsovertredingen, een daling van de V_{85}-snelheid en een verandering van het keuzegedrag in de dilemmazone (vaker stoppen bij oranje). Daarnaast leiden SRLC's ook tot ongewenste neveneffecten in de vorm van bruuskere remmanoeuvres en een verhoogd risico op kop-staartaanrijdingen. Dit betekent echter niet dat SRLC's niet doeltreffend zouden zijn. In tegendeel, Vlaamse en internationale studies hebben eerder aangetoond dat deze vorm van onbemande verkeershandhaving leidt tot een reductie van het aantal zware verkeersongevallen. Aangezien waarschuwingsborden de neveneffecten lijken te nuanceren wordt aanbevolen om de bestuurders goed te informeren dat ze een SRLC-kruispunt naderen. Dat kan via een waarschuwingsbord maar ook andere middelen zijn denkbaar zoals bijvoorbeeld een markering op de rijbaan of informatie via navigatiesystemen. De resultaten van het onderzoek tonen immers aan dat bestuurders op een minder abrupte en dus veiligere en comfortabelere manier remmen als ze weten dat ze een SRLC naderen. Bovendien blijkt ook dat bestuurders onvoldoende afstand houden. Te korte of onvoldoende volgafstanden zijn een belangrijke oorzaak van kop-staartongevallen. Bestuurders die voldoende afstand houden (≥ 2 sec.), geven zichzelf de tijd en ruimte om de verkeerssituatie te beoordelen en gepast te reageren. Hierdoor is het belangrijk dat bestuurders gesensibiliseerd worden om voldoende afstand te houden. Daarnaast kunnen campagnes ook zinvol zijn om bestuurders te informeren over het gewenste gedrag bij de faseverandering van groen naar oranje. Plots remmen kan immers een factor zijn bij kop-staartaanrijdingen. In dat verband is het nuttig om bestuurders te informeren dat er niet geflitst wordt wanneer ze door oranje rijden. Hierdoor kan het gedrag van bestuurders ter hoogte van kruispunten met SRLC's geharmoniseerd worden zodat kop-staartaanrijdingen voor een belangrijk deel vermeden kunnen worden.

Drivers’ behavioral responses to combined speed and red light cameras. Follow-up study: effectiveness of red light cameras (extended version of the report in English)

Summary

Background: Numerous signalized intersections worldwide have been equipped with enforcement cameras in order to tackle red light running and often also to enforce speed limits. However, various impact evaluation studies of red light cameras (RLCs) showed an increase of rear-end collisions (up to 44%).

Objective: The principal objective of this study is to provide a better insight in possible explaining factors for the increase in rear-end collisions that is caused by placing combined speed and red light cameras (SRLCs).

Method: Real-world observations and driving simulator-based observations are combined. Video recordings at two signalized intersections where SRLCs were about to be installed are used to analyze rear-end conflicts, interactions and driver behavior at two conditions (i.e. with and without SRLC). Furthermore, one of these intersections was rebuilt in a driving simulator equipped with an eye tracking system. At this location, two test conditions (i.e. SRLC and SRLC with a warning sign) and one control condition (i.e. no SRLC) are examined. The data of 63 participants were used to estimate the risk of rear-end collisions by means of a Monte Carlo Simulation.

Results: The results of the on-site observation study reveal decreases in the number of red and yellow light violations, a shift (i.e. closer to the stop line) in the dilemma zone and a time headway reduction after the installation of the SRLC. Based on the driving simulator data, the odds of rear-end collisions (compared to the control condition) for the conditions with SRLC and SRLC + warning sign is 6.42 and 4.01 respectively.

Conclusion: The real-world and driving simulator observations indicate that the risk of rear-end collisions increases when SRLCs are installed. However, this risk might decrease when a warning sign is placed upstream.

1 Introduction

Numerous signalized intersections worldwide have been equipped with enforcement cameras in order to tackle red light running and often also to enforce speed limits. Both red light running and speeding are considered to be substantive problems, frequently leading to collisions. Collisions caused by red light running are typically associated with side impacts, which often lead to severe injuries (Garber, Miller, Abel, Eslambolchi, & Korukonda, 2007; Polders, Daniels, Hermans, Brijs, & Wets, 2014). Red light running at signalized intersections has a significant impact on road safety since this leads to more serious collisions, being side collisions or collisions with vulnerable road users (Kloeden, Ponte, & McLean, 2001; Retting, Ulmer, & Williams, 1999; Shin & Washington, 2007; SWOV, 2011). Urban areas are at greater risk for red light running collisions (De Pauw, Daniels, Brijs, Hermans, & Wets, 2014; Retting, Williams, Preusser, & Weinstein, 1995) since 22% of the collisions in these areas are caused by red light running (Retting et al., 1995). Therefore, road authorities most of the time place red light cameras (RLCs) at signalized intersections to prevent red light running and improve road safety (De Pauw et al., 2014; Llau & Ahmed, 2014; Martinez & Porter, 2006). Studies have shown that RLCs lead to a reduction of up to 44% in red light running (Retting, Ulmer, et al., 1999; Retting, Williams, Farmer, & Feldman, 1999). However, rear-end collisions tend to occur more frequently at these intersections. This is often the result of a sudden braking maneuver of the leading vehicle, resulting in the fact that the following vehicle cannot stop in time (Shin & Washington, 2007). The effects of RLCs on the number of collisions are discussed in more detail below.

1.1 Effectiveness of red light cameras

In general, the effectiveness of RLCs appears to be studied less extensively than the effectiveness of speed cameras. The studies which have been carried out primarily focus on the effects of RLCs on red light running and collisions (i.e. rear-end and side) at intersections. Høye (2013) investigated the effects of RLCs in a meta-analysis. This meta-analysis replicated the results from a previous meta-analysis by Erke (2009). The difference with Erke's study lies in the fact that Høye used a larger sample of RLC studies and provided an answer to the criticisms that were raised by Lund et al. (2009) on Erke's study. Høye (2013) included more recent studies in her meta-analysis and RLC studies that examined the effect of RLCs on the number of intersection collisions were only included when enough information was provided to compute effect estimates and statistical weights. Based on a total of 28 before-after studies, Høye (2013) found a non-significant decrease of all injury collisions by 13%. The number of right angle side collisions decreased by 13%, but the rear-end collisions increased by 39%. Furthermore, the effectiveness of RLCs tended to be higher when warning signs for the RLCs were set up at main entrances to areas with RLC enforcement than when each intersection with a RLC was signposted separately.

The aforementioned studies only examined the effect of cameras that detect red light running. Some recent studies also investigated the effects of combined speed and red light cameras (SRLCs) . These studies are not included in Hoye's meta-analysis.

De Pauw et al. (2014) found an increase of 5-9% of the total injury collisions after the installation of SRLCs at intersections. However, the fatal and serious injury collisions showed a significant decrease of 14-18%. The increase in the number of injury collisions can be mainly attributed to the increased number of rear-end collisions (44%). This number of rear-end collisions had a stronger rise at intersections in urban areas (+70%) than intersections outside the built-up area (+33%).

A time series analysis showed that right angle collisions decreased by 46% at SRLCs intersections, but that there had also been an increase of 42% in rear-end collisions (Vanlaar, Robertson, & Marcoux, 2014). Results indicated that there were significantly fewer red light running violations after installing a SRLC. Furthermore, SRLCs had a protective effect on speeding behavior (also during green phases) at the intersections.

In conclusion, it can be said that all available studies have found a decrease in the number of side collisions after the SRLC was installed. On the other hand, the existing literature also consistently observed an increase in the number of rear-end collisions.

1.2 Dilemma zone

One of the main problems with signalized intersections is that drivers have to make a decision whether or not to stop at the yellow onset (Wilson, 2006; Yan, Radwan, Guo, & Richards, 2009; Zaal, 1994). This decision can be difficult and depends on the current speed and position of the vehicle, the vehicle type (Gates, Noyce, Laracuente, & Nordheim, 2007), the time-to-stop line, the time-to-cross intersection, the presence of an (S)RLC (Huang, Chin, & Heng, 2006) and whether the driver is a leading or following vehicle (Huang et al., 2006; Elmitiny, Yan, Radwan, Russo, & Nashar, 2010).

When the length of the yellow period is insufficient for the driver to stop comfortably, or to pass the stop line before the red phase has started, the driver is considered to be in the dilemma zone. The dilemma zone is a theoretical area of an intersection approach where a driver must take a decision (i.e. stop or go) when the traffic light has switched to yellow (McGee et al., 2012; Wilson, 2006; Yan et al., 2009). The boundaries of the dilemma zone are approximately 2.0-5.5s from the stop line (Bonneson, Middleton, Zimmerman, Charara, & Abbas, 2002; Federal Highway Administration, 2005; McGee et al., 2012). The actions of the driver (e.g. accelerate or brake) increase the potential for a dangerous situation (e.g. rear-end collision) to occur.

