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Effectiveness of speed cameras in reducing speed: a systematic review

Eduardo Cesar Amancio [a], Tatiana Maria Cecy Gadda [a], Matheus David Inocente Domingos [a], Jorge Tiago Bastos [b], Gabriela da Costa Bonetti [a], Sara Maria Pinho Ferreira [c], Anelise Schmitz [d], Oscar Oviedo-Trespalacios [e,*]

[a] Federal University of Technology – Paraná (UTFPR), Academic Department of Civil Construction, Graduate Program on Civil Engineering, Campus Ecoville - Deputado Heitor Alencar Furtado Street, 5000 CIC Curitiba, Brazil

[b] Federal University of Paraná (UFPR), Department of Transportation, Graduate Program on Urban Planning, Centro Politécnico - Cel. Francisco H. dos Santos Avenue, 100, Jardim das Américas, Curitiba, Brazil

[c] University of Porto (FEUP), Department of Civil Engineering and Georesources, Roberto Frias Street, 4200-465 Porto, Portugal

[d] Federal University of Paraná (UFPR), Department of Transportation, Centro Politécnico - Cel. Francisco H. dos Santos Avenue, 100, Jardim das Américas, Curitiba, Brazil

[e] Delft University of Technology, Jaffalaan 5 2628 BX Delft P.O. Box 5015 2600 GA, the Netherlands

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ABSTRACT

Speeding has been identified as one of the most common risk factors for the occurrence and severity of traffic accidents. One of the most economical and widespread strategies for speed management is the installation of Speed Cameras (SC). In light of the growing body of evidence in this field and the need for a coherent synthesis of research findings, challenges and gaps, this paper provides a systematic review and an integrated overview of the current state of knowledge on the topic. Five electronic databases (SCOPUS, Web of Science, PubMED, TRID and PROQuest) were used to identify relevant studies. Records were identified, screened, and assessed using a structured multi-stage review process consistent with established systematic review procedures. The included studies reported investigations related to the SC impact on driving speed. A systematic classification scheme was adapted to summarize the study's characteristics. Ninety-four studies were identified. As a result, issues in the study objects, methods and procedures of SC evaluation and impact on vehicle speed assessment were discussed. In particular, due to the complex road environment, other factors also impact driving speed patterns. Additionally, it is demonstrated that the impact of SC on speeds has been assessed by four methods: self-reported questionnaires and location, time, and cross-sectional speed analysis. Complementary research on the following themes would provide interesting insights on SC related studies: understanding how other urban environment factors can influence SC effectiveness; settlement of compliance distance, continuous speed measuring methods associated with time and location speed analysis, and evaluation of the impact of road type, speed limit, and geometry.

1. Introduction

Prevention and reduction in the number and severity of road traffic accidents is an ongoing challenge for transport policymakers. According to the World Health Organization, traffic accidents are the eighth leading cause of death in the world. In absolute numbers, 1.35 million people lost their lives in traffic in 2016 (WHO, 2018). One of the most common risk factors in such accidents is the vehicle speed, which influences both the probability and the severity of a crash. The faster the vehicle is travelling, the greater the energy expended on those involved in the accident, and the greater the injuries (Aarts and Van Schagen, 2006; De Pauw et al., 2014; Wilson et al., 2010). An increase of 1 kph in a vehicle speed results in approximately a 3 % increase in the risk of accidents with injuries, and a 4–5 % increase in the risk of accidents with deaths (WHO, 2018). In addition, previous research has consistently shown a high rate of disrespect for the speed limit by regular drivers. As

* Corresponding author.

E-mail addresses: eduardoamancio@alunos.utfpr.edu.br (E.C. Amancio), tatianagadda@utfpr.edu.br (T.M. Cecy Gadda), matheusdomingos@utfpr.edu.br (M.D. Inocente Domingos), jtbastos@ufpr.br (J.T. Bastos), gabrielabonetti@alunos.utfpr.edu.br (G. da Costa Bonetti), sara@fe.up.pt (S.M. Pinho Ferreira), anelise.schmitz@ufpr.br (A. Schmitz), O.OviedoTrespalacios@tudelft.nl (O. Oviedo-Trespalacios).

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a solution for such a problem, one of the most economical and widespread strategies in the world is the deployment of Speed Cameras (SC).

Some previous reviews focused on the effectiveness of speed cameras. Soole et al. (2013) conducted a literature review about the effects of Average Speed Cameras (ASC) related to compliance with the speed limit and the number of accidents. Pilkington and Kinra (2005) analyzed 14 studies in a systematic review. The authors restricted the investigation by analyzing the impact of SC on preventing accidents and traffic deaths. Besides not restricting the area of device employment, the authors have also considered different types of SC (fixed and mobile). Another systematic review conducted with 22 articles had an even more generic scope. Sadeghi-Bazargani and Saadati (2016) contemplated the analysis of several speed management measures (speed camera, road geometry, speed limit, vehicle warning sign, etc.) in both rural and urban contexts.

Several syntheses have examined SC, yet they differ substantially in scope, outcomes, and analytical depth. Early evidence summarized by Pilkington and Kinra (2005) demonstrated consistent reductions in collisions, injuries, and fatalities, although based largely on observational before–after designs with methodological limitations. Subsequent reviews refined this perspective: Wilson et al.(2010) focused primarily on injury and mortality outcomes, while Høye (2014) conducted a meta-analysis emphasizing section control and average speed enforcement, explicitly identifying behavioral responses such as the "kangaroo jump" phenomenon. In parallel, the critical review by Thomas et al. (2008) synthesized international evidence on automated enforcement programs, highlighting overall safety benefits but also noting heterogeneity in study designs and enforcement contexts. Other reviews have further combined speed enforcement with broader speed management strategies, diluting the specific contribution of SC to speed behavior. Consequently, the evidence base on speed outcomes remains fragmented across study designs, measurement approaches, and contextual settings. Moreover, changes in traffic composition, including the increasing penetration of advanced driver assistance systems (ADAS) capable of supporting speed regulation (Kaye et al., 2024), further complicate direct comparisons with earlier evidence and reinforce the need for updated syntheses focused specifically on speed outcomes.

This paper aims to address this gap by reviewing available evidence to evaluate the effectiveness of speed cameras in terms of speed reduction. We argue that this review provides a contribution to policies and research development because: (1) it is necessary to collect additional evidence on the effectiveness of speed management devices, given the direct relationship between speeding and severity of accidents; (2) the present study differs from previous reviews concerning the inclusion criteria, that is, the specific object of study (all types of speed cameras) and the specific indicator for evaluating their effect (speed variation); and (3) it summarizes a group of procedures, methodologies and techniques for assessing the impact of speed cameras helping the development in this research area.

The article is organized into four sections. The next section contains the research methodology and the protocols for collecting relevant papers. The third section consists of a systematic analysis of the literature. Finally, the fourth section encompasses the conclusions that summarize the main findings and highlight the research paths forward.

2. Methods

2.1. Search protocol

The search was conducted in Google Scholar and academic databases (i. e. PROQUEST, SCOPUS, TRID, Web of Science and PubMED). All searches included the terms "speed camera", "camera enforcement" or "speed enforcement" as mandatory, followed by the words "effectiveness", "evaluation", "road safety", "speed behavior", "speed analysis", "speed limit". These terms were sought in the title, abstract and keywords of the manuscripts. Similar terms were grouped with the expression "or", and each group was combined with the expression "and". Asterisk, question mark and dollar sign ("*", "?" and "$") were also used at the end of each word, in order to cover plural and spelling variations.

The search protocol covers only articles. Other publication forms (e.g. unpublished working papers, master's and doctoral dissertations, newspaper, books and reports) were not included. There was no restriction on the year of publication. The research was concluded in December 2024.

Grey literature (e.g., technical reports, theses, and dissertations) was excluded by design, as the review protocol prioritised peer-reviewed journal and conference publications to enhance methodological rigour and reporting consistency. No restrictions were applied regarding publication year or language during the database searches. Although records in languages other than English were identified, all studies meeting the full inclusion criteria were ultimately published in English. The final language distribution therefore reflects the screening outcome rather than an a priori restriction.

2.2. Inclusion and exclusion criteria

A set of cumulative inclusion criteria was considered: (1) original research; (2) analysis of speed camera (mobile, fixed or average); and (3) analysis related to impacts on speed. Three different criteria were defined for the exclusion of articles: (1) study object (e.g., red light cameras, police enforcement); (2) analysis criteria (e.g., impacts on crashes or public opinion, cost-benefit analysis, etc.); and (3) off-topics (fuel savings, computer and technological science, etc.).

2.3. Material synthesis

The study selection process was structured using elements of the PRISMA framework (Moher et al., 2009). Fig. 1 presents the flow of records through identification, screening, eligibility, and inclusion stages.

Initially, 710 articles were identified through electronic databases, including 90 duplicates. Titles and abstracts were screened for initial exclusion. 456 articles that did not meet the criteria were excluded. The full texts of the remaining studies were then obtained and reviewed using the same exclusion criteria. A total of 92 articles were excluded in this step. In addition, the references of all included studies (77) were searched and screened for relevant studies. As a result, 17 new articles were included. Finally, 94 documents were used in the analysis.

2.4. Systematic classification scheme (SCS)

A Systematic Classification Scheme (SCS) was adopted based on previously published research (Hachicha and Ghorbel, 2012; Lage Junior and Godinho Filho, 2010) and adapted by other systematic review studies, including Jawi et al. (2017) and Oviedo-Trespalacios et al. (2019); Oviedo-Trespalacios et al. (2016). The proposed SCS for this research included four main topics (bibliometry, object of study, methods and procedures and main outcomes), as described in Fig. 2. Each topic included a series of questions intended to summarize the SC analysis from the selected articles.

In particular, the proposed SCS helped in mapping variations in speed camera types, methodologies, procedures, and outcomes. Two reviewers independently screened titles/abstracts and assessed full-text eligibility. Disagreements were resolved through discussion and consensus; if consensus could not be reached, a third senior reviewer would arbitrate. This procedure is consistent with PRISMA reporting recommendations and reduces selection bias.

2.5. Quantitative synthesis: Meta-analysis of mean speed reduction

A meta-analysis was conducted for the subset of eligible field studies

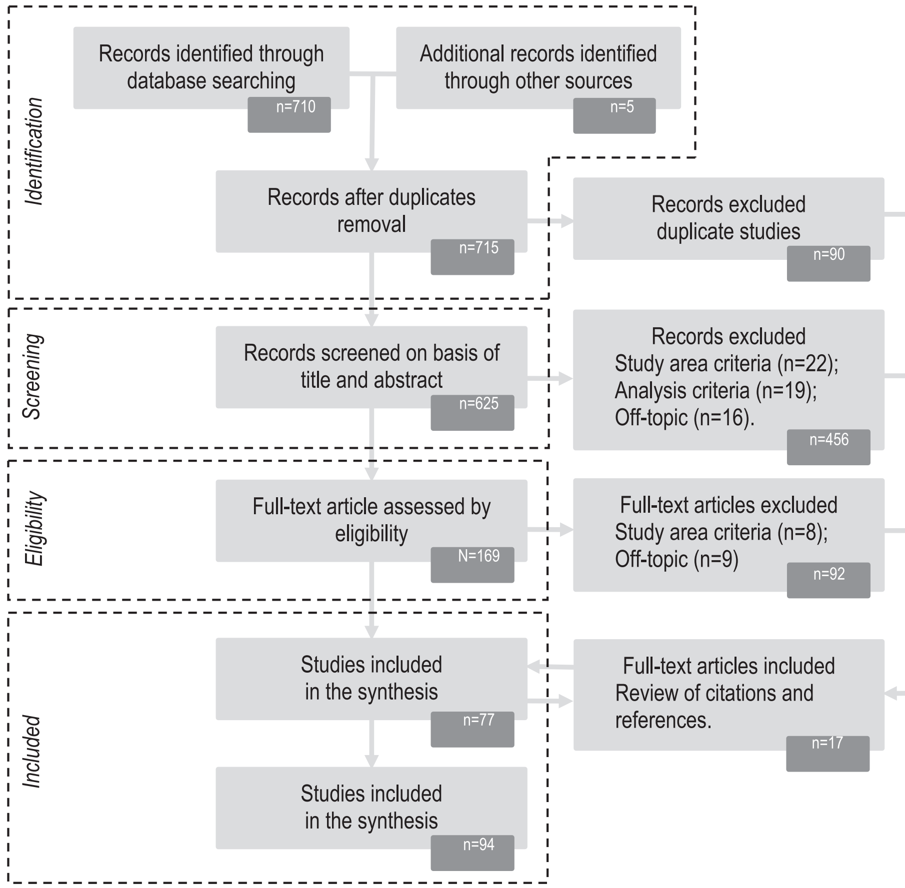


Fig. 1. PRISMA flow chart methodology.

