Accident Analysis and Prevention 147 (2020) 105741

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Advanced vehicle technologies and road safety: A scoping review of the evidence

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ARTICLE INFO

Editor: M.A. Abdel-Aty

Keywords:
Advanced vehicle technologies
Advanced driver assistance systems
Driving
Drivers
Age

ABSTRACT

The proliferation of Advanced Vehicle Technologies (AVTs) has generated both excitement and concern among researchers, policymakers, and the general public. An increasing number of driver assistance systems are already available in today's automobiles; many of which are expected to become standard. Therefore, synthesizing the available evidence specific to the safety of AVTs is critical. The goal of this scoping review was to summarize this evidence with a focus on AVTs that require some driver oversight (i.e., Levels 0–3 as per the Society of Automotive Engineers (SAE) levels of automation taxonomy).

A scoping review of research literature on AVTs was conducted for studies up to March 2018. Inclusion criteria consisted of: any study with empirical data of AVTs that included male and female drivers aged 16 years and older, healthy people (i.e., without impairments), passenger vehicles, driving simulators and/or large databases with road safety information that could be analyzed for the purpose of examining AVTs (SAE Levels 0–3), as well as measures of driving outcomes.

A total of 324 peer-reviewed studies from 25 countries met the inclusion criteria for this review with over half published in the last 5 years. Data was extracted and summarized according to the following categories: measures used to evaluate the effect of AVTs on road safety (objective) and driver perceptions of the technology (subjective), testing environment, and study populations (i.e., driver age). The most commonly reported objective measures were longitudinal control (50 %), reaction time (40 %), and lateral position (23 %). The most common subjective measures were perceptions of trust (27 %), workload (20 %), and satisfaction (17 %). While most studies investigated singular AVTs (237 of 324 studies), the number of studies after 2013 that examined 2 or more AVTs concurrently increased. Studies involved drivers from different age groups (51 %) and were conducted in driving simulators (70 %). Overall, the evidence is generally in favour of AVTs having a positive effect on driving safety, although the nature and design of studies varied widely.

Our examination of this evidence highlights the opportunities as well as the challenges involved with investigating AVTs. Ensuring such technologies are congruent with the needs of drivers, particularly younger and older driver age groups, who are known to have a higher crash risk, is critical. With automotive manufacturers

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https://doi.org/10.1016/j.aap.2020.105741
Received 24 June 2019; Received in revised form 10 August 2020; Accepted 18 August 2020
Available online 24 September 2020

keen to adopt the latest AVTs, this scoping review highlights how testing of this technology has been undertaken, with a focus on how new research can be conducted to improve road safety now and in the future.

1. Introduction

Motor vehicle collisions (MVC) remain one of the leading causes of injury, disability and death across all age groups (Lozano et al., 2012). By the year 2030, MVCs are projected to be the fifth leading cause of death worldwide (World Health Organization, 2013). Global estimates indicate approximately 80,000 MVCs occur each day with 3000 deaths resulting from these collisions (The PLoS Medicine Editors, 2010; World Health Organization, 2013). Between 2015 and 2017, there was an alarming, upward trend in the number of traffic-related fatalities in the United States - the largest increase in over half a century (Boudette, 2017). This increase has been attributed to multiple factors, including speeding, drug-impaired and distracted driving, as well as more leniency in the enforcement of regulations, including use of seatbelts (Boudette, 2017). Given the ongoing concerns with human driving behaviour and resulting consequences on road safety, urgent action at a population level is needed to prevent MVCs and/or to reduce fatalities and injuries. In recent years, advanced vehicle technologies (AVTs) have been framed as a potential strategy to improve road safety.

AVTs are electronic, in-vehicle systems that can perform or assist drivers in performing various behind-the-wheel tasks for which humans may be prone to error and/or complacency. Examples of AVTs include, but are not limited to: forward collision warning (FCW) systems (e.g., Eichelberger and McCartt, 2014; Kusano and Gabler, 2012), adaptive cruise control (ACC) systems (e.g., Marsden et al., 2001), lane departure warning (LDW) systems (e.g., Navarro et al., 2010), and blind spot detection systems (e.g., Chun et al., 2013). The Society of Automotive Engineers (SAE) categorizes driving automation systems into six different levels in accordance with the level of oversight required from the human driver (SAE, 2018). These technologies range from ‘no automation’ (Level 0) where the driver is still in complete control of the vehicle to ‘full automation’ (Level 5), meaning the technology in question has total control of the vehicle. At the time this review was conducted, only AVTs levels 1–3 were commercially available. AVTs are being developed and deployed at an accelerated pace. For example, as of 2018, rear-view camera systems became mandatory for all new automobiles sold in North America (National Highway Traffic Safety Administration, NHTSA 2014a,b). Correspondingly, research focused on the impact of AVTs on road safety is also growing. However, the categorization and labelling of AVTs in research and in practice remains fraught with challenges. In a report published by the AAA Traffic Safety Foundation (American Automobile Association, 2019), the differential naming of such technologies was highlighted as a major challenge for the automotive industry. For example, a system like Automated Emergency Braking (AEB), would be classified as SAE Level 1 if the technology stops or slows down the vehicle for the driver. However, when AEB is combined with a lane keeping system, for example, then this technology would be considered Level 2 since it is the combination of two level 1 technologies working alongside. For the current review, AEB is considered a warning and crash mitigation AVT (Table 1).