Especially when drivers approach a signalized intersection with a high speed, the dilemma zone problem may result in some drivers stopping abruptly while others decide not to stop (or even accelerate). Such variation in driving behavior can lead to collisions (mainly rear-end collisions) on the intersection approach (Institute of Transportation Engineers (ITE), 2009; Yan et al., 2009).

1.3 Warning signs

SRLC warning signs (SRLCWSs) can be used to announce that the next intersection will be equipped with a SRLC. Such warnings may have the potential to reduce the probabilities of collisions nearby intersections (Yan et al., 2009; Zaal, 1994). These warning signs can either be placed at all SRLC intersections or at the start of an area with multiple SRLC intersections. If SRLCWSs are only installed nearby these main entrances, spillover effects are more likely to occur because most drivers will not be aware of the exact locations of the SRLCs (Høye, 2013).

Zaal (1994) concluded that drivers will have more respect for red lights when not all SRLC intersections are signposted, which increases the favorable (i.e. prevention of red light running) and decreases the unfavorable (i.e. sharp braking maneuvers) effects of SRLCs. However, Zaal (1994) also indicated that generalized signposting (e.g. only at the boundaries of a certain area) can have a disadvantage. Generalized signposting may reduce the deterrent effect of site specific signposting, which possibly results in an increase of the number of collisions at potentially dangerous intersections.

Yan et al. (2009) investigated the effectiveness of pavement markings with the word message “Signal Ahead”, which were positioned upstream of signalized intersections. Results indicated that such markings had positive effects on the driving behavior at signalized intersections. The marking reduced the probabilities of both conservative-stop and risky-go decisions. Moreover, the marking contributed to a lower red light running rate and resulted in a lower deceleration rate for drivers who stopped at higher speed limit intersections.

Because rear-end collisions are the most common collision type at signalized intersections, Ni & Li (2013) studied the effectiveness of green signal countdown devices (GSCD). GSCD display the remaining seconds of the current signal status. These devices have been widely installed in Asia, but have both advantages and disadvantages. GSCD shortened the dilemma zone and reduced the number of rear-end collisions near the stop line during the yellow phase. On the other hand, these devices evoked risky car following behavior and resulted in higher rear-end collision probabilities during the flashing green phase (i.e. end of green phase). Therefore, Ni & Li (2013) recommended that GSCD should be installed cautiously.

2 Objectives

A lot of studies have already focused on the road safety performance of red light cameras. However, little is known about the mechanisms contributing to the increase in rear-end collisions. The present study is designed to investigate the behavioral responses of drivers approaching signalized intersections with combined speed and red light cameras (SRLCs) in urban areas. The principal objective of this study is to provide a better insight in possible explaining factors for the increase in rear-end collisions that is caused by placing SRLCs. For this purpose, real-world observations and driving simulator-based observations are combined. Video recordings at two signalized intersections are used to analyze rear-end conflicts, interactions and driver behavior at two conditions (i.e. with and without SRLC). Furthermore, one of these intersections was rebuilt in the driving simulator at Hasselt University's Transportation Research Institute. At this location, two test conditions (i.e. SRLC and SRLCWS) and one control condition (i.e. no SRLC) are examined. Drivers' decision making behavior, looking behavior and the odds of rear-end collisions are examined under these three conditions.

3 Methodology

Two signalized intersections where SRLCs were about to be installed were selected for an on-field behavioral observation study in a before-and-after design. The intersections are both located in urbanized areas but differ in traffic flows, speed limits, number of intersection legs and number of signal cycles per hour. Both intersections are situated in the province of Antwerp, Belgium (see figures 1a and 1b). The intersection in Kapellen is also recreated in a driving simulator. The primary characteristics of both intersections are presented in table 1.

Table 1. Site Characteristics.

Characteristics	Study Sites	
	Kapellen	**Mechelen**
Approach lanes	2x1	2x1
Intersection arms	4	3
Speed limit (kph)	50	70
Cycle lane	Adjacent to roadway	Adjacent to roadway
Separate lane for left turn	35m long	84m long
Number of signal cycles per hour	Day: 52 Night: 76	Day: 36 Night: 36
Area	Urbanized	Urbanized
Function	Functional and recreational activities (home, work, shopping, etc.)	Functional and recreational activities (home, work, shopping, etc.)

(a) (b)

Figure 1. Study site (a) Kapellen and (b) Mechelen.

3.1 Behavioral observation study

A before and after study was implemented at two urban signalized intersections. A video-based data collection system was used to record the road user behavior before and after the installation of SRLCs. The cameras captured the vehicles as they approached the intersection from one intersection leg. The cameras were mounted at lighting poles next to the roadside at 70m (Kapellen) and 80m (Mechelen) upstream of the intersection and aimed downstream at the intersection so that the rear of the vehicles was visible. From this angle, the cameras could capture all the required intersection and vehicle characteristics, such as brake light indications, traffic signal color, vehicle location regarding the stop line, distance between vehicles in a car following situation and the decision of the driver during the yellow phase. The cameras were installed at a height of approximately 9m to allow for accurate extraction of vehicle trajectories and accurate measurement of distances.

3.1.1 Data

Table 2 provides an overview of the data collection and analysis specifics. Video recordings were performed for two weeks at each intersection during the before and after period. The observations for the after period started six weeks after the installation of the SRLCs to reduce the novelty effect. Furthermore, the drivers were not informed about the installation of the cameras and no warning signs were present at the intersections to inform the drivers that they were approaching a SRLC intersection. Afterwards, two observers went through the video recordings and selected 24h of video data for both intersections in the two conditions for detailed analyses. The video data were selected according to predefined criteria to limit any differences between the before and after period to a minimum:

1. Only periods with dry road surface conditions were selected.
2. The duration of the selected time periods in the before and the after period should be the same. These should be selected from at least three different days to reduce the risk of introducing day-specific influences.
3. Weekdays are preferred over weekends.
4. Preferably the weekdays of the after period should be consistent with the selected weekdays in the before period.

Table 2. Data Characteristics.

Study sites	Kapellen	Mechelen
Data characteristics		
BEFORE period	**December 2012**	**June 2013**
Total days recorded	14	14
AFTER period	**May 2013**	**October 2013**
Total days recorded	14	14
Data analysis characteristics		
BEFORE period	**Dry pavement**	**Dry pavement**
Hours [1]	24	24
Weekdays	Tuesday Wednesday Thursday Friday	Tuesday Wednesday Thursday Friday
Number of signal cycles	Day: 832 Night: 608	Day: 576 Night: 288
AFTER period	**Dry pavement**	**Dry pavement**
Hours[1]	24	24
Weekdays	Tuesday Thursday Friday	Monday Tuesday Thursday Friday
Number of signal cycles	Day: 832 Night: 608	Day: 576 Night: 288

[1] Total analyzed time period consisted of a full day (e.g. 24 hours) spread over several weekdays to avoid biased data resulting from day-specific random factors

The selected video data were processed using T-Analyst a semi-automated video analysis system developed at Lund University (T-Analyst, 2014). The system transforms the image coordinates of each individual pixel to road plane coordinates, which allows the software to accurately determine the position of an object in the image. By tracking the position of a road user throughout the video, its trajectory is calculated. This allows the calculation of road users' speeds and positions, distances to fixed objects and traffic conflict indicators in an accurate and objective way.

Data were extracted from the video according to three different encoding procedures:

1) Red/yellow/green light crossing: for every vehicle approaching the intersection, vehicle type, exit movement (left/right/straight through) and the phase of the traffic light at the moment the vehicle crosses the stop line are registered. In this study, a vehicle runs the red, respectively the yellow signal when the vehicle crosses the stop line one second after the onset of the red/yellow phase. According to the Belgian traffic law, it is forbidden to run the red lights in any circumstance and drivers risk severe penalties if they are caught. Yellow light running is allowed by the traffic regulations but drivers should stop if they are able to. As such, time gains are the only benefits drivers have when running the red/yellow signal.

2) Dilemma zone behavior: the decision process of the drivers confronted with a yellow traffic light is examined for every vehicle that is captured by the camera during the yellow phase. In this

study, the dilemma zone is defined as the area in which more than 10% but less than 90% of the drivers decide to stop at the onset of the yellow phase (Zegeer, 1977).

3) Rear-end conflicts: potential rear-end conflict situations are identified by selecting every situation where the first vehicle in a car following process brakes for the yellow light. Subsequently, the second vehicle is captured by the camera at the moment the first vehicle applies the braking maneuver. When these situations are identified, the conflict severity and characteristics are analyzed by means of the minimal time to collision indicator (TTC_{min}). TTC_{min} is the lowest TTC-value that is reached during an encounter process and is calculated by means of the relative distance between two vehicles and their relative speed. TTC_{min} is an indicator for the maximum chance of a conflict. The lower the TTC_{min}, the larger the probability of an collision.