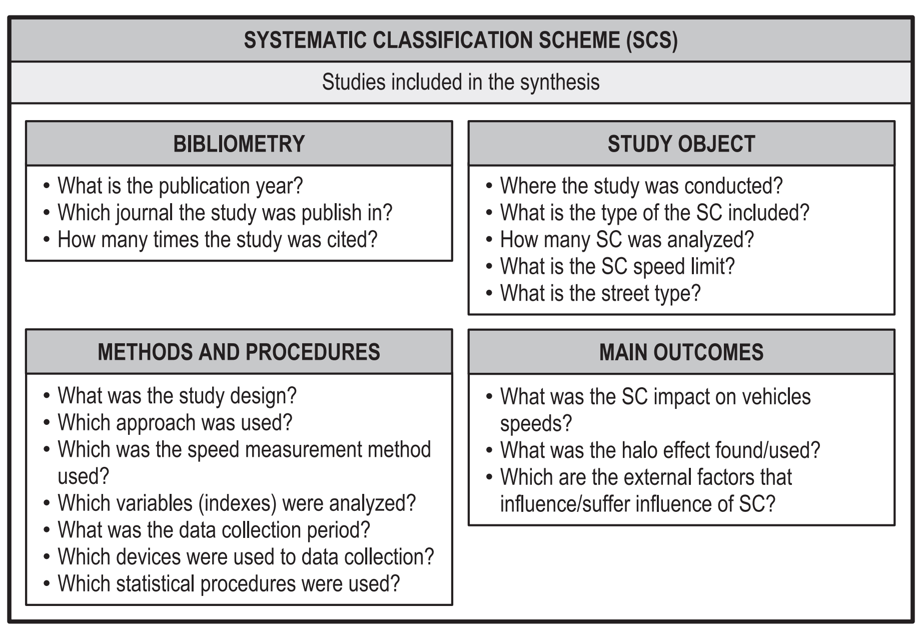


Fig. 2. Systematic classification scheme (SCS).

reporting mean vehicle speed and variability under comparison conditions. In addition to the narrative synthesis, we implemented a quantitative synthesis when sufficient data were available. Studies were eligible for meta-analysis if they (i) reported empirical field data (excluding simulators), (ii) evaluated speed cameras using time-speed or location-speed analyses, and (iii) provided mean speed and an estimate of variability (standard deviation or standard error) with sample size for each condition, or equivalent statistics enabling effect size computation. The primary outcome was the mean difference (MD) in vehicle mean speed (km/h), with negative values indicating speed reductions associated with SC deployment. All speed units were harmonised to km/h (1 mph = 1.609 km/h). Random-effects models (restricted maximum likelihood) were used due to expected heterogeneity, which was quantified using I^2.

3. Results

This section compiles the systematic evaluation of the included articles, and it is divided into four sub-sections according to the topics identified in the SCS, as shown in the forthcoming paragraphs.

3.1. Bibliometry

The first published study identified in this review was from 1982 (Hauer et al., 1982), and the most recent ones were from 2024 (Amancio et al., 2024; Mostafi et al., 2024; Snober et al., 2024). In recent years, there has been a growing number of studies on SC. In particular, 56 studies (almost 65 %) were published in the last 10 years. Road safety is not a new research field. However, as SC effectiveness in reducing speed is an emerging study object, the total number of studies in this topic is still substantially small.

From the 94 articles retrieved, 83 were journal articles and 11 were conference papers. The 83 journal articles were published in 35 different journals. Accident Analysis and Prevention (ISSN 0001-4575) was the most frequent journal in the group of publications, accounting for 18 articles, followed by Transportation Research Record (ISSN 0361-1981) with 13 articles and Transportation Research part F: Traffic Psychology and Behavior (ISSN 1873-5517) with 4 articles. The most cited study is Mountain et al. (2005), reaching 51 citations, followed by Chen et al. (2000) with 39 citations, Mountain et al. (2004) with 33 citations and Retting et al. (2008b) with 20 citations. These citations' accounting is dated when the articles' search was completed.

3.2. Object of study

Table 1 shows the main characteristics of the studies analyzed in the selected publications and Fig. 3 shows the number of studies conducted and the nomenclature used in each country.

The majority of the studies were conducted in the United States, China and Canada, each accounting for 19, 8 and 8 articles, respectively. Four types of speed cameras were identified in the reviewed articles: fixed speed camera (FSC), mobile speed camera (MSC), Average Speed Cameras (ASC) and manual speed cameras (MAN). The number of analyzed equipment varied from 1 (Benekohal et al., 2008; Bloch, 1998; Champness et al., 2005; Chin, 1999; Akpa et al., 2015; Montella et al., 2015b; Pan et al., 2020; Woo et al., 2007; Yang and Ma, 2016; Ziolkowski, 2014) up to 372 (Onuean et al., 2020). Some studies did not specify the number of SC analyzed. In general, the articles analyzed SC in arterial streets and rural roads with speed limits varying from 50 to 120 km/h. However, some studies have focused on streets with lower speed limits, such as residential and local streets and school zones (Hassan et al., 2017; Hu and McCartt, 2016; Quistberg et al., 2019; Retting et al., 2008a; Retting and Farmer, 2003; Snober et al., 2024).

SCs are known by different nomenclatures. While 71 of the 94 studies used the terms Speed Camera (SC) and speed enforcement (SE), other studies used other synonymous or similar words grouped (see Fig. 3): speed camera enforcement (10), photo enforcement (5), photo-radar (3), camera enforcement (2), radar (2), speed photo enforcement (2), radar speed camera (2), traffic enforcement (1), traffic violation monitoring (1), speed-radar photo enforcement (1), speed control (1), speed limit enforcement (1) and surveillance (1).

3.3. Methods and procedures

The selected articles were categorized according to their study design, applied approaches, employed variables, data collection period

Table 1
Main characteristics from the selected papers on SC.

Author	Place	Speed camera		Street characteristics	
		Type*	Quant	Speed limit	Street type
(Ali et al., 1997)	Kuwait	FSC	8	80 and 120 km/h	Rural and Arterial
(Amancio et al., 2024)	Brazil	FSC	16	60 km/h	Arterial
(Bar-Gera et al., 2017)	Israel	FSC	22	70, 80, 90 and 100 km/h	Rural
(Benekohal et al., 1993)	USA	MSC	2	45 mph	Rural
(Benekohal et al., 2008)	USA	MSC	1	55 mph	Rural
(Bloch, 1998)	USA	FSC	1	40 km/h	Collector
(Casey and Lund, 1993)	USA	MSC	5	30–45 mph	Arterial
(Champness et al., 2005)	Australia	MSC	1	100 km/h	Rural
(Chen et al., 2000)	Canada	MSC	30	–	Rural
(Chen et al., 2002)	Canada	MSC	–	80 and 90 km/h	Rural
(Chen et al., 2020)	Hong Kong, China	FSC	–	50 km/h	Arterial
(Chin, 1999)	Singapore	FSC	1	50 km/h	–
(Chitturi et al., 2010)	USA	MSC	3	55 mph	Arterial
(Cunningham et al., 2008)	USA	MSC	3	–	Rural
(Cunningham et al., 2011)	USA	FSC	–	–	Rural
(Čygas et al., 2018)	Lithuania	FSC	–	50 to 90 km/h	Rural
(Akpa et al., 2015)	South Africa	ASC	1	100 km/h	Arterial
(Franz and Chang, 2011)	USA	MSC	3	50, 55 and 65 mph	Rural
(Freeman et al., 2017)	Australia	FSC e MSC	–	–	Arterial
(Fu and Liu, 2023)	China	FSC	2	60 and 100 km/h	Rural
(Gavėnienė et al., 2020)	Lithuania	ASC	25	90 km/h	Rural and Arterial
(Goldenbeld and Van Schagen, 2005)	Netherlands	MSC	12	80 km/h	Rural
(Gonzalo-Orden et al., 2018)	Spain	FSC	3	50 km/h	Arterial and collector
(Gouda and El-Basyouny, 2017a)	Canada	MSC	9	50 km/h	Arterial and collector
(Gouda and El-Basyouny, 2017b)	Canada	MSC	9	50 km/h	Arterial and collector
(Gunarta and Kerr, 2005)	New Zealand	FSC	3	50 km/h	–
(Hajbabaie et al., 2011)	USA	MSC	–	55 mph	–
(Hassan et al., 2017)	UAE	FSC	–	–	Residential streets and school zones
(Hauer et al., 1982)	Canada	MSC	4	60 and 80 km/h	Rural
(Hu and McCartt, 2016)	USA	FSC	36	25–35 mph	Urban arterial road

(continued on next page)

Table 1 (*continued*)

Author	Place	Speed camera		Street characteristics	
		Type*	Quant	Speed limit	Street type
(Islam and El-Basyouny, 2013)	Canada	MSC, MAN	–	50 km/h	Collector
(Jägerbrand and Antonson, 2016)	Sweden	FSC	–	90 km/h	Rural
(Jägerbrand et al., 2018)	Sweden	FSC	–	90 km/h	Rural
(Karimpour et al., 2021)	USA	MAN	6	40, 45 and 50 mph	Rural and Arterial
(Kronprasert and Sutheerakul, 2020)	Thailand	FSC	5	80 and 90 km/h	–
(Kumphong et al., 2019)	Thailand	FSC	3	80 km/h	Arterial
(Li et al., 2016)	Canada	MSC	–	–	Anterial and Collector
(Liu et al., 2011)	China	FSC	5	60 and 80 km/h	Rural
(Lu and Cheng, 2010)	China	–	2	50 km/h	Urban Expressaway
(Luoma et al., 2012)	Finland	FSC	13	60, 80 and 100 km/h	Rural
(Malekpour et al., 2022)	Iran	FSC	20	–	–
(Marciano et al., 2015)	Virtual simulation	FSC	–	50 e 90 km/h	–
(Medina et al., 2009)	USA	FSC	3	55 mph	Rural
(Montella et al., 2015b)	Italy	ASC	2	80 kph	Rural
(Montella et al., 2015a)	Italy	ASC	1	80 kph	Rural
(Mostafi et al., 2024)	Canada	FSC	2	50 and 60 km/h	–
(Mountain et al., 2004)	UK	FSC	62	30 mph	–
(Mountain et al., 2005)	UK	FSC e MSC	79	30 mph	Arterial
(Naghawi et al., 2018)	Jordan	FSC	21	60–70 km/h	Arterial
(Oliveira et al., 2015)	Brazil	FSC	35	60 km/h	–
(Onuean et al., 2020)	Korea	FSC	372	–	Arterial
(Pan et al., 2020)	China	FSC	1	40 km/h	Arterial
(Pantangi et al., 2019)	USA	MSC	–	30 and 20 mph	Rural and Arterial
(Pauw et al., 2014)	Belgium	FSC	2	120 km/h	Rural
(Pérez-Acebo et al., 2021)	Poland and Spain	FSC	4	50 km/h	Rural built-up areas
(Punzo et al., 2012)	Italy	ASC	4	80 km/h	Rural
(Quistberg et al., 2019)	USA	FSC	4	20 mph in school times	–
(Retting and Farmer, 2003)	USA	FSC	7	25–30 mph	Residential and school zones
(Retting et al., 2008a)	USA	FSC	5	25–40 mph	Arterial
(Retting et al., 2008b)	USA	FSC	6	65 mph	Rural
(Shim et al., 2020)	South Korea	ASC	9	100 and 110 km/h	Rural
(Shin et al., 2009)	USA	FSC	6	65 mph	Rural
(Snober et al., 2024)	Qatar	FSC	2	50 km/h	Local
(Tankasem et al., 2019)	Thailand	FSC	4	80 km/h	Arterial
(Tavolinejad et al., 2021)	Iran	FSC	3	80 and 100 km/h	Rural
(Vadeby and Forsman, 2017)	Sweden	MSC	7	80 and 90 km/h	Rural
(Vanlommel et al., 2015)	Belgium	ASC	2	90 and 120 km/h	Rural
(Wilmots et al., 2016a)	Belgium	MSC	3	70 km/h	Rural
(Wilmots et al., 2016b)	Belgium	MSC	2	70 and 90 km/h	Rural
(Woo et al., 2007)	Taiwan (China)	FSC	1	50 kph	Rural
(Yang et al., 2016)	China	FSC	1	120 km/h	Rural
(Zhang et al., 2011)	China	FSC	3	100 and 120 km/h	Rural
(Ziolkowski, 2014)	Poland	FSC	1	50 km/h	Arterial
(Ziolkowski, 2017)	Poland	ASC	19	90 km/h	Rural
(Ziólkowski R, 2018)	Poland	ASC	2	50, 70 and 90 km/h	Rural
(Ziolkowski, 2019)	Poland	ASC	8	50 and 90 km/h	Rural

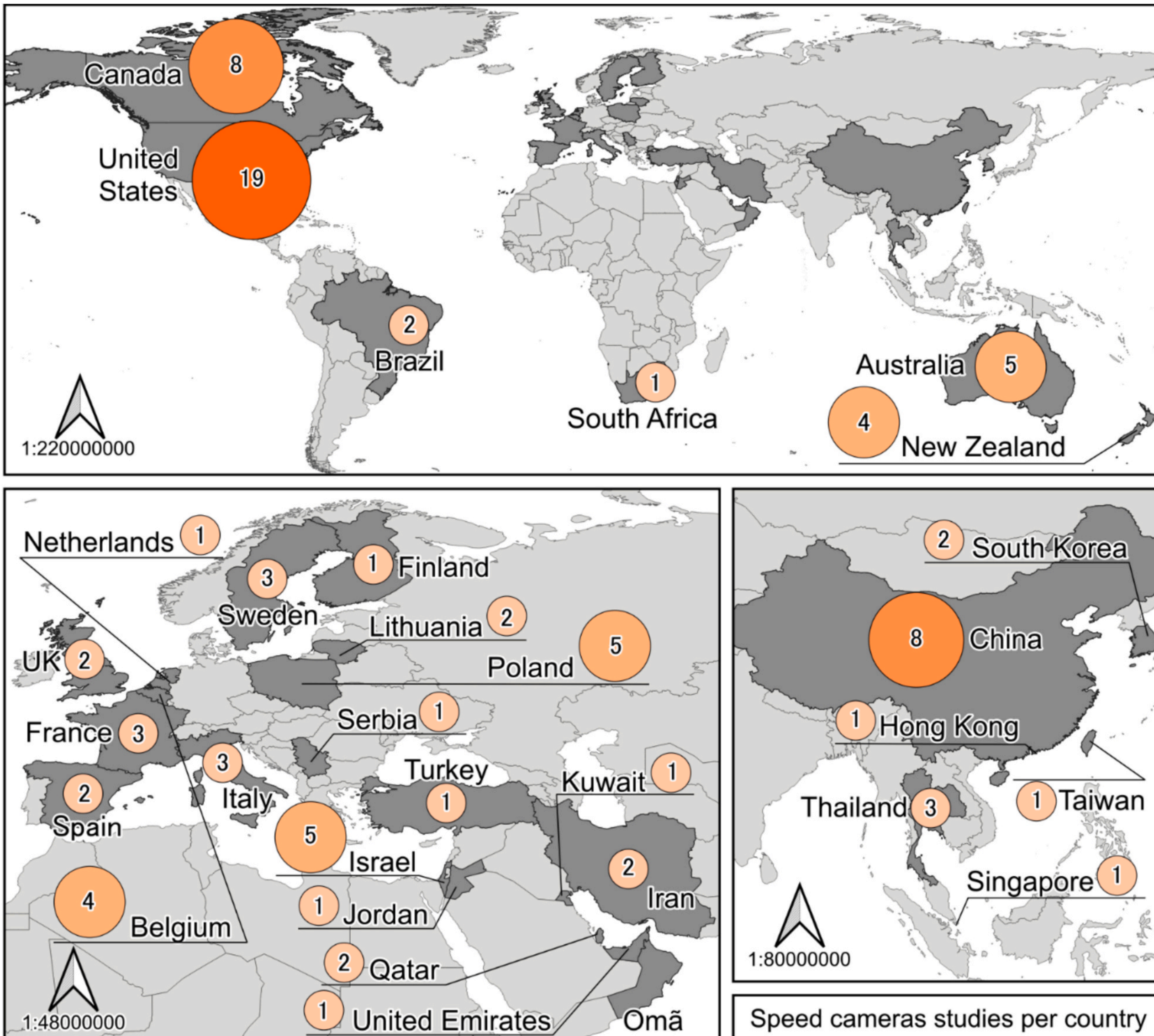
* Speed camera type: FSC – Fixed speed camera; MSC – Mobile speed camera; ASC – Average speed camera; MAN – Manual speed camera.

and device used, and statistical procedures to deduce the research findings. Basically, two main study designs have been identified: speed analysis and self-reported questionnaires.