A detailed overview of the collected variables for each encoding procedure is presented in table 3.

3.1.2 Data analysis

3.1.2.1 Descriptive statistics

Pearson's chi-square tests and the independent T-test (Field, 2009) are used to identify the characteristics of drivers' behavior.

3.1.2.2 Logistic Regression Models

Logistic regression models are built to predict the probability of a stop/go decision when a driver is confronted with the yellow phase. These models can be used to predict the probability of a certain event when the dependent variable is a dichotomous variable and the independent variables are continuous or categorical (Allison, 1999; Field, 2009). The functional form of the chosen logistic regression models is the following (Allison, 1999):

$$\mathrm{logit} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \qquad (1)$$

Where

- Logit is the predicted natural logarithm of the odds ratio: ln (P/1-P)
- β_0 is the intercept (constant)
- β_n are the partial logistic regression coefficients. β_1 expresses the influence of x_1 on the logit.
- Every x_n (independent variable) has its own partial logistic regression coefficient β_n.

Odds ratios (OR = Exp(B)) are calculated to determine the rate of decrease ($0 \leq OR < 1$) or increase ($OR > 1$) of the probability of the outcome when the value of the independent variables increases with one unit (Field, 2009). The logistic regression models were developed by the use of the LOGISTIC-procedure in SAS 9.3. The model fit was assessed using the Hosmer and Lemeshow test which indicates if the final model provides a better fit than the null model. If the chi-square goodness-of-fit is not significant at CI 95%, the model has an adequate fit. Since this statistic gives no indication of the error reduction of the final model, Nagelkerke's R^2 was also used. Variance Inflation Factors (VIF) are used to identify multicollinearity between the independent variables. O' Brien (2007) suggests that VIFs higher than 4 indicate a high correlation. Since all variables in the end models have VIFs lower than or near 1, there are no multicollinearity issues in the presented models.

Table 3. Variable summary on-field behavioral observation study.

Variables	Kapellen		Mechelen	
	Before	**After**	**Before**	**After**
Red/yellow/green light crossing	N = 4478	N =4571	N =12538	N =12137
Vehicle				
Car	3747	3811	9331	9149
SUV	131	134	453	531
Truck	207	212	1362	1339
Bus	59	42	71	76
Van	293	257	1142	927
Motorcycle	17	75	146	87
Moped	19	32	19	15
Other	8	8	14	13
Maneuver				
Left turn	916	916	1077	1107
Right turn	449	384	0	0
U-turn	0	0	1	1
Going straight	3109	3275	11460	11029
Traffic light phase				
Red	9	4	3	3
Yellow	143	123	156	123
Green	4326	4444	12379	12137
Dilemma zone behavior	N = 316	N = 303	N = 239	N = 236
Free flow - car following situation at the onset of the yellow phase				
Yes	287	278	210	202
No	29	25	29	34
Speed (m/s) - at the onset of the yellow phase				
Mean	12.24	12.11	13.36	13.06
S.D.	3.10	2.73	3.18	2.88
Min.	3.00	2.00	2.90	1.90
Max.	21.00	20.00	22.00	20.40
Distance to stop line (in m) – the distance of the vehicle to the stop line at the onset of the yellow phase [a]				
Mean	32.25	24.67	34.58	33.81
S.D.	19.37	15.78	14.58	14.73
Min.	0.29	0.73	0.20	0.40
Max.	68.80	56.33	61.41	58.30
Time headway[b] (in s) - the time between the front of the lead vehicle passing a				

point on the roadway and the front of the following vehicle passing the same point.				
Mean	1.90	1.72	1.88	1.65
S.D.	0.95	0.74	0.72	0.75
Min.	0.61	0.60	0.44	0.45
Max.	4.20	3.80	3.91	3.42
Distance headway (in m) - the distance between the two vehicles at the onset of the yellow phase				
Mean	20.88	16.97	21.19	20.04
S.D.	11.51	6.97	9.74	9.26
Min.	4.30	4.21	6.10	6.20
Max.	50.40	29.30	52.80	42.00
Time to stop line[c] (in s) - the time that remains until a vehicle would reach the stop line at the onset of the yellow phase.				
Mean	2.69	2.09	2.67	2.63
S.D.	1.69	1.38	1.22	1.22
Min.	0.03	0.05	0.01	0.45
Max.	9.15	6.91	6.98	7.40
Decision – decision of the driver at the time of the yellow phase				
Stops	158	136	84	112
Drives through	158	147	155	124
Traffic light phase - the color of the traffic light phase at which the vehicle makes the decision to drive through				
Red	10	1	3	3
Yellow	148	146	152	121
Vehicle				
Car	254	218	165	156
SUV	15	18	10	9
Truck	18	11	32	33
Bus	5	4	1	5
Van	24	22	30	32
Motorcycle	0	10	1	1
Moped	0	0	0	0
Other	0	0	0	0
Maneuver - maneuver of the vehicle at the onset of the yellow phase				
Left turn	62	57	45	52
Right turn	34	11	0	0
U-turn	0	0	0	0
Going straight	220	215	194	184
Rear-end conflicts	N =8	N =5	N =8	N =5

Speed V1[d] (in m/s) - the speed of V1 at the onset of the yellow phase				
Mean	8.44	9.4	7.91	8.05
S.D.	2.32	3.11	2.51	3.93
Min.	6.0	4.0	4.0	1.11
Max.	12.0	12.0	12.50	11.3
Speed V2[e] (in m/s) - the speed of V2 at the onset of the yellow phase				
Mean	8.75	11.0	8.55	8.07
S.D.	2.56	3.40	2.17	4.91
Min.	6.0	5.0	5.4	2.11
Max.	13.0	13.5	11.60	12.6
Speed evasive action V1[d] (in m/s) – the speed of V1 at the onset of the evasive action of V2				
Mean	6.63	8.90	6.0	5.93
S.D.	2.57	3.63	1.74	3.97
Min.	4.0	2.5	3.3	1.0
Max.	11.0	11.0	8.2	10.8
Speed evasive action V2[e] (in m/s) – the speed of V2 at the onset of its evasive action				
Mean	9.25	11.2	7.74	8.21
S.D.	2.74	3.78	2.22	4.12
Min.	6.0	4.5	4.0	2.2
Max.	14.0	13.5	11.50	12.4
Intermediate distance (in m) - the distance between the two vehicles at the onset of the evasive action				
Mean	18.15	11.94	13.26	14.42
S.D.	7.71	5.16	3.84	3.65
Min.	7.90	6.89	7.50	10.90
Max.	28.90	19.21	17.90	19.60
Distance to stop line V1[d] (in m) – the distance of the V1 to the stop line at the onset of the yellow phase [g]				
Mean	20.39	22.10	29.43	28.70
S.D.	9.91	4.78	10.30	9.23
Min.	1.32	17.24	12.90	12.70
Max.	33.66	28.47	43.50	36.40
Time to stop line V1[d] (in s) - the time that remains until V1 reaches the stop line at				

the onset of the yellow phase				
Mean	2.55	2.75	3.79	2.77
S.D.	1.57	1.68	1.06	0.83
Min.	0.22	1.68	1.93	1.55
Max.	4.81	5.59	5.24	3.87
Minimum Time to Collision (TTC_{min}) (in s) - minimum value of the time until two road users would have collided had they continued with unchanged speeds and directions				
Mean	2.34	1.66	2.71	2.07
S.D.	0.75	0.89	0.69	0.94
Min.	0.90	0.90	2.03	1.01
Max.	3.80	2.90	3.83	3.67
Time to Accident (TA) (in s) - the time that remains to an accident at the moment the evasive action is initiated, presupposed that the road users had continued with unchanged speeds and directions				
Mean	7.96	6.95	8.44	5.73
S.D.	3.96	2.66	4.40	5.19
Min.	3.80	3.00	4.20	1.71
Max.	15.40	9.50	16.02	11.59
Time headway[f] (in s) - the elapsed time (in s) between the front of V1 passing a point on the roadway and the front of V2 passing the same point.				
Mean	2.00	1.54	1.81	1.63
S.D.	0.66	0.89	0.66	0.23
Min.	1.30	0.70	1.10	1.50
Max.	3.00	2.90	3.20	2.00
Distance headway (in m) - the distance between the two vehicles at the onset of the yellow phase				
Mean	17.73	15.04	14.65	17.66
S.D.	8.45	6.26	3.52	2.70
Min.	7.61	8.48	8.80	14.70
Max.	34.94	24.21	17.90	21.70
Vehicle V1				
Car	7	5	7	4

SUV	0	0	0	0
Truck	0	0	0	1
Bus	0	0	0	0
Van	1	0	1	0
Motorcycle	0	0	0	0
Moped	0	0	0	0
Other	0	0	0	0
Vehicle V2				
Car	6	3	4	4
SUV	2	0	0	0
Truck	0	1	1	0
Bus	0	0	0	0
Van	0	1	1	1
Motorcycle	0	0	2	0
Moped	0	0	0	0
Other	0	0	0	0
Maneuver V1 [d] - maneuver of V1 involved in the conflict				
Left turn	2	1	1	0
Right turn	3	0	0	0
U-turn	0	0	0	0
Going straight	3	4	7	5
Maneuver V2 [e] - maneuver of V2 involved in the conflict				
Left turn	2	1	1	0
Right turn	3	0	0	0
U-turn	0	0	0	0
Going straight	3	4	7	5

[a] Vehicle has not passed the stop line

[b] Calculated at the onset of the yellow phase as a function of distance headway and relative speeds

[c] Calculated as a function of the instantaneous distance to the stop line and speed

[d] V1 = first vehicle or leader in the car following process

[e] V2 = second vehicle or follower in the car following process

[f] Measured at the onset of the yellow phase

[g] Vehicle has not passed the stop line

3.2 Driving simulator experiment

3.2.1 Participants

Sixty-three volunteers (all gave informed consent) participated in the study. No outliers were identified based on the three interquartile distance criterion. Thus, the sample contained 63 participants (39 men), approximately equally divided over four age categories from 20 to 75 years old (mean age 46.2; SD age 18.1). All participants had at least two years of driving experience.

3.2.2 Driving simulator and eye tracker

The experiment was conducted on a medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated). It is a fixed-based (i.e. drivers do not get kinesthetic feedback) driving simulator with a force-feedback steering wheel, brake pedal, and accelerator. The simulation includes vehicle dynamics, visual/auditory (e.g. sound of traffic in the environment and of the participant's car) feedback and a performance measurement system. The visual virtual environment was presented on a large 180° field of view seamless curved screen, with rear view and side-view mirror images (figure 2). Three projectors offer a resolution of 1024 x 768 pixels and a 60Hz frame rate. Data were collected at frame rate.

The eye movements of the participants were recorded while driving through the scenario, making use of a camera-based eye tracking system (faceLAB 5 Seeing Machines) (figure 2). The recorded eye tracking data were analysed with the EyeWorks software package.

Figure 2. Driving simulator and eye tracking equipment

3.2.3 Scenario

3.2.3.1 Road segment development

To rebuild the selected location in the driving simulator environment, a procedure called geo-specific database modeling (Yan, Abdel-Aty, Radwan, Wang, & Chilakapati, 2008) was adopted. In order to reproduce the existing situation as realistic and detailed as possible, we made use of photographs, videos, detailed field measurements, AutoCAD drawings, and Google Street View. A picture of the real world environment and the simulated replica can be found in figure 3.

3.2.3.2 Scenario design

The overall scenario is a systematic combination of the real life replicated section with a set of 2-4km long filler pieces, differing from the analysis sections with respect to design, speed limit, and surrounding environment and meant to provide some variation throughout the scenario.

Figure 5 gives an overview of the intersection, including the positioning of the SRLC and SRLCWS. The analysis zone has a length of 500m, where the stop line at the intersection is set at the relative distance of 0m (cf. figure 5). The traffic lights are placed 5m beyond the stop line (i.e. down the road). Participants were always confronted with a leading vehicle (at 65m) and a following vehicle (at 25m) when approaching the intersection. These vehicles did not influence the stop/go decision of the participants, since the distance headway was sufficiently large and the leading vehicle always drove through the green phase. The signal light turned from green to yellow when participants were 2.5s removed from the stop line (i.e. time to stop line of 2.5s).

All participants were exposed to 3 conditions (i.e. passed the intersection 3 times):

- Control condition: no SRLC was installed
- SRLC condition: a SRLC was installed 15m before the stop line
- SRLCWS condition: a SRLC was installed 15m before the stop line and a red light camera warning sign (SRLCWS) (cf. figure 4) was placed 50m before the stop line.

3.2.3.3 Procedure and design

Participants were asked for their voluntary cooperation and requested to fill out a form with some personal data (e.g. gender, driving experience, date of birth, etc.). After a general introduction, drivers acquainted themselves with the driving simulator by handling various traffic situations (e.g. highway, curves, traffic lights, urban and rural areas) during two practice trips of 4km each. Subsequently, the eye tracking equipment was calibrated. Then participants completed the experimental trip of 14.8km, resulting in a randomized within (3 conditions: control, SRLC, SRLCWS) subjects design. Subjects were asked to drive as they normally would do with their own car and apply the traffic laws as they would do (or would not do) in reality. A GPS voice instructed them during the trip.

Figure 3. Real world vs. simulator image at intersection.

Figure 4. Red light camera warning sign (SRLCWS).

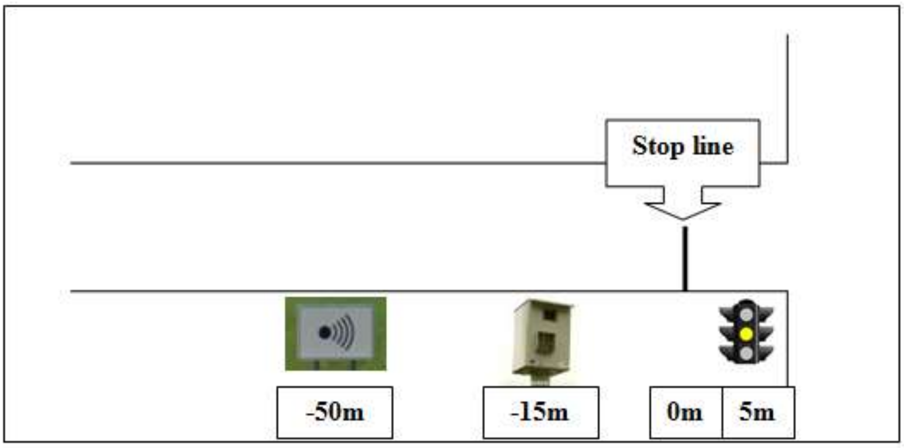


Figure 5. Scenario overview.

3.2.4 Data collection and analysis

3.2.4.1 Dependent measures

Driving performance measures for both longitudinal and lateral control were recorded by the simulator. For this study, measures for longitudinal control are particularly of interest. The speed (in m/s) of the participants at the yellow onset is used in the Monte Carlo Simulation below. Furthermore, mean acceleration/deceleration (acc/dec) [in m/s²] is also an important measure regarding the probability of rear-end collisions. Another dependent measure (i.e. distance headway) needed for the Monte Carlo Simulation was gathered at the real world location by means of observations.

Concerning the eye tracking data, the percentage of participants that fixated on the regions of interest (ROI) and the mean fixation duration are analyzed when the participants approached the intersections. Here we make a distinction between the participants who stopped for the yellow light (i.e. ‘stop’) and drove through (i.e. ‘go’).

3.2.4.2 Data analysis

The odds of rear-end collisions for each condition are estimated by means of a Monte Carlo Simulation using a normal distribution. The distance headway data observed at the real world location (i.e. field observations) are gathered from the behavioral observations described above. Since no setting with a SRLCWS has been implemented on field, the data could only be collected for the control (n = 18) and SRLC (n = 9) conditions. Therefore, the data from the SRLC condition are also used for the SRLCWS condition. To calculate the risk of rear-end collisions for each condition, the following parameters are used:

- Following vehicle
  - V_0: mean speed (in m/s) at the yellow onset (based on simulator data). Since the participants are the leading vehicle and we have no speed data for the following vehicle, the speed of the following vehicle is assumed to be comparable to the speed of the leading vehicle.
  - a: maximum deceleration value (in m/s^2) based on simulator data, assuming that the driver in the following vehicle can adjust his/her behavior based on the leading vehicle and even can make an emergency stop when necessary. Since the highest overall value is selected, the maximum deceleration rate is constant for all conditions.
  - $t_{reaction}$: reaction time (in s) based on the literature (Caird, Chisholm, Edwards, & Creaser, 2007; Liu, Bonsall, & Young, 2003; Yan et al., 2008), calculated with respect to the decision of the leading vehicle to stop.
- Distance headway: distance (in m) between the rear of the leading vehicle and the front of the following vehicle (observed at real world location).
- Leading vehicle
  - V_0: mean speed (in m/s) at the yellow onset (based on simulator data).
  - a: mean deceleration value (in m/s^2) based on simulator data.

For the leading vehicle no reaction time was included in the Monte Carlo Simulation because the reaction time of the following vehicle was selected with respect to the stopping maneuver of the leading vehicle. The Monte Carlo Simulation was performed using Microsoft Excel with 100,000 iterations for each condition. The stopping distance is calculated for both the following and leading vehicle. A rear-end collision will occur when the sum of the stopping distance of the following vehicle and the distance headway is larger than the stopping distance of the leading vehicle.