Speed analysis was the most implemented study design for investigating SC effectiveness, accounting for about 78 articles, including four articles that present both study designs: speed analysis and questionnaires. All speed analysis reviewed studies compared at least two samples: with and without the SC influence. Hence, we proposed a classification and grouped the articles into three comparison approach categories (CAC), as shown in Fig. 4.

I Location speed analysis (LSA) – applies a comparison between sites with and without SC deployment. Since it is not possible to collect data in the period before the SC installation (before and after study), another way to analyze the impact in vehicle speeds is through LSA (Gunarta and Kerr, 2005). This approach requires that the site without SC (comparison group) must be as similar as possible to where SC was installed in order to eliminate confounding factors.

II Time speed analysis (TSA) – it is also called "before and after study". It is used when speed data samples are compared in different periods. That is, before and after the SC deployment. Some studies also analyzed the warning/testing period, related to the period when the SC is already deployed, but the ticketing process is not in progress. Even though the data used in this approach are commonly related to the same road section, they can be related to different time lengths. This variation required different sample sizes, which is usually treated by statistical processes.



COUNTRY	NOMENCLATURE	COUNTRY	NOMENCLATURE
Australia	SC (2), SE (2), SEC (1)	New Zealand	SC (4), SE (1)
Belgium	SC (2), SCTL (1), SE (1)	Poland	RSC (1), SC (2), SE (1), SEC (1), SLE (1), SUR (1)
Brazil	SC (2), SEC(1)	Qatar	SC (2)
Canada	PE (4), PR (2), SE (3)	Servia	TE (1)
China	SC (4), SE (4), TVM (1)	Singapore	SC (1)
Finland	SE (1)	South Africa	SE (1)
France	SE (3)	South Korea	SC (1), SE (1)
Hong Kong	SE (1)	Spain	RSC (2)
Iran	SC (2)	Sweden	SC (3)
Israel	SC (2), SE (2), SEC (1)	Taiwan	SC (1), SE (1)
Italy	SE (3)	Thailand	SC (1), SE (1), SEC (2)
Jordan	SC (1)	Turkey	SC (1), SE (1), SEC (2)
Kuwait	SC (1)	United Kingdon	SC (1), SEC (1)
Lithuania	SC (2)	United Emirates	R (1), SC (1)
Netherlands	SE (1)	United States	CE (2), PE (1), PR (1), R (1), SC (2), SE (6), SEC (4), SPE (2), SRPE (2)

CE - Camera enforcement; PE - Photo enforcement; PR - Photo radar; R - Radar; RSC - Radar speed camera; SC - Speed camera; SCTL - Speed control; SE - Speed enforcement; SEC - Speed enforcement camera; SPE - Speed photo enforcement; SUR - Surveillance; TE - Traffic enforcement; TVM - Traffic violation monitoring

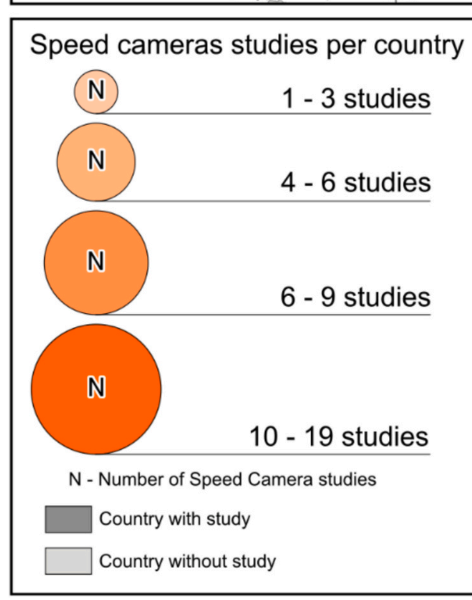


Fig. 3. Number of SC studies and nomenclature used.

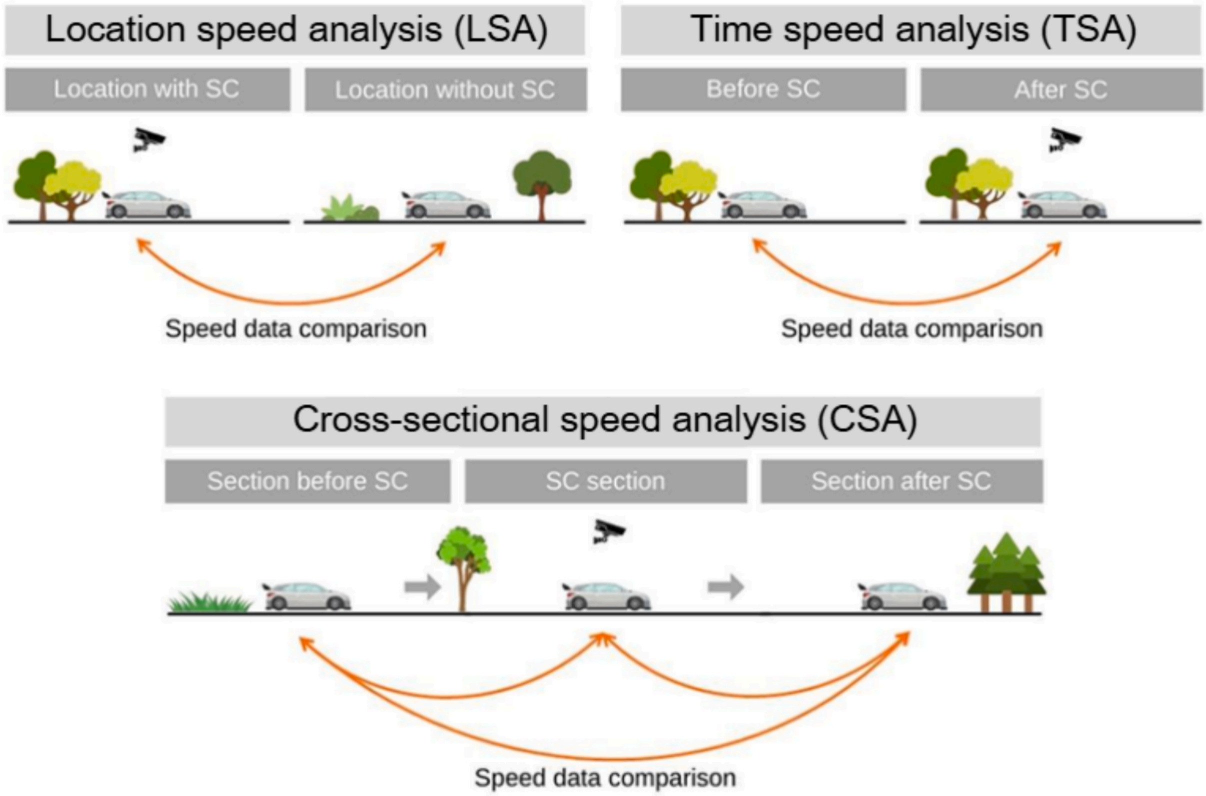


Fig. 4. Comparison approach categories (CAC) for speed analysis studies.

III Cross-section speed analysis (CSA) – this technique is adopted when the comparisons are made between different sections of the same street/road and in the same period. Differently from the two previous approaches, where the aim is to analyze the SC installation impact, this one is recommended to analyze the impact of SC on speed profiles. It is common to adopt three sections: before the camera, at the camera location and after the camera.

Most of the studies presented the TSA approach, accounting for 44 articles, followed by CSA and LSA with 33 and 28 articles, respectively. Thirty studies presented more than one CAC.

The studies were also divided according to the type of speed measurement method (SMM): punctual (P), continuous (C), and average (A). Although the three CAC can be used for both SMM, almost all of the articles used punctual measurement and only 12 used continuous measurement while six used average measurement. Table 2 contains the included studies related to speed analysis design and the adopted CAC, indicators, collection period, procedures used and statistical procedures applied.

The indicators and the collection period, which influence the statistical analysis, usually depend on the study design. The most applied indicator was mean speed (59 studies), followed by percentage of exceeding speed (44 articles). Speed dispersion is another indicator frequently used, especially because it is most associated with risk than mean speed (Franz and Chang, 2011; Islam and El-Basyouny, 2013). It is commonly measured by standard deviation or speed variance. However, Vanlommel et al. (2015) used the difference between V25 and V85 to measure this indicator.

Data collection time varied from periods shorter than one month to periods up to 6 years. Twelve studies investigated SC through continuous speed measurements (Marciano et al., 2015; Ziolkowski, 2014). This type of data enables continuous evaluation of the SC halo effect (Bar-Gera et al., 2017).

The study design varied depending on the data collection procedure. In particular, 11 articles used data supplied for local authorities and nine out of them applied the TSA design. This is potentially due to the large size and cover period of the database. In contrast, when the study combined CSA design with punctual or continuous speed data, the period of data collection was substantially short. The statistical methods also varied across the articles, but regression models, comparison methods, time series analysis and ANOVA were commonly used.

A widely applied approach is the use of control sites, especially for LSA. In these cases, it is important to choose control sites with characteristics similar to the SC site in order to eliminate the confounding factors. Furthermore, even in other approaches for measuring the influence of SC in driver speeds, it is important to eliminate confounding factors. Some criteria used for the studies are: distance from other speed control devices (Amancio et al., 2024; Liu et al., 2011 Tavolinejad et al., 2021; Zhang et al., 2011), distance from traffic lights (Amancio et al., 2024; Tavolinejad et al., 2021), roadway geometry (Goldenbeld and Van Schagen, 2005; Karimpour et al., 2021; Liu et al., 2011; Medina et al., 2009; Retting et al., 2008b; Tavolinejad et al., 2021; Wilmots et al., 2016a, 2016b; Zhang et al., 2011), distance from intersections (Liu et al., 2011; Zhang et al., 2011), the same speed limit (Amancio et al., 2024; Goldenbeld and Van Schagen, 2005), similar topographic profile (Amancio et al., 2024; Karimpour et al., 2021; Liu et al., 2011; Medina et al., 2009; Zhang et al., 2011), the researcher collecting speeds should be hidden (Liu et al., 2011; Zhang et al., 2011), free-flow condition (Amancio et al., 2024; Liu et al., 2011; Wilmots et al., 2016a; Woo et al., 2007), traffic volume (Retting et al., 2008b; Wilmots et al., 2016a) and similar historic of speed-related injury crashes (Wilmots et al., 2016a, 2016b).

While keeping the above-mentioned reservations in mind, it is interesting to note how some confounding factor was eliminated. For example, to determine free-flow condition, different criteria are used among the studies. Benekohal et al. (2008) Chitturi et al. (2010), Hajbabaie et al. (2011) and Medina et al. (2009) considered free-flowing conditions when there was a headway bigger than four seconds

Table 2
Methods and procedures of speed analysis studies.