Concerning the looking behavior, several regions of interest (ROI) are selected: leading vehicle, traffic light, rear view mirror, speedometer (on screen, below the rear view mirror), SRLC, and SRLCWS. The mean fixation duration for these ROI are analyzed using the EyeWorks software package. Fixation durations of less than 0.05s are not taken into account. Subsequently, paired samples t-tests at a 5% confidence level were conducted using SPSS.

4 Results

4.1 Behavioral observation study

4.1.1 Red/yellow/green light running

As displayed in table 3, there are significant associations between red and yellow light running and the presence of a SRLC. Results show a significant decrease in red and yellow light running for both intersections combined, indicating that the odds of drivers obeying the red and yellow phase are 1.20 times higher in the presence of a SRLC.

Table 4. Overview of red/yellow/ green light running

Location	Before SRLC			After SRLC			χ^2	Odds	df
	Red + Yellow	Green	N	Red + Yellow	Green	N			
Kapellen	152	4326	4478	127	4444	4571	2.872°	1.06°	1
Mechelen	159	12379	12538	128	12009	12137	2.446	1.18	1
Both intersections	311	16705	17016	255	16453	16708	4.634*	1.20*	1
* p < .05; °p < 0.10									

The presence of a SRLC seems to influence the violation behavior of drivers in certain vehicle types more strongly. For both intersections, the effect of a SRLC was very favorable for the violation behavior of truck drivers (X^2 (1, N = 3120) = 3.671, p = 0.055). This seems to represent the fact that, based on the odds ratio, the odds of truck drivers obeying the red and yellow phase were 1.71 times higher in the presence of a SRLC.

4.1.2 Dilemma zone behavior

The results of the logistic regression show that the drivers' decision to stop or go at the onset of the yellow phase is influenced by several factors (table 4). The dependent variable is the probability that a driver decides to run the yellow phase. The results indicate that the time-to-stop line significantly influences the decision to run the yellow phase. If the time-to-stop line increases (i.e., if the car is still further away from the stop line), the probability that drivers decide to run the yellow phase will decrease and vice versa. Drivers are also more likely to run yellow when they drive straight through. The presence of a SRLC at the intersections is found to influence the decision to stop or go at the onset of yellow since significantly less drivers decide to drive through the yellow phase if a SRLC is present. Finally, the results also indicate that the decision to run yellow depends on the location. Significantly less drivers decide to run yellow at the intersection in Kapellen compared to the intersection in Mechelen. This difference might be related to the difference in speed limits at both locations (i.e. 50 km/h at Kapellen and 70 km/h at Mechelen).

Table 5. Logistic regression results for decision behavior at the onset of yellow.

Variables[1]	**Logistic regression results: odds of driving through at the onset of yellow**		
	Kapellen (N = 598; Y = 305)	Mechelen (N = 475; Y= 279)	Combined model (N = 1043; Y=584)
Intercept	3.1784***	6.4521***	4.7309***
Time-to-stop line	-1.7447 (**0.18**) ***	-2.3059 (**0.10**)***	-1.9845 (**0.14**)***
Movement			
Going straight	0.6702 (**3.13**)***	0.4871 (**2.65**)***	0.6913 (**3.50**)***
Left turn	-0.1998 (1.31)°	Reference	-0.1296 (**1.54**)°
Right turn	Reference	/	Reference
Red light camera			
Yes	-0.4488 (**0.41**)***	-0.5108 (**0.36**) ***	-0.4838 (**0.38**)***
No	Reference	Reference	Reference
Free flow			
Yes	0.5348 (**2.91**) **		
No	Reference		
Intersection			
Kapellen			-0.5450 **(0.34)*****
Mechelen			Reference
Hosmer and Lemeshow test[2]	χ^2= 8.7222 (df=8 , p= 0.3663)	χ^2= 7.9695 (df=8 , p= 0.4365)	χ^2= 10.9686 (df=8 , p= 0.2035)
Nagelkerke R^2 [3]	0.6558	0.6232	0.6385

NOTE: [1] Values present the parameter estimates of the logistic regression model. For categorical variables with more than 2 categories, the category is indicated;

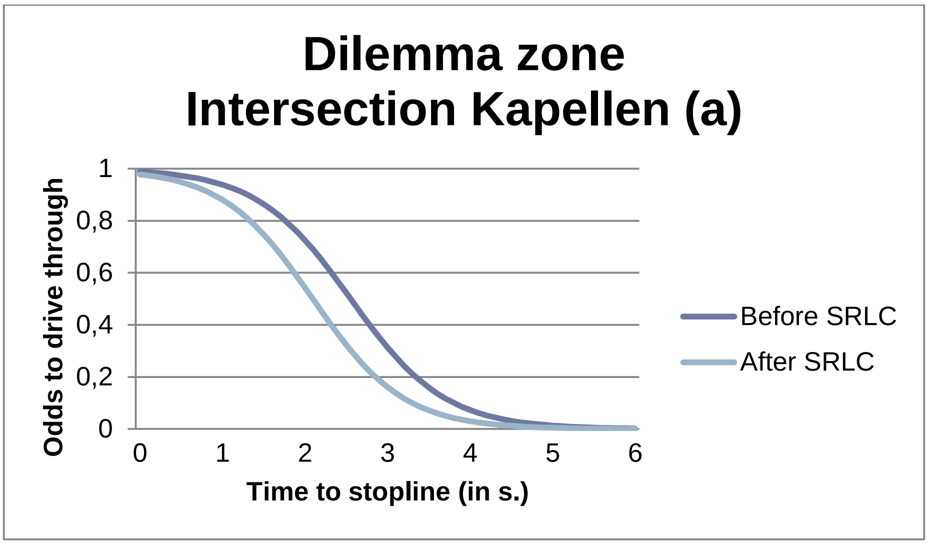
[2] The Hosmer and Lemeshow goodness-of-fit test indicates a good fit for all models;

[3] The statistic indicates the error reduction of the model in percentages; e.g. 0.3087 is equal to an error reduction of 30.87%;

Odds ratios between ().Odds ratio values that are significant at p ≤ 0.05 are highlighted in bold.

*** p≤0.01 (significant at 99% CI); ** p≤0.05 (significant at 95% CI); * p≤0.10 (significant at 90% CI); ° p>0.10 (not significant at 90% CI)

Since the presence of a SRLC influences the decision whether to stop or not at yellow, the SRLC also influences the location of the dilemma zone at both signalized intersections. Figures 6a and 6b illustrate this shift of the dilemma zone. The length of the zone remained the same at the intersections (Kapellen ± 2.5s; Mechelen ± 2.0s) after the installation of the SRLCs compared to the situation with no SRLC.



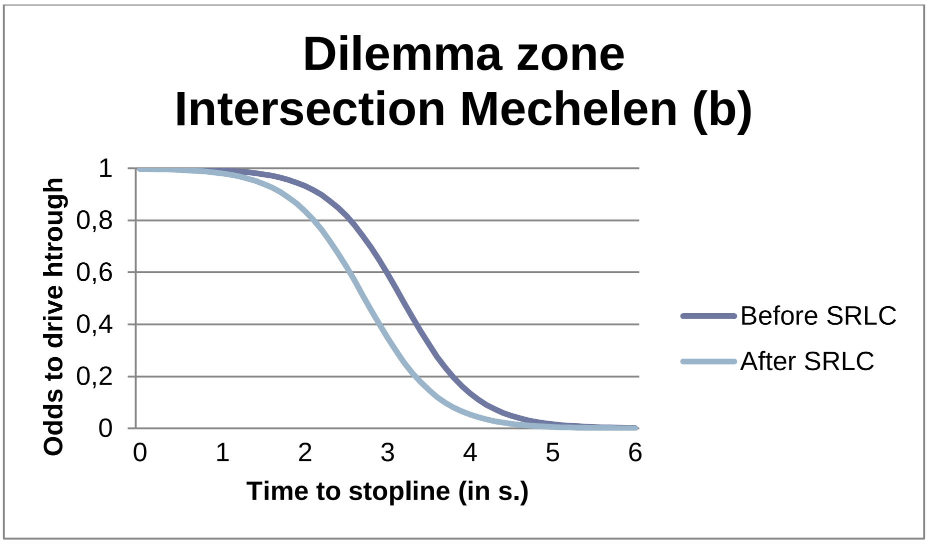


Figure 6. Change in dilemma zone at (a) Kapellen and (b) Mechelen.

However, the installation of a SRLC appears to shift the dilemma zone more closely towards the stop line:

- Kapellen: 10% of the drivers decides to stop at 1.3 sec. and 90% stops at 3.8 sec. of the stop line before the installation of the SRLC compared to 0.9 sec. (10%) and 3.3 sec (90%) after the installation of the SRLC.

- Mechelen: 10% of the drivers decides to stop at 2.2 sec. and 90% stops at 4.2 sec. of the stop line before the SRLC compared to 1.7 sec. (10%) and 3.7 sec (90%) after the SRLC.

These results suggest that drivers' stopping behavior is influenced by SRLCs. In case a SRLC is present, drivers tend to stop earlier and even tend to stop at the onset of yellow when they are very close to the stop line.

4.1.3 Following behavior

Multiple studies (Brackstone, Sultan, & McDonald, 2002; Michael, Leeming, & Dwyer, 2000; Rajalin, Hassel, & Summala, 1997) state that a time headway of 2s (e.g. “two seconds rule”) is the minimum time gap to follow a vehicle safely on a dry road surface. Table 5 compares the time headways of vehicles in a car following situation at the onset of the yellow phase before and after the SRLC installation.

Table 6. Comparison of Time headways (in s.) before and after SRLCs.

Location	Before SRLC			After SRLC			95% CI for Mean Difference	r[1]	t	df
	M	SD	N	M	SD	N				
Kapellen	1.92	0.88	37	1.69	0.75	29	-0.18, 0.64	0.14	1.12	64
Mechelen	2.06	0.79	37	1.64	0.70	39	0.71, 0.75	0.15*	2.41*	74
Both intersections	1.99	0.83	74	1.67	0.72	68	0.64, 0.58	0.20*	2.47*	140
[1] effect size; * p < .05										

As table 5 shows, there is a significant difference between the time headways before and after the SRLC. The time headway decreases after the installation of the SRLC. As such, it indicates that the installation of SRLCs has a significant, but small effect on drivers’ car following behavior.

4.1.4 Occurrence of rear-end conflicts

Table 6 provides the summary statistics (mean values) for the observed rear-end conflict situations at the onset of yellow. The speed at the moment of evasive action is measured at the time that the following vehicle brakes since this is a prerequisite for the occurrence of a rear-end conflict. The Minimum Time-to-Collision (TTC_{min}) indicator is used to assess the conflict severity. All rear-end conflicts with a TTC_{min} less than or equal to 2s are considered to be serious conflicts (Kraay & van der Horst, 1988). The time headway between both vehicles also has a significant influence on the occurrence of rear-end collisions (Huang et al., 2006). As such, the time headway is also an important indicator for rear-end conflicts. In accordance with the “two-seconds-rule”, potential rear-end conflict situations are characterized by a time headway < 2s.

Table 7. Characteristics of rear-end conflict situations.

TTC_{min}	Before SRLC				After SRLC				90% CI for Mean Difference	r[3]	t	df
	M[1]	SD	#serious conflicts[2]	N	M[1]	SD	#serious conflicts[2]	N				
Kapellen	2.34	0.98	3	8	1.66	0.89	3	5	-0.29, 1.65	0.36	1.266	11
Mechelen	2.71	0.69	0	8	2.08	0.94	3	7	-0.11, 1.38	0.39	1.516	13
Both intersections	2.53	0.84	3	16	1.90	0.90	6	12	0.62; 1.19	0.35*	1.893*	26
Time headway												
Kapellen	2.00	0.66	4	8	1.54	0.89	4	5	-1.40, 0,48	031	-1.08	11
Mechelen	1.81	0.66	6	8	1.60	0.19	4	7	-0.77, 0.36	0.21	-0.78	13
Both intersections	1.90	0.65	10	16	1.45	0.64	8	12	-0.87, -0.03	0.34*	-1.85*	26
[1]average TTC_{min}/time headway (in s); [2] conflicts with TTC_{min}/time headway < 2s; [3]effect size; * p < .10												

The results in table 6 reveal significant differences in rear-end conflict severity. The rear-end conflicts tend to be more severe in the presence of a SRLC. The time headway in rear-end conflicts situations also appears to be significantly lower after the installation of the SRLC. Overall, these results indicate that SRLCs have a moderate effect on rear-end conflicts.

4.2 Driving simulator experiment

4.2.1 Stopping behavior

In the control condition 7 participants (i.e. 11%) stopped for the yellow sign. For the SRLC and SRLCWS conditions the number of participants who did not drive through was 8 (i.e. 13%) and 19 (i.e. 30%), respectively. This means that most drivers drove through the yellow phase in the control condition (n = 56), followed by the conditions SRLC (n = 55) and SRLCWS (n = 44). The results of the chi-square analysis indicate that the proportion of drivers that decided to stop is significantly higher (X^2 (2, N = 189) = 9.540, p = 0.008) in the SRLCWS condition compared to the control and SRLC conditions.

4.2.2 Risk of rear-end collisions

Table 7 presents the parameter values (including SD) that were used for the Monte Carlo Simulation. The stopping distances for both the following and the leading vehicle were calculated. For the following vehicle this calculation was based on the reaction time and the braking distance while the stopping distance of the leading vehicle was only based on the braking distance. A simulated rear-end collision occurred when the sum of the stopping distance of the following vehicle plus the distance headway was larger than the stopping distance of the leading vehicle. Given the fact that there were 100.000 iterations for each condition, the number of simulated rear-end collisions was 1973; 12646; and 7984 for the control, SRLC, and SRLCWS condition respectively. As the resulting odds of a rear-end collision in the SRLC (6.42) and the SRLCWS condition (4.01) compared with the control condition were clearly above 1, the revealed probability of a rear-end collision in those conditions is higher than in the control condition.

Table 8. Parameter values (mean and SD) used for the Monte Carlo Simulation.

	Control condition	SRLC condition	SRLCWS condition
Following vehicle			
V_0 (in m/s)	12.69 (1.42)	12.29 (1.95)	11.03 (1.84)
a (in m/s²)	-7.14	-7.14	-7.14
$t_{reaction}$ (in s)	0.75 (0.25)	0.75 (0.25)	0.75 (0.25)
Distance headway (in m)	19.81 (8.56; n = 18)	14.01 (5.51; n = 9)	14.01 (5.51; n = 9)
Leading vehicle			
V_0 (in m/s)	12.69 (1.42)	12.29 (1.95)	11.03 (1.84)
a (in m/s²)	-2.83 (1.42)	-4.28 (2.15)	-3.45 (2.36)

4.2.3 Looking behavior

4.2.3.1 Number of participants that fixated on ROI

Figure 7a shows that the number of participants that fixated on the ROI is approximately equal for the 3 conditions when participants drove through (i.e. ‘go’). However, in the SRLCWS condition participants fixated more on the SRLC compared to the SRLC condition. Remarkable is that 50% of the participants who did not stop at the intersection fixated on the SRLCWS and that approximately 70% fixated on the traffic light (in each condition).