Author	CAC*	SMM**	Indicators	Data collection		Statistical procedures
				Period	Procedure	
(Ali et al., 1997)	CSA	P	Mean, standard deviation and percentage exceeding	3 months	Mobile camera	–
(Amancio et al., 2024)	CSA	C	Mean, mean error, standard deviation	2 years	Naturalistic data	Comparison tests
(Bar-Gera et al., 2017)	TSA CSA	C	Mean, V85 and median speed	3 years	Probe vehicle data	–
(Benekohal et al., 1993)	TSA LSA	P	Mean, standard deviation, minimum, maximum and percentage exceeding	2 days	Mobile camera	–
(Benekohal et al., 2008)	CSA	P	Mean and percentage exceeding	–	Mobile camera	–
(Bloch, 1998)	TSA CSA	P	Mean and percentage exceeding	4 weeks	Mobile camera	–
(Carnis, 2008)	TSA		Mean and percentage exceeding		Supplied by authorities	–
(Casey and Lund, 1993)	TSA	P	Mean and percentage exceeding	4 weeks	Mobile camera	–
(Champness et al., 2005)	TSA CSA	P	Mean, standard deviation, V85, V90, V95 and percentage exceeding	–	Mobile camera	–
(Chen et al., 2000)	TSA CSA	P	Mean and percentage exceeding	1 year	Mobile speed camera and device in the pavement	–
(Chen et al., 2002)	TSA CSA	P	Mean and standard deviation	2,5 years	Mobile speed camera and device in the pavement	–
(Chen et al., 2020)	LSA TSA	P	Mean and percentage exceeding	14 months	Mobile speed camera and device in the pavement	Time series analysis
(Chin, 1999)	LSA TSA	P	Mean, V85 and percentage exceeding	3 months	Mobile speed camera	Comparison tests
(Chitturi et al., 2010)	LSA CSA	P	Mean and percentage exceeding	2 months	Mobile camera	–
(Cunningham et al., 2008)	TSA LSA	P	Mean, median speed, V85 and percentage exceeding	5 months	Mobile camera	–
(Cunningham et al., 2011)	TSA CSA	P	Mean	–	–	–
(Čygas et al., 2018)	CSA	P	Mean and percentage exceeding	12 days	Fixed camera	–
(Ebot Eno Akpa et al., 2015)	CSA	C	Mean, standard deviation, V85 and maximum	–	GPS	–
(Franz and Chang, 2011)	TSA CSA	P	Mean, V85 and percentage exceeding	3 weeks	Mobile camera	–
(Fu and Liu, 2023)	CSA	C		13 days	GPS	–
(Gavėnienė et al., 2020)	TSA	A	Percentage exceeding	9 months	Supplied by authorities	–
(Goldenbeld and Van Schagen, 2005)	TSA LSA	P	Mean and percentage exceeding	6 years	Supplied by authorities	Kolmogorov-Smirnov and Shapiro-Wilk tests
(Gonzalo-Orden et al., 2018)	CSA	P	V50 V85	–	Mobile speed cameras	–
(Gouda and El-Basyouny, 2017a)	TSA	P	Percentage exceeding	2 months	Mobile speed camera	Time series intervention analysis; two-sample e *t*-test
(Gouda and El-Basyouny, 2017b)	TSA	P	Percentage exceeding	2 months	Mobile speed camera	Two-sample test
(Gunarta and Kerr, 2005)	LSA	P	Standard deviation	3 months	Mobile speed cameras in a car	Regression analysis
(Hajbabaie et al., 2011)	TSA	–	Mean, standard deviation and percentage exceeding	–	Mobile camera	T, least-significant-difference, chi-square and Kolmogorov-Smirnov tests
(Hauer et al., 1982)	TSA LSA	P	Mean and standard deviation	5 weeks	Mobile camera	–
(Hu and McCartt, 2016)	LSA TSA	P	Mean and percentage exceeding	3 months	Fixed speed cameras	Regression analysis
(Islam and El-Basyouny, 2013)	TSA LSA	P	Mean, standard deviation and percentage exceeding	>2 months	Equipment in pavement	ANOVA, *t*-test and F-test
(Jägerbrand and Antonson, 2016)	CSA	C	Mean and standard deviation	–	Simulator	–
(Jägerbrand et al., 2018)	CSA	C	–	–	Simulator	ANOVA and multi-variated regression
(Karimpour et al., 2021)	CSA	P	Mean and percentage exceeding	6 months	Equipment in pavement	–
(Keall et al., 2001)	LSA	P	Mean	–	Mobile camera	–
(Keall et al., 2002)	TSA LSA	P	Mean and V85	–	–	–
(Kronprasert and Sutheerakul, 2020)	TSA	P	Mean, standard deviation, V85 and percentage exceeding	4 months	–	–
(Kumphong et al., 2019)	TSA	P	Mean and V85	–	Mobile speed camera	*t*-test
(Liu et al., 2011)	LSA CSA	P	Mean, standard deviation and V85	3 months	Mobile camera	T and Kolmogorov-Smirnov tests
(Lu and Cheng, 2010)	CSA	P	Mean, standard deviation, V50, V85, V95 and percentage exceeding	3 months	Mobile camera	–
(Luoma et al., 2012)	TSA LSA	–	Mean, standard deviation and percentage exceeding	8 weeks	Mobile camera	–
(Malekpour et al., 2022)	CSA	C	–	5 months	GPS	–

(*continued on next page*)

Table 2 (*continued*)

Author	CAC*	SMM**	Indicators	Data collection		Statistical procedures
				Period	Procedure	
(Marciano et al., 2015)	CSA	C	Mean, variance and speed slope	3 days each participant	Driving simulator	ANOVA
(Medina et al., 2009)	LSA	P	Mean, V15, V85 and percentage exceeding	1 year	–	–
(Montella et al., 2015a)	TSA	A	Mean, standard deviation, V85	3 years	Fixed camera	–
(Montella et al., 2015b)	TSA	P	Mean, standard deviation, V85 and percentage exceeding	–	–	Kruskal Wallis and Z test
(Mostafi et al., 2024)	TSA CSA	P	Percentage exceeding	3 years	Mobile speed camera	
(Mountain et al., 2004)	TSA	P	Mean, V85, standard deviation, percentage exceeding and mean speed of speeders	6 years	Supplied for local authorities	Regression analysis *t*-test
(Mountain et al., 2005)	TSA	P	Mean, V85, standard deviation, percentage exceeding and mean speed of speeders	6 years	Supplied for local authorities	Regression analysis
(Naghawi et al., 2018)	TSA	P	Percentage exceeding	6 years	Supplied for local authorities	*t*-test
(Oliveira et al., 2015)	LSA CSA	P	Mean and percentage exceeding	13 days	Mobile speed camera	Chi-square, t-Student, Fisher's exact test, ANOVA
(Onuean et al., 2020)	LSA	P	Over speed limit	4 months	Supplied for local authorities	–
(Pan et al., 2020)	CSA	P	Mean and standard deviation	2 days	Mobile camera	–
(Pantangi et al., 2019)	LSA CSA	C	–	3 years	GPS/naturalistic	–
(Pauw et al., 2014b)	TSA LSA CSA	P	Mean and percentage exceeding	3 years	Infra-red traffic logger and equipment in	Regression and multiple regression models
(Pérez-Acebo et al., 2021)	CSA	P	Mean, V85, percentage exceeding and maximum	–	Mobile and fixed cameras	–
(Punzo et al., 2012)	TSA	A	Mean, standard deviation and percentage exceeding	5 months	–	–
(Quistberg et al., 2019)	TSA	P	Mean, percentage exceeding, mean speed of speeders and traffic volume	27 months	Supplied for local authorities	Regression analysis
(Retting and Farmer, 2003)	LSA TSA	P	Mean and percentage exceeding	18 months	Mobile speed camera	Regression analysis
(Retting et al., 2008a)	LSA TSA	P	Mean and percentage exceeding	1 year	Mobile speed camera	Regression analysis
(Retting et al., 2008b)	TSA LSA	A	Mean, standard deviation and percentage exceeding	–	Mobile camera and supplied by authorities	Regression and multiple regression models
(Sadia et al., 2018)	–	–	Mean and standard deviation	–	Simulator	–
(Shim et al., 2020)	LSA CSA	P	Mean and standard deviation	2 years	Fixed camera	–
Shin et al. (2009)	TSA	P	Mean and standard deviation	1,5 years	Fixed camera	–
(Snober et al., 2024)	CSA	C	Mean and percentage exceeding	–	Driving simulator	ANOVA
(Tankasem t al., 2019)	TSA	P	Mean and tickets	7 months	Fixed speed cameras	Mann-Whitney test
(Tavolinejad et al., 2021)	LSA	C	Mean speed, standard deviation and percentage exceeding	<1 year	GPS	Kolmogorov-Smirnov and T tests
(Vadeby and Forsman, 2017)	TSA	P	Mean speed, standard deviation, V15, V50, V85 and percentage exceeding	–	Equipment in pavement	–
(Wilmots et al., 2016b)	TSA LSA	P	Mean speed, V85 and percentage exceeding	6 months	Mobile camera	Regression models
(Wilmots et al., 2016a)	TSA	P	–	5 weeks	Mobile camera	–
(Woo et al., 2007)	TSA	P	Mean, standard deviation and percentage exceeding	–	Mobile camera	ANOVA
(Yang et al., 2016)	CSA	P	Mean	1 day	Mobile camera	–
(Zhang et al., 2011)	LSA CSA	P	Mean, V85 and percentage exceeding	4 months	Mobile camera	–
(Ziolkowski, 2014)	CSA	C	Instantaneous speed	–	GPS	–
(Ziolkowski, 2017)	CSA	P	Mean, V85 and percentage exceeding	–	Fixed camera	–
(Ziólkowski R, 2018)	LSA	A	Mean, standard deviation and V85	–	Fixed camera	–
(Ziolkowski, 2019)	LSA	A	Mean, standard deviation, V15, V85 and percentage exceeding	1 month	Fixed camera	–

*SMM – speed measurement method (P – punctual; C – continuous, A – average).
[*] CAC – comparison approach category (TSA – time speed analysis; LSA – location speed analysis; CSA – cross-section speed analysis).

between cars. Pauw et al. (2014) considered 21 passenger cars per minute or a speed higher than 80 km/h as a free-flow condition. Hakkert et al. (2001) considered free-flow conditions when the traffic volume was less than 600 vehicles per lane per hour.

In addition, LSA approaches must choose control sites far enough away to avoid the spillover effect (Goldenbeld and Van Schagen, 2005). Likewise, to avoid bias, it is important in TSA approaches not to inform drivers about the future SC deployment (Montella et al., 2015b).

The effect of SC in reducing speed has also been reported in qualitative studies through surveys with self-reported questionnaires. These studies investigated the knowledge about the existence of SC in such locations (Hassan et al., 2017; Hu and McCartt, 2016; Naghawi et al., 2018; Retting et al., 2008a); the exposure level to SC (Freeman et al., 2017); the changes in speed choice related to SC presence (Chen et al., 2020; Hu and McCartt, 2016; Naghawi et al., 2018; Retting et al., 2008a); opinions about the SC related penalties/fines (Hu and McCartt, 2016; Naghawi et al., 2018); opinions about SC effectiveness (Hu and McCartt, 2016; Naghawi et al., 2018); differences between covert and overt SC (Hassan et al., 2017) and between police officer enforcement and SC enforcement (Naghawi et al., 2018); the effects of warning signs

Table 3
Speed reduction results of speed analysis studies.

Author	Main indicators				
	Mean speed	Standard deviation	V85	Speed impact	Percentage exceeding
(Ali et al., 1997)	−14.3 kph	−0.84 kph			
(Amancio et al., 2024)	−1.33 %				
(Bar-Gera et al., 2017)	−7.33 kph				
(Benekohal et al., 1993)	−13 kph to −16 kph				−7% (cars) −18.7 % (trucks)
(Benekohal et al., 2008)	−3.2 mph to −7.3 mph				−40 % (cars) −17 % (heavy vehicles)
(Bloch, 1998)	−8,3 kph				−30,2%
(Carnis, 2008)	−4 kph				−60 % (cars) −50 % (heavy vehicles) −36 % (motorcycle)
(Casey and Lund, 1993)	−7% to −10 %				−87 % to −90 %
(Champness et al., 2005)	−5.95 kph	−0.66 kph		−88.6 % to −91.5 %	−72.9 %
(Chen et al., 2000)	−2.4 kph	–	–	−75 %	−50 %
(Chen et al., 2002)	−2.8kph	−6%			
(Chin, 1999)	−25.65 %	–	−23.55 %	–	−77.7 %
(Chitturi et al., 2010)	−6.3 mph (cars) −5.3 mph (heavy vehicles)				
(Cunningham et al., 2008)	−0.67 mph		+0.77 mph		−18.7 %
(Cunningham et al., 2011)	+3.5 % (cars) +5.7 % (trucks)				
(Čygas et al., 018)				−17 %	−5%
(Akpa et al., 2015)	−15.70 %	−5.50 %			
(Gavėnienė et al., 2020)				−1.9 %	−10.9 %
(Goldenbeld and Van Schagen, 2005)	−4 kph				−12 %
(Gonzalo-Orden et al., 2018)	–	–	−14.42 %	–	–
(Gouda and El-Basyouny, 2017a)	–	–	–	–	−10 % – −17 %
(Gouda and El-Basyouny, 2017b)	–	–	–	–	−19 %
(Gunarta and Kerr, 2005)	−2.2 kph	−0.12 kph	–		–
(Hajbabaie et al., 2011)	−5 mph to −7 mph				
(Hauer et al., 1982)	−5.9 kph				
(Hu and McCartt, 2016)	−10.2 %	–	–	–	−62 %
(Islam and El-Basyouny, 2013)	−2.94 kph				
(Karimpour et al., 2021)	−1.7 mph			−13.4 %	−22 %
(Keall et al., 2001)	−2.3 kph				
(Keall et al., 2002)	−2.3 kph	−2.9 kph			
(Kronprasert and Sutheerakul, 2020)	−5.6 kph	−2.5 kph	−11 kph		−18.6 %
(Kumphong et al., 2019)	−1.3 kph	−3.9 kph	−2.4 kph		–
(Liu et al., 2011)	−14.1 kph (60 kph) −14.2 kph (80 kph)		−19.8 kph (60 kph) −17 kph (80 kph)		−47 % (60 kph) −7% (80 kph)
(Lu and Cheng, 2010)	−2.85 kph	+0.3 kph and −0.1 kph	−3 kph		
(Luoma et al., 2012)	−2.5 kph	−1.1 kph			−11.8 %
(Medina et al., 2009)	−1.48 mph (cars) −2.13 mph (trucks)		−1.1 mph (cars) + 0.1 mph (trucks)		
(Montella et al., 2015a)		−26 % (cars) −20 % (heavy vehicles)		−84 % (cars) −77 % (trucks)	
(Montella et al., 2015b)	−10 % (cars) −5% (heavy vehicles)	−26 % (cars) −20 % (heavy vehicles)	−14 % (cars) −8% (heavy vehicles)	−72 % to −84 %	−45 %
(Mountain et al., 2004)	−4.4 mph	−1.2 mph	−5.9 mph		−35 %
(Mountain et al., 2005)	−4.1 mph	−1.1 mph	−5.3 mph		−32.9 %
(Mostafi et al., 2024)					−43.54 %
(Naghawi et al., 2018)	–	–	–		−20 % – −66 %
(Oliveira et al., 2015)	−16.75 %	−44.9 %	–		−99 %
(Pan et al., 2020)	−10.2 kph	−3 kph			
(Pauw et al., 2014)	−6.4 kph			−86 %	−80 %
(Pérez-Acebo et al., 2021)	−10.45 kph		−13 kph		−50 %
(Punzo et al., 2012)	−11 %	−33 %		−92 %	−66 %
(Quistberg et al., 2019)	−1.5 mph	+15.4 %	–		−50 %
(Retting and Farmer, 2003)	−14 %	–	–	–	−82 %
(Retting et al., 2008a)	−4.0 mph	–	–	–	−66 %
(Retting et al., 2008b)	−6 mph				−13.33 %
(Sadia et al., 2018)	−0.7 kph	+10.2 kph			
(Schechtman et al., 2016)	−7.56 kph				
(Shim et al., 2020)	−10.7 kph	−5.45 kph			
(Shin et al., 2009)	−8.7 mph	−2.3 mph			
(Tankasem et al., 2019)	−9.6 %	–	–	–	–
(Tavolinejad et al., 2021)	−3.10 mph				