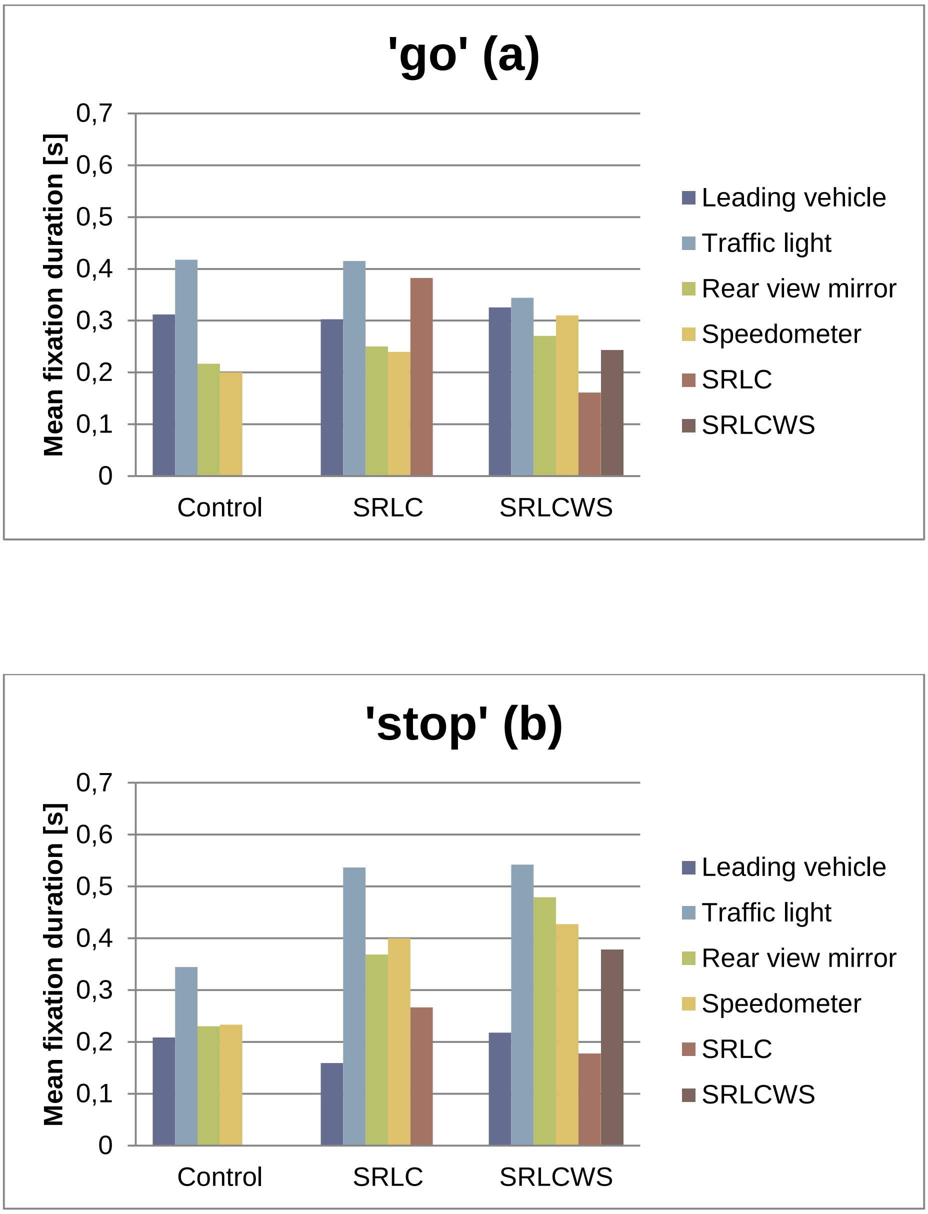
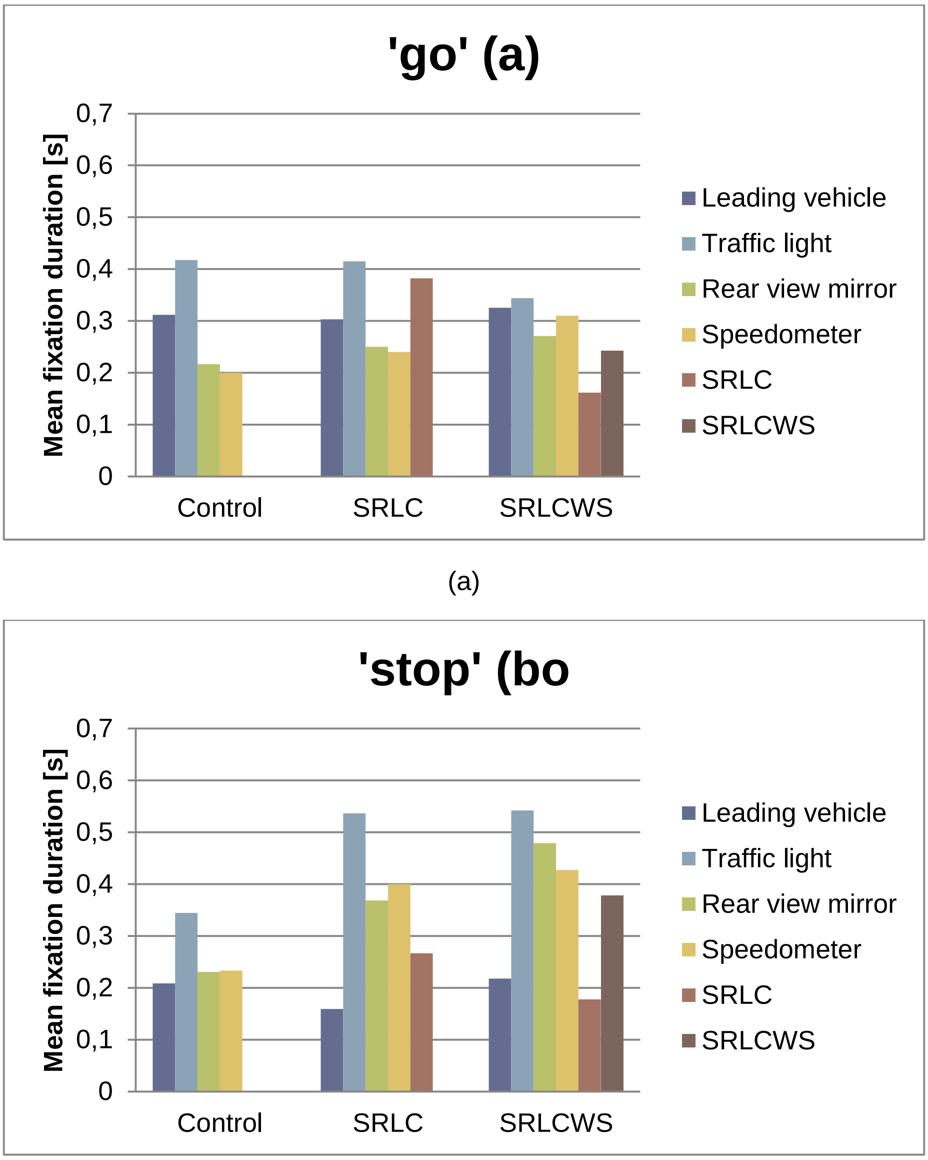


Figure 7. Number of participants that fixated on ROI (a) ‘go’ and (b) ‘stop’.

Figure 7b depicts the looking behavior of the participants who stopped. Here, 100% of the participants fixated on the traffic light in the control and SRLC condition, compared to 72% in the SRLCWS condition. Furthermore, more participants fixated on the SRLC in the SRLC condition than in the SRLCWS condition. In the SRLCWS condition almost 70% of the participants fixated on the warning sign.

4.2.3.2 Mean fixation duration

The mean fixation duration for the participants who drove through the yellow light and the ones that stopped are visualized in figures 8a and 8b, respectively. For the ‘go’ situation, no significant differences for the ROI between the conditions exist. The mean fixation duration for the SRLC tends to differ between the SRLC and SRLCWS condition, but this difference is not significant (t (13) = 1.47; p = 0.167).



(a)

Figure 8. Mean fixation duration for (a) ‘go’ and (b) ‘stop’.

For the participants who stopped (cf. figure 8b) there seems to be a difference in mean fixation time for the traffic light, rear view mirror and speedometer between the control and SRLC condition. These differences are however not statistically significant at a 5% confidence level. Between the conditions SRLC and SRLCWS no statistically significant differences appear at a 5% confidence level either. However, a significant difference in mean fixation time for the SRLC exists between the SRLC and SRLCWS condition at a 10% confidence level (t (4) = 2.46; p = 0.070).

5 Discussion

5.1 Drivers' behavior

5.1.1 Decision behavior

The analyses show a clear impact of SRLCs on drivers' decision whether or not to enter the intersection on yellow/red signal. Firstly, for the full population of motorized road users in the on-site observations, there is a significant reduction in the number of drivers passing through the yellow and red signal. For drivers facing a signal switch to yellow, there is a clear shift in the dilemma zone. The shift is consistent for both observed locations. The dilemma zone moves approximately 0.5s closer towards the stop line. This indicates that also drivers who are closer to the stop line are more inclined to stop when a SRLC is installed at a signalized intersection. Analyses also indicated that, the time to stop line (in line with Huang et al., 2006 and Lum & Wong, 2003) and the driving direction of the vehicle influence the likelihood of stopping for the yellow light. While a higher compliance with the traffic light may generally be considered as a favorable effect, this higher compliance may also partly be responsible for the increase in rear-end collisions. Huang et al. (2006) suggest that the risk for rear-end collisions at intersections with RLCs will decrease for vehicles with a longer estimated time-to-stop-line, but that the risk may increase for vehicles with a shorter time-to-stop-line, especially at higher driving speeds. The simulator experiment showed a strong increase in stopping propensity in case the SRLC is accompanied by a SRLCWS: when a warning sign is installed, 30% of the drivers stop for the yellow light. This is in line with Yan et al (2009).

5.1.2 Following behavior

The on-site observations show a reduction in the time headway between road users after installation of SRLCs. Shorter gap times, especially gap times lower than 2s, are considered to constitute a safety risk (Brackstone et al 2002, Huang et al, 2006, Michael et al 2000; Rajalin et al 1997). If SRLCs lead to shorter gap times between vehicles this is likely to cause more collisions, especially rear-end collisions. Although this result is based on a relatively low number of situations, it may indicate a behavioral effect that could (partly) explain the increase in rear-end collisions at intersections with SRLCs.

5.1.3 Looking behavior

To our knowledge, no study has investigated the looking behavior of drivers nearby intersections equipped with SRLCs and SRLCWSs to date. Concerning the looking behavior, no statistically significant differences were found between the 3 conditions. However, some interesting conclusions can be listed up:

- 'Only' 70% of the drivers who did not stop fixated on the traffic light. However, this does not necessarily mean that the other 30% of the drivers did not notice the traffic light (cf. peripheral vision; (Dewar & Olson, 2007)).
- A higher percentage of the participants who stopped observed the SRLC (62% vs. 28%) and the SRLCWS (68% vs. 51%) compared to the participants who did not stop. This finding emphasizes that people are more inclined to stop when they see a SRLC, or when they know that they are approaching one. It is therefore important that the SRLC is sufficiently conspicuous to drivers.
- Mean fixation duration for both rear view mirror and speedometer is longer in the SRLCWS condition compared to the SRLC condition. Different from that, mean fixation duration for the SRLC was longer in the SRLC condition than in the SRLCWS condition. This can possibly be explained by the fact that participants who have already noticed the SRLCWS, do not look at the SRLC anymore. The longer fixation duration for the rear view mirror in the SRLCWS condition may indicate that drivers check whether they have other road users closely behind them, in order to evaluate the risk of a rear-end collision in case they would stop if a signal

change would take place. Such anticipation may help to reduce the number of rear-end collisions at signalized intersections with SRLCs.