(*continued on next page*)

Table 3 (*continued*)

Author	Main indicators				
	Mean speed	Standard deviation	V85	Speed impact	Percentage exceeding
(Vadeby and Forsman, 2017)	−11.5 %	−33 %	−15.5 %		−83.33 %
(Wilmots et al., 2016b)			−2.5 kph		
(Woo et al., 2007)	−4.5 kph				
(Yang et al., 2016)	−4.25 kph				
(Zhang et al., 2011)	−8.1 kph to −10.2 kph		−4 kph to −11.8 kph		−50 % to –23.4 %
(Ziolkowski, 2014)	−26.7 %	–	–	–	–
(Ziólkowski, 2018)	−20.67 %				
(Ziolkowski, 2019)	−11.6 % (90 kph) −5.4 % (50 kph)	−4.5 % (90 kph) −4.1 % (50 kph)	−10.1 (90 and 50 kph)		−29.1 % (90 kph) −14.8 % (50 kph)

*N.S. – Not significant difference.

(Hassan et al., 2017); opinions about the expansion of SC programs (Naghawi et al., 2018; Retting et al., 2008a); and the SC effects on professional drivers (Chen et al., 2020).

Self-reported results could explain speeding circumstances and the relationship with SC. Although survey data suffers from several disadvantages related to memory, interpretation bias and social desirability, it could help in connecting findings and providing valuable insight into drivers' conflicts with SC, which are not detected in controlled studies. Thus, it is necessary to combine observational and self-reported methods to enable an accurate and comprehensive understanding of SC effectiveness (Gunarta and Kerr, 2005).

3.4. Main outcomes

The next sections discuss the main results found in the reviewed articles, according to the three questions presented in the last topic of the SCS.

3.4.1. What was the impact of SC on vehicle speeds?

All studies included in this literature review consistently report a positive effect of speed cameras on reducing vehicle speeds. This convergence of evidence is summarized qualitatively in Table 3 and Table 4 and further quantified through the meta-analysis and Fig. 5, presented below.

A random-effects meta-analysis was conducted including 13 studies employing Time Speed Analysis (TSA) or Location Speed Analysis (LSA) designs that reported, or allowed the derivation of, mean speed changes with associated measures of variance. All effects were harmonized to mean speed change in km/h, with negative values indicating speed reductions at enforced locations or after implementation. The pooled estimate indicates a statistically significant reduction in mean vehicle speed associated with SC, with a combined effect size of − 7.57 km/h (95 % CI: −10.48 to − 4.66 km/h) under a random-effects REML model (Fig. 5). This result provides robust quantitative evidence that SC is associated with substantial reductions in average driving speeds across a wide range of road environments and enforcement contexts. Between-study heterogeneity was high (I^2 = 99.5 %), reflecting the substantial diversity in study settings, enforcement modalities, roadway types, baseline speed limits, and traffic compositions. Importantly, despite this heterogeneity, the direction and magnitude of the effect were remarkably consistent across sensitivity analyses, supporting the conclusion that speed enforcement produces meaningful reductions in mean vehicle speed across diverse settings.

The so-called "kangaroo jump", which is an abrupt speed reduction close to the SC location and abrupt speed jumps downstream away from the camera range, has been widely identified in the literature (Amancio et al., 2024; Chen et al., 2020; Gonzalo-Orden et al., 2018; Liu et al., 2011; Malekpour et al., 2022; Marciano et al., 2015; Oliveira et al., 2015; Retting et al., 200b).

Sometimes this speed jump resulted in a speed higher than before the SC. Hence, it has been suggested that drivers tend to achieve a higher speed after the SC in order to compensate for the speed and time lost due to the previous speed reduction (Amancio et al., 2024; Gonzalo-Orden et al., 2018; Oliveira et al., 2015).

The "kangaroo jump" reveals a limited effect of SC on speeding (Gonzalo-Orden et al., 2018; Marciano et al., 2015; Mountain et al., 2004; Oliveira et al., 2015). Additionally, the breaking effect of "kangaroo jump" also has implications for road safety (Pauw et al., 2014). However, there is some evidence in the literature that SC can provide speed reduction in areas away from the camera (Chen et al., 2000, 2020; Chin, 1999; Goldenbeld and Van Schagen, 2005; Hakkert et al., 2001; Retting et al., 2008a; Retting and Farmer, 2003; Yang and Ma, 2016). Not unexpectedly, this speed reduction is smaller than that at SC sites. This effect is called "spill over" or "deterrent effect" and its reduction may have profound implications, since it reflects the driving behavior with the uncertainty of being caught and with the alertness level increased (Champness et al., 2005; Chen et al., 2020; Chin, 1999; Franz and Chang, 2011).

Also, there is a lower occurrence of "kangaroo jump" in clustered SC zones, which could indicate a key to the effective control of speeding behavior through SC employment. This could be because committing a "kangaroo jump" multiple times in a relatively short distance is potentially tedious and cognitively demanding (Malekpour et al., 2022). Intercity trips tend to present a higher probability of "kangaroo jump" than urban trips. Similarly, the "kangaroo jump" is more present in day trips than night trips (Malekpour et al., 2022).

While some studies demonstrated that SC might reduce speed variance through mean speed standard deviation reduction (Kumphong et al., 2019; Marciano et al., 2015; Mountain et al., 2004; Mountain et al., 2005; Oliveira et al., 2015; Punzo et al., 2012), one study found no significant changes (Gunarta and Kerr, 2005) while another found even an increase in speed variance due to SC employment (Quistberg et al., 2019).

The literature review supports the conclusion that SC reduces different road users' speeds. However, this reduction may be greater for some specific vehicles and lower for others. In this sense, SC is more effective on heavy vehicles in terms of achieving higher compliance with speed limit and a lower degree of speeding than cars (Benekohal et al., 2008, 1993; Chitturi et al., 2010; Cunningham et al., 2011; Gunarta and Kerr, 2005; Medina et al., 2009; Oliveira et al., 2015; Retting et al., 2008a). One reason for this compliance may be that truck drivers use trucker-to-trucker communication and SC detector devices more frequently than car drivers (Benekohal et al., 1993; Cunningham et al., 2011). However, there is insufficient evidence regarding the impact of this type of alertness system on SC effectiveness. A clear example of this is that none of the reviewed references included the telephone usage impact on SC effectiveness. On the other hand, this speculation is in line with the results of a lower percentage of reduction in speeding of heavy vehicles than cars (Carnis, 2008; Chin, 1999; Hajbabaie et al., 2011; Montella et al., 2015a; Montella et al., 2015b). Once drivers of these vehicles are aware of SC, they may adjust their speed considerably before the SC site. Nevertheless, contrasting all these outcomes

Table 4
Main outcomes of survey studies.

Author	Methods/procedures	Driver sample characteristics	Topics	Key findings
(Bates et al., 2016)	***Survey type***: online survey; ***Responses:*** 237;***Period:*** between October 2013 and June 2014; ***Application local:*** e-mail list from a major metropolitan university and an undergraduate student research pool;***Statistical procedures:*** descriptive statistics; hierarquical multiple regression model.	***Gender:*** 71.8 % female and 28.2 % male;***Age:*** mean age of 18.67 years; ***Age licensed (years):*** novice drivers.	***Topics:*** socio-demographic characteristics; warning of police presence; police avoidance; perceptions of procedural justice; procedural justice components; self-reported speeding	Self-reported offending behavior increase over time; there is a need to develop effective and evidence-based countermeasures to reduce offending by young novice drivers;
(Chen et al., 2020)	***Survey type:*** face-to-face survey; ***Responses:*** 401;***Period:*** between October 2018 and February 2019; ***Application local:*** public bus, taxis, public light bus stations, and outside the licensing offices of the HK Transport Department.	***Gender:*** 100 % male***Age (years):*** 37.7 % (< 45), 37.9 % (46–55) and 24.4 %(> 55);***Median driving exposure:*** 9.7 % (less than 8 h), 48.4 % (8 to 9 h) and 41.9 % (more than 9 h);***A.I.*:*** all drivers have license for bus, minibus, taxi, etc., and driving for income; 79 % of the sample drivers have attained at least secondary education	***Topics:*** regarding speed choices; driving history and safety perceptions; and demographics and employment characteristics of professional drivers.	Specifically, drivers who were recently issued a ticket are more likely to speeding than their peers to be deterred by DOPs when traveling in the warning section; driver age does not have a strong association with speeding behavior in the standard section.
Delhomme et al. (2014)	***Survey type***: online survey; ***Responses:*** 1192;	***Gender:*** 49.7 % men and 50.3 % female;***Age:*** 18–25 years;***Median driving exposure:*** approximately 4185 km travelled in the last 12 months;***Average age licensed (years):*** three groups: novice (< 1 year of driving experience), beginner (>1 year and < 3 years of driving experience, and more-experienced (>3 years of driving experience).	***Topics:*** socio-demographical; gender; employment status; number of crashes; sanctions within the last 12 months.	Social norms, perceived difficulty over speeding and probability of negative consequences arriving to them if highly transgressing speed limits were associated to a decrease in young drivers' speed behavior; road safety campaigns and trainings targeting young drivers should be focused on these factors.
(Freeman et al., 2017)	***Survey type***: online and pen-paper; ***Responses:*** 536; ***Statistical procedures:*** descriptive statistics, bivariate correlation, t-testes, linear regression.	***Gender:*** 51 % female and 49 % male; ***Age:*** 18–73 years; ***Median driving exposure:*** 6–10 h per week; ***Average age licensed (years):*** 14.58.	***Topics:*** demographic; license status; speeding behavior; convicting history.	Greater exposure to FSC than MSC; Younger drivers reported lower levels of perceptions regarding the threat of sanctions; drivers who consciously exceed the speed limit may be more aware (or sensitive) to the threat of speed enforcement approaches; 6.2 % reported that they 'often', 'nearly always' or 'always' exceeded the speed limit by more than10 km/h in a town.
(Hassan et al., 2017)	***Survey type***: face-to-face survey; ***Questions:*** 43; ***Responses:*** 1000 distributed and 442 answered; ***Statistical procedures:*** regression analysis; ***Application local:*** public areas (e.g. squares, malls, governmental authorities); ***A.I.*:*** Drivers sample represented the age proportion of real driver population.	***Gender:*** 73 % male, 27 % female; ***Age (years):*** 41(18–30), 48 % (31–45), 12 % (>45).	***Topics (n° of questions):*** demographic (5); tendency about speeding (7); responses to speed enforcement and management devices (11); awareness and education (10); opinion, evaluation and decisions (10).	Running late, low values of posted speed limit and no sufficient police enforcement makes drivers drive over speed limits (82 %); almost 55 % of participants are familiar with the locations of existing radars; about 67 % claimed that they can easily recognize the locations of fixed radars when they drive on any road
(Hu and McCartt, 2016)	***Survey type***: telephone surveys; ***Questions: Responses:*** 2470 distributed and 900 answered; ***Statistical procedures:*** logical regression models and Chi-square test; ***Period:*** November 2014.	***Age (years):*** +18.	–	95 % knew about the program; 62 % support it and 86 % support it in school zones; 76 % reduce their speeds; 59 % had received at least 1 speed camera citation; 75 % knew someone else who received a citation; speed cameras were associated with a 10 % reduction in mean speeds; 62 % reduction in the likelihood that a vehicle was traveling more than 10 mph above the speed limit at camera sites.
(Ilgaz and Saltan, 2021)	***Survey type***: face-to-face survey; ***Responses:*** 729; ***Period:*** 20/05/2013 – 24/085/2013; ***Application local:*** all five gates of one university; ***Statistical procedures:*** descriptive statistics, chi-square test;	***Gender:*** 67.7 % males and 32.3 % females; ***Age:*** 21–50 years.	***Topics:*** social-demography; driver's personal characteristics; driver behavior; opinions about traffic enforcement.	Gender and education level affect opinions of drivers on SC: man with lower education level showed negative opinion on SC;
(Kergoat et al., 2017)	***Responses:*** 245; ***Application local:*** University of Paris; ***Statistical procedures:*** multivariate analysis;	***Gender:*** 51 % male and 49 % female; ***Age:*** mean 22.2 years; ***Median driving exposure:*** an average of 7500 km driven per year; ***Average age licensed (years):*** 2.8 years.	***Topics:*** Driving habits, behaviors, attitudes on driving speed.	Unknown speed-enforcement location decreases driving speed; men perceived threat as greater than women in a known enforcement location; no differences between SC and policemen enforcement; not knowing SC location is a way of enhancing vulnerability.

(*continued on next page*)

Table 4 (*continued*)

Author	Methods/procedures	Driver sample characteristics	Topics	Key findings
(Kronprasert and Sutheerakul, 2020)	***Responses:*** 400; ***Statistical procedures:*** Chi-square.	***Gender:*** 275 male and 125 female; ***Age:*** 5.2 % less than 23 years, 54.1 % 23–40 years and 40.6 % more than 40 years; ***Road user:*** 4.7 % motorcycle, 67.8 % passenger car, 9.2 % van, 5.7 % bus and 12.5 % truck.	***Topics:*** attitude towards behavior; subjective norm; perceived behavioral control and intentions of speeding.	Drivers recognize that speeding is the major cause of accidents; most of the drivers were unaware of the speed limit of mountainous roads; and most of the respondents agreed with SC effectiveness.
(Naghawi et al., 2018)	***Survey type***: face-to-face survey; ***Questions:*** 19 ***Responses:*** 301; ***Period:*** November 2016	***Gender:*** 67.6 % male and 32,4 female ***Age:*** 83.4 % younger than 35 years old; 88.4 % had a private driving license while 7.5 % had a public driving license and 4.1 % had other types of driving license.	***Topics (n° of questions):*** demographic (4) and SC related questions (15)	Approximately 30 % of drivers think that drivers should not be informed about camera locations; 85.4 % reduce their speed at SC locations; 56.1 % indicated that SC affect their behavior at similar locations with no SC; 76.9 % think that behavior of other drivers is affected by SC; 72.1 % stated that SC discourage them from braking traffic laws.
(Retting et al., 2008a)	***Survey type:*** telephone surveys; ***Questions:*** 5; ***Responses:*** 800; ***Period:*** approximately 6 months in advance of camera and 6 months following; ***Statistical procedures:*** logical regression models; chi-square.	***Gender:*** Before: male: 299; female: 501; After: male: 309; female: 491 ***Age (years):*** Before: 18–34: 107; 35–64: 518; +65: 175; After: 18–34: 106; 35–64: 519; +65: 175;	***SC related questions:*** driver's perception about speeding as a public health problem, exposure level to speeding and opinions about the SC expansion.	Support for SC was higher among females and older drivers; six months after enforcement began, 60 % of drivers were aware of the camera program and 62 % supported it. 57 % said speed cameras had caused them to reduce their speeds
(Retting et al., 2008b)	***Survey type***: telephone surveys; ***Questions:*** 2; ***Responses:*** 600.	***Gender:*** Before: male: 136; female: 164; During: male: 107; female: 193; ***Age (years):*** Before: 18–34: 30; 35–64: 169; +65: 94; During: 18–34: 35; 35–64: 178; +65: 87.	***Topics:*** Opinions about SC program and acceptance in operation	Public opinion surveys found widespread concerns about speeding on the Loop101 free way and high levels of support for SC on this road.
(Sadia et al., 2018)	***Responses:*** 297;	***Gender:*** 44 % female and 56 % male; ***Age:*** majority between 25 and 34 years; ***Average age licensed (years):*** majority more than 3 years.	***Topics:*** Driver characteristics, demography data and subjective attitudes and perceptions	Gender, age, and driving frequency are all significant in determining speed selection; traffic speed, enforcement, and time-saving-benefits are also related to speed selection.
(Schechtman et al., 2016)	***Survey typ*** : face-to-face; ***Responses:*** 1993; ***Period:*** four periods between October 2010 to June 2013; ***Application local:*** twelve gas stations near SC sites; ***Statistical procedures:*** linear regression and sigmoidal models.	***Gender:*** 1461 males and 522 females; ***Age (years):*** 18–21: 5 %; 22–30: 24 %; 31–64: 65 %; More than 64: 6 %	–	Time pressure was the main motivation to speed; enforcement was the main motivation to respect speed limit; drivers predict positive impact of SC on safety on future behavior; vehicle type, gender and perceived posted speed showed more explanatory power to SC effectiveness.
(Shaaban, 2017)	***Survey type***: face-to-face; ***Responses:*** 446; ***Statistical procedures:*** Binary logistic regresion;	***Gender:*** 343 male and 103 female; ***Age (years):*** 18–25: 171; 26–50: 173; More than 51: 102.	–	The high violation fine and the automation of the system were mentioned as the main reasons for making this strategy the most successful; fixed-speed cameras, police enforcement, and mobile speed cameras, were conferred almost the same success percentage; rewarding safe drivers and introducing more automated enforcement methods were selected as the most successful proposed strategies.Munity service for traffic tickets came in third, followed by defensive driving school.
(Stanojević et al., 2013)	***Survey type***: online survey; ***Responses:*** 424; ***Application local:*** by e-mail;	***Gender:*** 278 males and 146 females; ***Age:*** approximately 34 years; ***Median driving exposure:*** around 10,000 km/year; ***Average age licensed (years):*** approximately 12 years.	***Topics:*** demography data, personal behaviors (speeding, seat belt, drunk driving) and their attitudes.	The lack of enforcement affects almost every type of behavior; speed cameras, speed limitation devices and devicesto prevent driving while under the influence of alcohol seemed to be supported to drivers mostly.

*A.I. – additional information

Karimpour et al. (2021) did not find a significant difference in the impact of speeds between trucks and cars.

SC were also analyzed based on taxi drivers' driving behavior (Carnis, 2008; Ebot Eno Akpa et al., 2015; Fu and Liu, 2023; Liu et al., 2020; Malekpour et al., 2022; Tavolinejad et al., 2021). In this respect, SC is not equitable, as taxi drivers are more exposed to the probability of being caught by enforcement systems. This also applies to truck drivers (Carnis, 2008). However, this greater exposure to SC makes taxi drivers more concerned about SC location and also more careful, as their profession depends on good driving (Fu and Liu, 2023; Liu et al., 2020).

In contrast, some researchers found that motorcyclists presented the highest mean speed at camera sites compared to other road users (Carnis, 2008; Oliveira et al., 2015). While V85 had a significant decrease, the mean speed did not present a reduction due to SC employment (Kumphong et al., 2019).

Time Apeed Analysis approach (TSA) can also be conducted related to "SC warning periods". A greater speed reduction is usually expected when the ticketing commences (Chen et al., 2000; Tankasem et al., 2019). In spite of these findings, there is very little information in the literature on the impact that SC warning periods have on speed

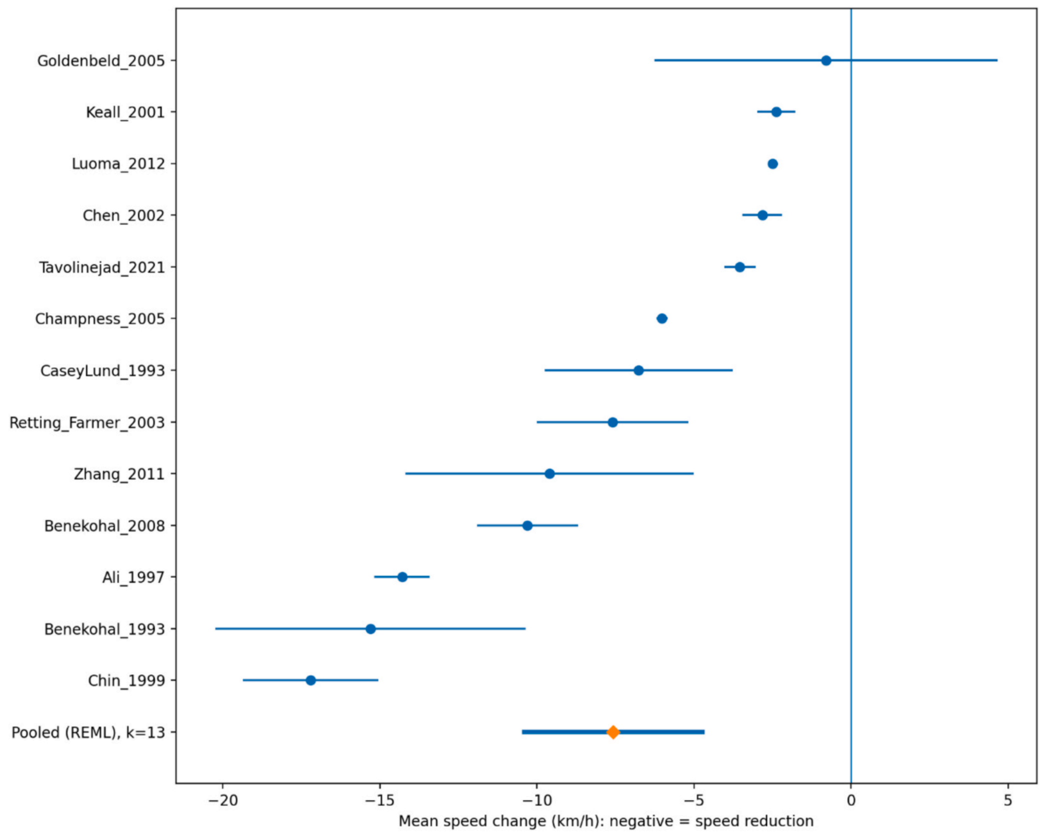


Fig. 5. Forest plot of mean vehicle speed changes associated with SC.

reduction, since these studies did not cover data before the SC employment and the analysis only included the warning and ticketing periods.

In general, SC is more effective in reducing speed than policemen or manual enforcement (Naghawi et al., 2018; Retting et al., 2008a; Tankasem et al., 2019), although there is evidence that there is no difference between these types of enforcement (Kergoat et al., 2017). In addition, when SC and policemen enforcement are combined, a positive effect in speed reduction is observed (Casey and Lund, 1993; Karimpour et al., 2021).

FSC tends to involve operations that are more overt and MSC tends to involve more hidden operations. Thus, drivers may not be aware of the MSC presence and consequently feel greater exposure to FSC compared with MSC (Freeman et al., 2017). In this sense, hidden SC are the most efficacious, since drivers cannot rely on being able to see another visible SC to warn them to adjust their speeds, which may lead to greater caution generally (Franz and Chang, 2011; Keall et al., 2002, 2001; Kergoat et al., 2017; Marciano et al., 2015). Moreover, SC combined with display speed monitoring is more efficient in reducing vehicle speeds (Bloch, 1998; Marciano et al., 2015; Pérez-Acebo et al., 2021; Wilmots et al., 2016b; Woo et al., 2007).

The effects of the road traffic environment on SC effectiveness have been reported by many studies. These studies suggest that SC is more effective in reducing speeds in school zones (Casey and Lund, 1993; Quistberg et al., 2019). This effect is sustained over time, and enforcement should not be removed after lower speeds have been achieved, once drivers need ongoing reminders to respect the speed limit within school zones (Quistberg et al., 2019). Additionally, SC has also been investigated in work zones (Benekohal et al., 2008, 1993; Chitturi et al., 2010; Čygas et al., 2018; Franz and Chang, 2011; Hajbabaie et al., 2011; Medina et al., 2009). In this case, SC is effective in reducing excessive speeding (Chitturi et al., 2010; Čygas et al., 2018; Franz and Chang, 2011; Medina et al., 2009), being more effective in reducing speed in heavy vehicles than in cars (Benekohal et al., 2008, 1993; Chitturi et al., 2010) and has impact on the influence distance of heavy vehicles, but none on cars (Benekohal et al., 2008). Lastly, the lanes also have an impact on SC effectiveness. Speed reduction on medium lanes is greater than in shoulder lanes (Benekohal et al., 2008; Chitturi et al., 2010; Hajbabaie et al., 2011; Hakkert et al., 2001).

Although almost all studies found a positive effect of SC on reducing driving speeds and speed compliance, some studies found an increase in vehicle speeds (Cunningham et al., 2011; Jägerbrand and Antonson, 2016; Pauw et al., 2014). These results suggest that SC may not work in reducing vehicles speed or there are some confounding factors affecting speed data.

3.4.2. *What was the halo effect found/used?*

The speed effect of SC was considered in many studies with a focus on the analysis of the variables/indicators presented in Table 3. However, the SC's effectiveness in reducing speed can also be measured in terms of its distance/time halo effect. Firstly, we identified four types of SC influence distance, as shown in Fig. 5.

Fig. 5 represents a generic speed profile and the corresponding SC effect on speed reduction. Drivers commonly reduce the speed when passing through a SC site (deceleration distance), and accelerate again from it (acceleration distance). These two measurements result in the distance halo effect. The deceleration distance is also known as upstream distance, the acceleration distance is known as downstream distance, and the distance halo effect is known as adjustment distance.

The compliance distance, in turn, is defined as the distance around the SC in which the driver remains within the speed limit. This distance assumes that the driver's speed was above the speed limit. Consequently, this measurement is not always presented in a speed profile, since drivers can be in compliance before and/or after entering the adjustment distance. In particular, 32 studies used or found some influence on distance, as shown in Table 5.

Table 5
SC influence distance.