- Mean fixation duration for both rear view mirror and speedometer was longer for the participants who stopped in comparison with the participants who did not stop.
- Participants who stopped had a longer mean fixation duration for the SRLCWS compared to drivers who did not stop (0.38s vs. 0.23s).

5.2 Risk of rear-end conflicts & collisions

The results of the observation study indicate that SRLCs have a moderate effect on the occurrence of rear-end conflicts. Despite the small number of observed rear-end conflicts these results provide an indication that SRLCs increase the rear-end collisions risk. This is confirmed by the driving simulator experiment since the odds of a rear-end collision equals 1.00, 6.42 and 4.01 in the control, SRLC, and SRLCWS condition respectively. This indicates that the presence of a SRLC increases the risk of a rear-end collision. Several studies support this increase (up to 44%) in rear-end collisions (De Pauw et al., 2014; Erke, 2009; Høye, 2013; Persaud, Council, Lyon, Eccles, & Griffith, 2005; Pulugurtha & Otturu, 2014; Shin & Washington, 2007; Vanlaar et al., 2014). Interestingly, when a warning sign is positioned on the approaching segment towards the intersection, this risk decreases even though it remains higher compared to situations where no SRLC is present (i.e. control condition). Other studies (Høye, 2013; Ni & Li, 2013; Zaal, 1994) also found a lower risk of rear-end collisions when a warning sign was installed before (i.e. upstream) (S)RLCs. In general, such (S)RLCWS seem to reduce the unfavorable effects (such as hard braking maneuvers) of (S)RLCs.

Concerning the parameter values used for the Monte Carlo Simulation, we draw the following conclusions. Firstly, the mean driving speed at the yellow onset is highest in the control condition (12.69m/s), and lowest in the SRLCWS condition (11.03m/s). Both values lie below the speed limit of 50kph (i.e. 13.89m/s). The stimulus provided by either the presence of a SRLC or the combination SRLC and SRLCWS is probably responsible for this difference in speed. Subsequently, mean deceleration values of $-2.83 m/s^2$, $-4.28 m/s^2$, and $-3.45 m/s^2$ were found for the control, SRLC, and SRLCWS condition respectively. We can conclude that the deceleration value is highest for the SRLC condition, but decreases to a more ‘normal’ value in the SRLCWS condition. A normal, comfortable braking deceleration value that is recommended is $-3 m/s^2$ (Koppa, 2003; Liu et al., 2003; McGee et al., 2012; Yang, Han, & Cherry, 2013). Høye (2013) also found a smaller deceleration value when a warning sign was installed. Finally, the average distance headway (observed at the real world location) for the control (19.81m) and SRLC (14.01m) condition differs slightly, albeit these values are based on a limited dataset and are both lower than the average distance headway (25-35m) found in the literature (Liu et al., 2003; Yan et al., 2008).

5.3 Strengths, limitations and further research

One of the main assets of this study is the integrated approach of on-site behavioral observations with a driving simulator experiment. To the best of our knowledge, this research design is a unique approach to gain more insight in the effects of SRLCs. Both techniques strengthen each other by showing a number of results that are in line, and complement each other by resulting in different types of data. This has led to a more holistic insight in the behavioral effects of SRLCs.

The use of the semi-automated video analysis software was also important in this study. While this is still a rather time consuming way to analyze road user behavior, it allows for highly accurate, reliable, objective and flexible analyses of revealed micro-level road user behavior. More conventional techniques for field observations such as inductive loops, radars or human observers do not allow the level of detail in the analyses that has been achieved in this study.

Sometimes, the validity of driving simulator research is questioned. One may wonder how realistic the driving behavior of participants is in a simulated road environment compared to their actual driving behavior in a real-world environment (Fisher, Rizzo, Caird, & Lee, 2011). It must be said however that there is enough research showing that driving simulators generally reach high relative validity (i.e. comparing different scenarios in an experimental design) (Bella, 2009; Godley, Triggs, & Fildes, 2002; Törnros, 1998; Yan et al., 2008). However, the geo-specific database modeling technique increases the reliability and validity of the experiment and the results (Yan et al., 2008). In addition, the simulator used in this study is equipped with a 180° field of view, which satisfies the prescribed minimum of 120° field of view for the correct estimation of longitudinal parameters (Kemeny & Panerai, 2003). Therefore, we believe that the validity of the driving simulator experiment is ensured.

A limitation of the study is that the before/after design cannot observe the changes in driver behavior over time. Vanlaar et al. (2014) used a time-series analysis approach to evaluate the impact of a photo enforcement program on speeding and red light running, and found a first indication that the side effects of such an enforcement program decreases over time as drivers become more accustomed to the intervention.

Given the limited number of locations included in the study, it is difficult to infer effect estimations for other intersections. It can reasonably be assumed that the effects (change in dilemma zone, decision behavior, braking maneuvers, etc.) will evolve in the same direction. However, the absolute values or the magnitude of the SRLC(WS) effects on drivers' behavior may differ according to specific intersection characteristics such as speed/geometric and operational conditions.

Furthermore, due to the low number of traffic conflicts in the observation period, the conclusions about the impact of SRLCs on serious conflicts should be treated with caution. Future research should aim at analyzing longer time periods in order to collect more traffic conflict data for more robust conclusions. Also, the robustness of some of the input parameters for the Monte Carlo simulation that were based on the video analyses could possibly be improved by further increasing the observation periods.

This integrated approach shows some clear benefits of combining on-site behavioral observations with driving simulator experiments. Future research about road users' behavioral adaptations to road safety measures or to different infrastructural designs may therefore consider the use of such an integrated study design. Furthermore, the positive impact of the SRLCWS in the driving simulator experiment justifies a field experiment to assess its impact in a real world setting.

6 Conclusions

This study investigated the behavioral responses of road users approaching speed and red light camera sites to gain a better understanding of possible explaining factors for the revealed effects on collisions, in particular the observed increase in the number of rear-end collisions. The actual behavior of drivers approaching a SRLC intersection was observed by means of an on-site before and after study and a driving simulator study.

The results show that combined speed and red light cameras do influence road user behavior. The results of the on-site observation study reveal decreases in the number of red and yellow light violations and a shift (i.e. closer to the stop line) in the dilemma zone after the installation of the SRLC. The findings of the driving simulator study also reveal possible adverse effects of the presence of SRLCs on road user behavior such as stronger decelerations and a possible increase in the number of rear-end collisions. However, in case the presence of SRLCs is announced with warning signs, these adverse effects are somewhat reduced. Although, this latter effect is still unsure.

To conclude, the results reveal behavioral effects after the implementation of the combined speed and red light camera. The observed behavioral effects such as the shift in dilemma zone and the higher deceleration values are responsible for the increase in rear-end collisions mentioned in the international literature.

7 Recommendations

This study revealed some side effects of SRLCs. The identification of these side effects does not imply that SRLCs are not beneficial for road safety. On the contrary, Flemish and international studies have previously shown that this form of automated enforcement leads to a significant decrease in the number of severe crashes. Nevertheless, the Flemish Government can implement various measures to reduce these undesirable side effects.

Since warnings signs seem to nuance and even reduce the side effects to SRLCs to some extent, it is recommend that drivers are well-informed when they approach an intersection equipped with a SRLC. The driver can be informed in several ways: a warning sign at a considerable distance of the intersection, road markings or by means of a warning embedded in navigation systems. After all, the results of this study indicated that drivers brake less abruptly and thus in a more safe and comfortable way if they are aware that they approach a SRLC.

Moreover, it also appears that drivers keep insufficient distance to the vehicle in front of them. Inadequate following distances are a main cause of rear-end collisions. Drivers who keep adequate following distances (≥ 2 sec.), give themselves more time to assess the traffic situation and to respond accordingly. Therefore, it is crucial that drivers are informed to apply an adequate following distance.

Additionally, campaigns should also be applied to inform drivers about the desired behavior during the signal change from green to yellow. Sudden braking maneuvers are a causal factor in rear-end collisions. In this context, it is useful to inform drivers that they are not caught by the SRLC when they run the yellow signal. As a result, the driving behavior will be harmonized at SRLC intersections which leads to decreases in the number of rear-end collisions.

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