Author	Influence distance			Data type*	Quoted literature
	Deceleration	Acceleration	Halo effect		
(Bar-Gera et al., 2017)	1.5 km[a] and 0.8 km[b]	1.5 km[1] and 0.8 km[b]	–	[a]S and [b]R	–
(Benekohal et al., 2008)	–	1.5 mi	–	S	–
(Champness et al., 2005)	1 km[a]	2 km[a] and 500 m[b]	–	[a]S and [b]R	–
(Chen et al., 2002)	1 km	1 km	–	S	–
(Chin, 1999)	200–300 *m*	200–300 *m*	100 *m*	R	–
(Chitturi et al., 2010)	–	1.5 mi	–	S	–
(Franz and Chang, 2011)	2 mi	0.5 mi to 1 mi	–	S	–
(Fu and Liu, 2023)	8 m to 2180 *m*	10 to 580 *m*	–	R	–
(Gonzalo-Orden et al., 2018)	100–150 *m*	100–150 *m*	–	S	–
(Gouda and El-Basyouny, 2017a)	100–500 *m*	100–500 *m*	–	R	–
(Gouda and El-Basyouny, 2017b)	100–500 *m*	100–500 *m*	–	R	–
(Gunarta and Kerr, 2005)	–	400 *m*	–	S	–
(Hauer et al., 1982)	–	1 km to 2.5 km	–	R	–
(Jägerbrand and Antonson, 2016)	300 m to 500 *m*	300 m to 500 *m*	–	S	–
(Jägerbrand et al., 2018)	1000 m[a] and 500 m[b]	1000 m[a] and 500 m[b]	–	[a]S and [b]R	–
(Karimpour et al., 2021)	–	166 *m*	–	L	(Harwood et al., 1996)
(Li et al., 2016)	125 *m*	125 *m*	–	L	(Champness et al., 2005; Elvik, 2011)
(Liu et al., 2011)	1000 m[a] and 300-400m[b]	1000 m[a] and 300-400m[b]	–	[a]S and [b]R	–
(Lu and Cheng, 2010)	200 *m*	200 *m*	–	S	–
(Malekpour et al., 2022)	2500 *m*	2500 *m*	–	–	–
(Marciano et al., 2015)	150 *m*	150 *m*	–	S	–
(Medina et al., 2009)	–	1.5 mi	–	S	–
(Mountain et al., 2004)	1 km	1 km	–	S	–
(Mountain et al., 2005)	1 km	1 km	–	L	(Gains et al., 2004; Mountain et al., 2004)
(Oliveira et al., 2015)	–	200 *m*	–	S	–
(Pan et al., 2020)	100 *m*	100 *m*	–	S	–
(Pauw et al., 2014)	3 km	3.3 km	–	S	–
(Retting et al., 2008b)	0.5 mi to 2 mi	0.5 mi to 2 mi	–	–	–
(Tavolinejad et al., 2021)	150 *m*	150 *m*	–	S	–
(Woo et al., 2007)	200 m and 300 *m*	–	–	S	–
(Zhang et al., 2011)	–	–	–	–	–
(Ziolkowski, 2014)	204	82	–	R	–

* S – Suggested data; R – Result data; L – Literature data.

Among the 32 studies presented in Table 5, most of them suggested the deceleration and acceleration distance (suggested data). Ten studies found an influence distance (result data) and only one proposed the investigation of the compliance distance (Chin, 1999). Also, other studies have cited the influence distance in order to establish methodological decisions and evaluate other variables (literature data).

Chin (1999) and Gouda and El-Basyouny (2017a, 2017b) evaluated several distances around the SC, and then presented the distance halo effect. In contrast, Ziolkowski (2014) evaluated the influence distance between two points: the starting point, where the speed profile starts to slow down, and the end point, where the speed profile reaches a constant speed again. Li et al. (2016, Karimpour et al. (2021) and Mountain et al. (2005) used as halo effect the distance of 166 m, 250 m and 1 km, respectively, in their investigations, but the authors cited other studies to support these measurements.

After passing the SC site, drivers usually try to regain the previous speed level quite fast, and then the level of compliance drops drastically after the camera (Champness et al., 2005; Chin, 1999; Jägerbrand et al., 2018). Consequently, the acceleration distance is substantially shorter than the deceleration one (Chitturi et al., 2010). Additionaly, there is some evidence that SC does not even impact the speed of vehicles downstream or its impact is smaller than upstream (Benekohal et al., 2008; Casey and Lund, 1993; Medina et al., 2009; Pauw et al., 2014a). For MSC the downstream distance halo effect is slightly longer than for FSC (Champness et al., 2005; Franz and Chang, 2011).

For trucks, while some studies found that the distance halo effect was usually shorter than for cars, possibly because trucks have greater restraints on speed (Chin, 1999; Gunarta and Kerr, 2005), other studies found contrasting results. Benekohal et al. (2008) and Chitturi et al. (2010) concluded distance halo effect is greater for heavy vehicles than for cars. For taxi drivers, in turn, Fu and Liu (2023) did not find a significant difference in the distance halo effect between different time periods or days of the week.

Although short-distance halo effects were also related to other aggressive driving patterns such as rapid braking and accelerating maneuvers (Ziolkowski, 2014), there was no evidence that these deceleration/acceleration effects have any detrimental effect on safety (Mountain et al., 2004).

Some studies have also investigated the SC impact on time, or set a time period to analyze SC influence on vehicle speeds. Table 6 presents the time periods considered for some articles analyzed.

In Table 6 the majority of the studies suggested a specific time range to analyze the impact of SC on vehicle speeds (suggested data). Other

Table 6
SC influence of time.

Author	Time period					Data type*
	Before	During			After	
		Short-term	Long-term	Total		
(Bar-Gera et al., 2017)	1 month	1 month	1 year	1 year		S
(Benekohal et al., 1993)	2 h	2 h	3 h			S
(Bloch, 1998)	2 weeks	2 h		2 weeks		
(Casey and Lund, 1993)	2 days (S)			3 days (S)	2 days (S) 0 days (R)	S and R
(Champness et al., 2005)	2 h (S)			2 h (S)	2 h (S) 0 h (R)	S and R
(Chen et al., 2000)	3 months			1 year		S
(Cunningham et al., 2008)	1 month	2 months	1 year			S
(Gavėnienė et al., 2020)	3 months	3 months	3 months			S
(Gouda and El-Basyouny, 2017a)				5 days		R
(Goldenbeld and Van Schagen, 2005)	1 year			5 years		S
(Hauer et al., 1982)				3–6 days		R
(Islam and El-Basyouny, 2013)	6 days	6 days	8 days			S
(Kronprasert and Sutheerakul, 2020)	2 months			2 months		S
(Luoma et al., 2012)	4 weeks			4 weeks		S
(Montella et al., 2015a)	12 days	77 days	+/- 2 years**			S
(Montella et al., 2015b)	12 days	77 days	+/- 2 years**			S
(Pauw et al., 2014)	11–13 months			10–18 months		S
(Punzo et al., 2012)	1 week			1 week		S
(Retting et al., 2008b)	2 months	6 weeks	5 months**		6 weeks	S
(Shin et al., 2009)	31 days			244 days	69 days	S
(Vadeby and Forsman, 2017)	2 months			2 months		S
(Wilmots et al., 2016a)	1 week			1 week	3 weeks (S and R)	S and R
(Wilmots et al., 2016b)	1 week			1 week	3 weeks (S and R)	S and R

* S – Suggested data; R – Result data.
** More than one long-term period.

studies present an influence of time as a result of their analysis (result data).

Among 22 studies presented in Table 6, 16 of them analyzed vehicle speeds only before and during SC deployment. Eight of them were divided during the period into short-term and long-term, to investigate if there were differences in driver behavior over time. Furthermore, three studies used two long-term periods (Montella et al., 2015a, 2015b; Retting et al., 2008b). Six studies have also investigated vehicle speeds after SC has been uninstalled. Also, Shin et al. (2009) and Woo et al. (2007) analyzed the periods before, during, after and the reactivation period.

Some evidence suggested that the time halo effect increases with the time of enforcement (Gouda and El-Basyouny, 2017a; Hauer et al., 1982; Povey et al., 2003). Also, the upstream speed reduction is also impacted during the time of enforcement. As the time of enforcement increases, the speed reduction in upstream sections is greater (Hauer et al., 1982). However, contrasting these results, Bloch (1998) and Casey and Lund (1993) found that the impact of SC is not maintained in the short term or long term after uninstallation. In addition, SC should not be removed after lower speeds have been achieved (Quistberg et al., 2019).

Through analysis of both distance and time of influence, it is possible to set driving behavior patterns, as shown in Figs. 6 and 7.

As shown in Fig. 7, there are three driving behavior patterns over distance, and all of them have already been identified in the literature: kangaroo jump (Amancio et al., 2024; Chen et al., 2020; Gonzalo-Orden et al., 2018; Liu et al., 2011; Malekpour et al., 2022; Marciano et al., 2015; Oliveira et al., 2015; Retting et al., 200b), compensation (Amancio et al., 2024; Gonzalo-Orden et al., 2018; Oliveira et al., 2015), and cobra strike (Amancio et al., 2024).

In the speed analysis over time, it was observed that the short-term period presented higher speed reductions than the long-term period. We call this pattern "pendulum effect", once it represents a greater speed reduction followed by an approximation to the speed limit, similar to a pendulum movement, which tends to approximate to the center. This pattern was observed in 10 studies (Chitturi et al., 2010; Cunningham et al., 2008; Gavėnienė et al., 2020; Islam and El-Basyouny, 2013; Montella et al., 2015a, 2015b; Retting et al., 2008b; Schechtman et al., 2016; Wilmots et al., 2016a; Woo et al., 2007). Montella et al. (2015a) argued that drivers adjust their speed over time as they perceive a certain tolerance from SC in issuing fines, especially since, in the case of the road studies analisede, there were pre-defined and secret times for issuing fines.

Some studies presented contrasting results: Goldenbelg and Van Schagen (2005) and for large trucks in one highway analyzed by Retting et al. (2008b) found a speed reduction in the short-term period that remained constant in the long-term period. Furthermore, Bar-Gera et al. (2017) and Chen et al. (2000) concluded that speed drops consecutively in short- and long-term periods.

3.4.3. Which are the external factors that influence/suffer influence on SC?

SC effects can be influenced by differences in social, economic or traffic environments (Gunarta and Kerr, 2005). The driver's demography and his/her relationship with SC effectiveness were investigated in some studies (see Table 4). Female and older drivers were identified as those who most support SC programs (Retting et al., 2008a), and female, older and married drivers were identified as more cautious on speeding in the presence of SC (Chen et al., 2020; Freeman et al., 2017). On the other hand, male, high-income, and younger drivers were less likely to comply with the speed limit on SC sites (Chen et al., 2020; Freeman et al., 2017; Hassan et al., 2017). The evidence related to the driver's education level was not clear, since the results found in the literature were divergent. Examples of SC research that found low compliance levels from highly educated drivers include Ilgaz and Saltan (2021) and Hassan et al. (2017), in contrast to Chen et al. (2020), which shows the opposite.

The ticketing practice increases SC's impact on speed reduction (Chen et al., 2002, 2000). People avoid committing a crime due to the threat and fear of being legally punished, and this is typically associated with an evaluation of the crime's costs and benefits. In this sense, drivers with high monthly income tend to violate the speed limit in warning sections more than drivers with low monthly income, possibly because high-income drivers can afford to pay the fines (Chen et al., 2020). Determining the speeding fines as a percentage of driver's income might help in increasing the driver's compliance (Hassan et al., 2017).

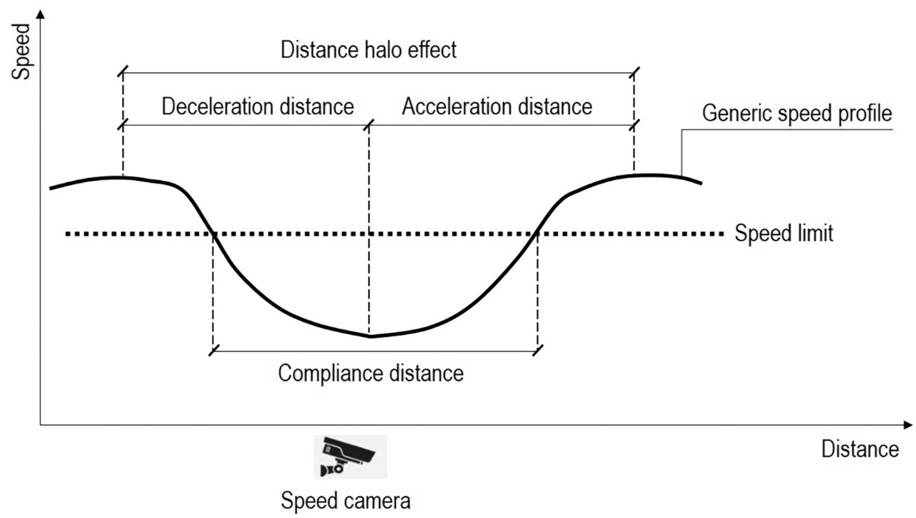


Fig. 6. Influence distances.

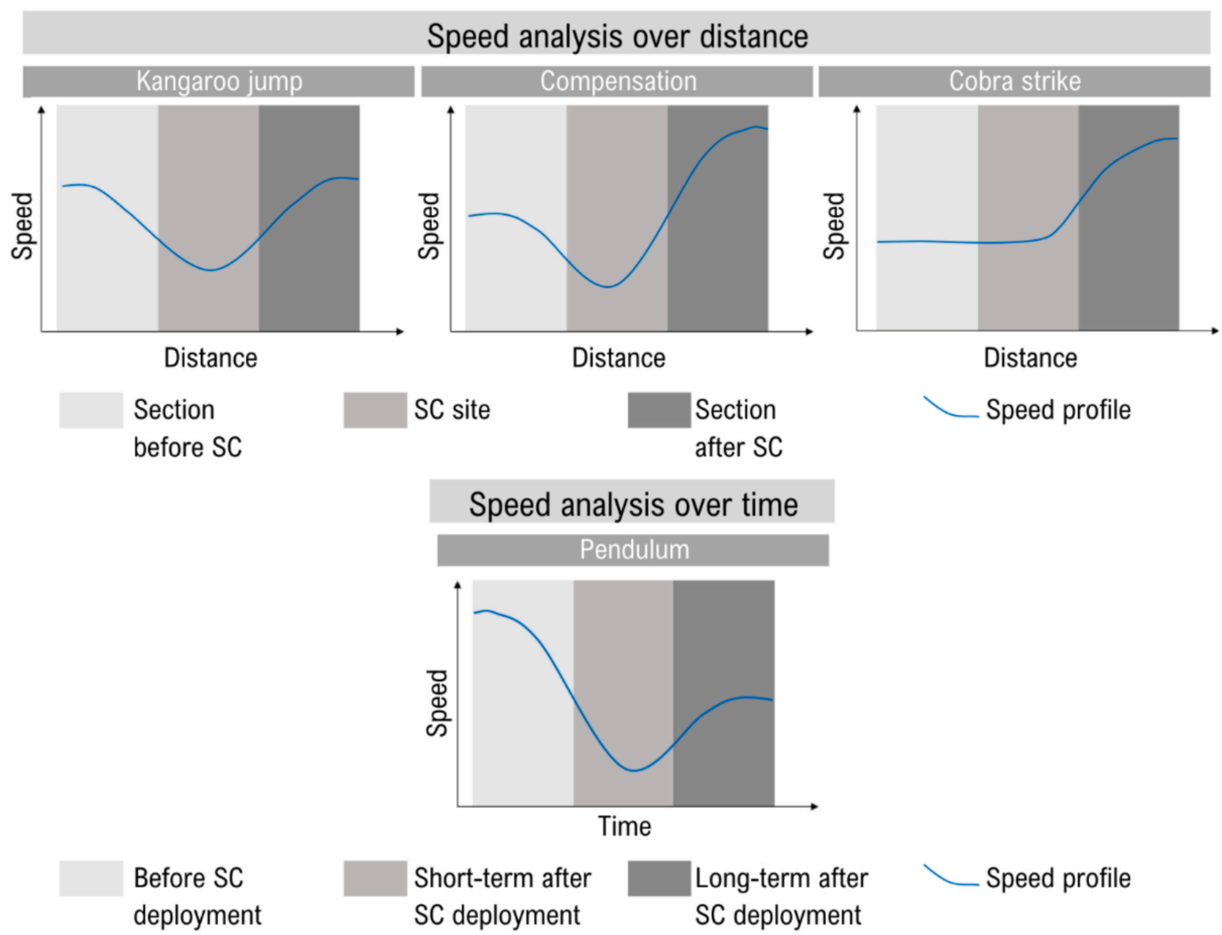


Fig. 7. Driving behavior patterns over distance and time.

Aggressive level was highlighted by some studies as another driver factor that influences SC effectiveness. Chen et al. (2000) found that the proportion of speeding vehicles exceeding the posted speed limit by 16 kph or more (most aggressive drivers) experienced a greater relative speed reduction compared with those speeding vehicles in general after SC employment. In addition, drivers who consciously exceeded the speed limit may be more aware (or sensitive) to the threat of SC (Freeman et al., 2017).

SC effects were enhanced when roads are wet, or visibility is poor (Gunarta and Kerr, 2005). Although there is evidence that daytime is a factor which does not influence SC effectiveness (Quistberg et al., 2019; Retting and Farmer, 2003), Tankasem et al. (2019) found that nighttime was related to the highest speed reduction caused by SC employment (9.8 % compared to 9.4 % during daytime and 9.6 % in a 24 h period).

A common assumption in the research is that different road geometries or topographic profiles may have an impact on SC effectiveness (Pan et al., 2020). Kronprasert and Sutheerakul (2020) argued that SC causes a positive effect in hazard sections of mountain roads. Amancio et al. (2024) found that flat topographic profiles showed greater speed reductions than downhill profiles and SC had little impact on vehicle speeds in uphill profiles. Contrasting these findings, Punzo et al (2012) found that in downhill profiles, the speed reduction caused by ASC is greater. Regarding rural roads that pass through short urban areas, Pérez-Acebo et al. (2021) recommended placing SC near the start of the built-up area and argued that longer urban areas decrease the speed more. Similarly, Li et al. (2016) argued that SC should be deployed in locations with a high rate of speed violations.

The literature reviewed supports the conclusion that weather conditions, daytime period and week of day have important effects on driver behavior near SC. Malekpour et al. (2022) found a greater tendency of drivers to present "kangaroo jump" during daytime than nighttime trips. In turn, Karimpour et al. (2021) and Tavolinejad et al. (2021) found no significant difference between daytime periods on SC effectiveness. Some studies analyzed both daytime and day of the week together. Islam and El-Basyouny (2013) concluded that the largest reduction in mean speed caused by SC occurred during nighttime on the weekend, contrasting the results found by Amancio et al. (2024) and Fu and Liu (2023), who found a greater reduction in mean speed caused by SC during daytime. Furthermore, Amancio et al. (2024) also found greater SC effectiveness on travels during workdays and under rainy conditions.

The references reviewed confirmed that there is a range of SC types beyond the classification shown in Table 1. On the other hand, there is insufficient evidence regarding the impact of each type of SC deployment (at roadside or on catielever) on SC effectiveness. Only one study has investigated this relationship and concluded that SC fixed on catilevers has a smaller reduction on mean speeds, however, a bigger reduction on percentage exceeding (Zhang et al., 2011).

Hours of enforcement per week and average hours of enforcement per visit were strongly correlated to expected speed reduction and the number of speed limit violations associated with MSC operations (Gouda and El-Basyouny, 2017a, 2017b). Moreover, SC warning signs deployment can reduce the "kangaroo jump" effect and increase speed reduction (Chen et al., 2020; Marciano et al., 2015; Pauw et al., 2014; Wilmots et al., 2016b). Although the effects of SC warning signs were studied, the research on other types of warning SC proximity (e.g., reading warning GPS alerts) is scarce.

4. Discussion

This systematic review synthesised evidence from 94 studies investigating the impact of Speed Cameras (SC) on vehicle speeds across diverse geographic, roadway, and enforcement contexts. The results consistently indicate that SC are associated with meaningful reductions in mean speed, speed dispersion, and the proportion of vehicles exceeding posted speed limits. The quantitative synthesis demonstrated a statistically significant pooled reduction in mean speed of −7.57 km/h, despite high heterogeneity across studies. This magnitude aligns with earlier reviews reporting speed reductions ranging from modest (Pilkington & Kinra, 2005) to substantial (Wilson et al., 2010), depending on road type, enforcement strategy, and baseline speed environment. Importantly, the consistency in the direction of effects across study designs reinforces the robustness of speed cameras as a speed management intervention, even when absolute effects vary. Beyond confirming overall effectiveness, the findings highlight substantial methodological heterogeneity, context dependency, and behavioural adaptation mechanisms that require careful interpretation.

Differences in reported speed reductions can be partly explained by roadway context and enforcement characteristics. Larger reductions are commonly observed on rural and high-speed roads, whereas urban and low-speed environments tend to exhibit more modest absolute changes. This pattern is consistent with behavioural theories suggesting that enforcement salience and perceived risk increase with higher baseline speeds and greater enforcement visibility. At the same time, the review revealed substantial variability in methodological approaches, including comparison strategies (time, location, and cross-sectional speed analyses), speed measurement techniques (punctual, continuous, and average), and selected indicators. While mean speed was the most commonly reported outcome, several studies emphasised speed variance and percentile speeds (e.g., V85) as more safety-relevant metrics. This heterogeneity complicates direct comparison across studies and contributes to the high I^2 observed in the meta-analysis, while also reflecting the complexity of real-world traffic environments and highlighting the need for more standardised reporting frameworks in future evaluations.

A recurrent finding across the reviewed literature is the presence of spatially localised behavioural responses, particularly the so-called "kangaroo jump" phenomenon. Several studies documented abrupt deceleration near SC locations followed by speed recovery or even overshooting downstream. This pattern suggests that while SC are effective in reducing speed at enforcement points, their influence may be limited in spatial extent when deployed in isolation. Another well-established effect identified in this review was the "compensation effect," in which drivers increase speed after enforcement to recover perceived time losses. More recently identified and still underexplored, the "cobra strike" describes no significant changes in speed at the SC location followed by aggressive acceleration, potentially increasing speed variability and safety risks. Building on the synthesis of empirical evidence, this review proposes the "pendulum effect" to describe variability in speed patterns over time following deployment.

Conversely, evidence of spillover or deterrence effects indicates that speed reductions can extend beyond SC locations under certain conditions. These effects were more frequently observed in corridors with clustered cameras, average speed enforcement systems, or when drivers face uncertainty about enforcement locations. Such findings underscore the importance of enforcement design and spatial configuration, rather than the mere presence of cameras, in shaping sustained speed compliance. Many studies explicitly acknowledged the influence of confounding factors, such as roadway geometry, traffic volume, nearby intersections, signalisation, and driver awareness. Although several investigations employed control sites or statistical adjustments, residual confounding remains a concern, particularly in observational TSA designs. Additionally, the predominance of punctual speed measurements limits the ability to fully capture dynamic driving behaviour and spatial adaptation, whereas continuous and naturalistic data sources—although less frequently used—show greater potential for identifying speed profiles, halo effects, and behavioural compensation mechanisms. Survey-based studies complemented observational findings by providing insight into driver perceptions, awareness, and acceptance of SC, though they remain subject to recall bias, social desirability bias, and limited causal inference. Overall, the findings support the role of SC as an effective component of speed management strategies but caution against their deployment as isolated measures, emphasising the importance of integration with complementary interventions such as signage, road design, and average speed control systems.

5. Future research

Future research should prioritise a more systematic examination of contextual moderators of Speed Camera (SC) effectiveness. Empirical studies are needed to quantify how roadway characteristics (e.g., road type, baseline speed, intersection density), traffic conditions (e.g., volume and flow variability), and environmental features (e.g., roadside advertising, enforcement visibility) influence speed reductions. Multilevel modelling approaches integrating roadway-, driver-, and environment-level variables would provide a more comprehensive understanding of these moderating effects.

Greater attention should also be given to demographic and behavioural heterogeneity. While existing questionnaire-based research suggests differences in risk perception and enforcement awareness across age, gender, and driving experience groups, future studies should link demographic characteristics to objectively measured speed profiles using naturalistic driving data or probe vehicle datasets. Such integration would strengthen the behavioural interpretation of speed adaptation mechanisms.

Standardisation of outcome measures is another critical priority. Although mean speed and the proportion of vehicles exceeding posted limits are commonly reported, substantial variation exists in the use of percentile speeds (e.g., V85, V95), dispersion metrics, and threshold-based indicators. Adoption of harmonised reporting standards would enhance comparability across studies and improve the robustness of future quantitative syntheses.

Longitudinal research designs are needed to investigate temporal dynamics and the durability of speed reduction effects. The concept of "time-varying speed camera effects" (Li et al., 2020) suggests that initial impacts may attenuate over time. Future evaluations should therefore assess speed outcomes at multiple post-installation intervals (short-, medium-, and long-term) and examine the influence of driver familiarity with enforcement locations and trip time pressures (Kong et al., 2020) using repeated-measures or panel methodologies.

Research should also extend beyond isolated enforcement points to evaluate corridor-level and spatial spillover effects. Studies examining speed profiles across extended road segments—particularly in environments with clustered cameras or Average Speed Camera (ASC) systems—would clarify whether compliance is sustained spatially rather than limited to enforcement sites.

Methodological advancements are equally important. Greater use of continuous speed measurement technologies, such as naturalistic driving studies (NDS), field operational tests (FOT), and high-resolution probe vehicle data, would enable second-by-second speed tracking and more precise identification of halo effects, behavioural adaptation, and influence distances (Simmons et al., 2016). Finally, future investigations should explicitly address confounding factors through controlled before–after designs with matched comparison sites, accounting for roadway geometry, topography, traffic density, headway, enforcement intensity, warning signage, and temporal variation (e.g., day of week and time of day). Strengthening methodological rigor in these areas will enhance causal inference and improve the evidence base guiding SC deployment.

6. Conclusions

This study aimed to systematically synthesise the scientific evidence on the effectiveness of Speed Cameras (SC) in reducing vehicle speeds and to clarify how these effects have been evaluated across diverse contexts. Through a structured and transparent review process informed by PRISMA principles, 94 empirical studies were identified, screened, and analysed. The findings consistently demonstrate that SC are associated with meaningful reductions in mean speed and the proportion of vehicles exceeding posted limits. The quantitative synthesis confirmed a statistically significant pooled speed reduction, reinforcing the robustness of this intervention despite considerable methodological heterogeneity. Beyond confirming overall effectiveness, this review contributes to the literature in three principal ways. First, it consolidates empirical evidence on behavioural adaptation mechanisms, including the "kangaroo jump," "speed compensation," and "cobra strike" effects, and introduces the "pendulum effect" to characterise temporal variability in speed behaviour following deployment. Second, it systematises the methodological landscape of SC research by synthesising evaluation procedures, outcome variables, and measurement approaches, and by proposing a structured classification framework based on data type and evaluation strategy. Third, it clarifies the spatial and temporal dimensions of SC influence, including enforcement distance and halo effects, thereby improving conceptual consistency in how these mechanisms are interpreted.

Overall, the evidence supports SC as an effective speed management measure with strong potential to improve speed compliance and reduce speeding, particularly when considered within broader enforcement and road safety strategies, given the well-established relationship between speed and crash risk. At the same time, the review highlights substantial variability in outcome definitions, measurement practices, and contextual conditions, underscoring the importance of methodological transparency and standardisation to strengthen cumulative knowledge in this field.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Eduardo Cesar Amancio, Tatiana Maria Cecy Gadda, Jorge Tiago Bastos and Gabriela da Costa Bonetti; data collection: Eduardo Cesar Amancio and Gabriela da Costa Bonetti; analysis and interpretation of results: Eduardo Cesar Amancio, Tatiana Maria Cecy Gadda, Jorge Tiago Bastos and Gabriela da Costa Bonetti; draft manuscript preparation: Eduardo Cesar Amancio, Tatiana Maria Cecy Gadda, Jorge Tiago Bastos, Matheus David Inocente Domingos and Gabriela da Costa Bonetti; review and editing: Tatiana Maria Cecy Gadda, Jorge Tiago Bastos, Matheus David Inocente Domingos. All authors reviewed the results and approved the final version of the manuscript.

CRediT authorship contribution statement

Eduardo Cesar Amancio: Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tatiana Maria Cecy Gadda:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Matheus David Inocente Domingos:** Investigation. **Jorge Tiago Bastos:** Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Gabriela da Costa Bonetti:** Investigation. **Sara Maria Pinho Ferreira:** Investigation. **Anelise Schmitz:** Investigation. **Oscar Oviedo-Trespalacios:** Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aap.2026.108488.

Data availability

No data was used for the research described in the article.

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