With an increasing number of AVTs available alongside more and more studies investigating such technologies, reviews have been undertaken by various researchers around the world to examine the effectiveness of AVTs in terms of safety; some which have focused on specific driver populations, such as older drivers (e.g., Classen et al., 2019; Eby et al., 2016; Rhiu et al., 2015). For example, Classen et al. (2019) reported that AVTs have moderate to high benefits for older drivers yet cautioned that there is a lack of sufficient evidence to make a determination regarding the relationship between AVTs and safety. In their recent meta-analysis of evidence specific to connected and automated vehicles (CAVs), Wang et al. (2020) noted much variance in the assessment methods, experimental conditions, and the types of drivers with which AVT-related research has been conducted. While their meta-analysis focused on CAVs, to our knowledge, there has yet to be a comprehensive examination of how studies of AVTs at SAE levels 0–3 have been undertaken, including the environments and driver demographics with which they have been assessed, as well as how objective measures of safety (e.g., crash rates) and subjective impressions by drivers are captured with regard to their interactions with these technologies.

Scoping the existing research on AVTs as conducted in the current study can map the current state of evidence to identify knowledge gaps for further studies. Therefore, the primary purpose of this scoping

Table 1
Transport Canada (TC) Classification of different types of advanced vehicle technologies (AVTs); current (see Figure 4 & 8) and examples of AVT names from original research studies.

Transport Canada (TC) Classification	TC's examples of different types of AVTs	Categorization of AVTs* used for review (*see Figure 4 & 8)	Examples of names of AVTs from included studies as per each TC classification
Vehicle Control	Roll Stability Control Traction Control	Electronic stability control	Electronic stability control
Warning and crash mitigation	Blind spot detection Forward collision warning and braking Lane departure warning Lane keeping assistance Automated Emergency Braking	Blind spot detection Forward collision warning Forward collision mitigation Lane departure warning Lane departure mitigation Non-forward collision warning and crash mitigation (W/M)	Side blind zone alert system (Kiefer et al., 2008) Headway monitoring and warning (Alkim et al., 2009) Lane-keeping system (Auckland et al., 2008) Longitudinal and lateral control system (Banks et al., 2016) Cooperative Intersection Collision Avoidance systems (Becic et al., 2012) Lateral drift warning (Jermakian et al., 2017)
Visibility	Advanced forward lighting systems Backing aids Night vision systems Pedestrian detection	Parking aids Adaptive headlights Night vision systems	Sensor system-based parking aid with rear-view camera (Hurwitz et al., 2010) Visibility Enhancement System (Sharfi et al., 2014) Active Park Assist (Reimer et al., 2016)
Other driver assistance	Adaptive Cruise Control Brake assist Driver monitoring Speed alert Tire pressure monitors	Adaptive Cruise Control Driver monitoring systems In-vehicle information systems Intelligent speed adaptation (ISA)	Automated steering (Borowsky et al., 2016) Advanced vehicular speed adaptation system (AVSAS) (Arhin et al., 2008) Haptic Steering guidance (Petermeijer et al., 2015) Navigation system (Chiang, 2005) Route Guidance System (Weyer et al., 2015)

review was to examine the state of evidence of AVTs for SAE levels 0–3, and to describe how these studies were conducted. More specifically, the objectives of this review were to describe: 1) the age of the driver populations with whom these AVTs have been examined; 2) the types of AVTs that have been examined; 3) the testing environments where these AVTs have been evaluated; 4) the objective and subjective measures that have been used to characterize the effectiveness of these AVTs; and to then 5) determine from the demonstrated evidence, whether these AVTs can improve road safety. This review is the first to our knowledge to examine the current state of research with regard to how AVTs, specifically, SAE levels 0–3, have been studied.

2. Methods

This scoping review used the Cochrane Collaboration methodology to search the literature (Higgins and Green, 2011) and has been conducted based on the six-stage framework for scoping reviews developed by Arksey and O'Malley (2005) and a modified method used by Colquhoun et al. (2014). This process involves identifying the research question, identifying relevant studies, selecting the studies, charting the data, collating, summarizing and reporting results, and ongoing consultation with stakeholders.

This review was completed in accordance with the PRISMA Extension for Scoping Reviews reporting guidelines (Tricco et al., 2018). Our authorship team, each of whom were involved in all steps of this review, have expertise in multiple fields including: human factors, rehabilitation medicine, occupational therapy, systematic reviews, information management, librarianship, psychology, engineering, injury epidemiology, and traffic safety policy. Our team also included representation from a diverse group of knowledge users, including government bodies responsible for transportation policy as well as industry stakeholders interested in the effect of AVTs on their drivers (e.g. postal services, automobile assurance, and organizations concerned with driving assessment and driver rehabilitation). At the outset of this review, these representatives assisted with formation of the research questions and the search terms. We also met with them at the end of the project where the results were discussed.

2.1. Inclusion and exclusion criteria

In keeping with the procedures for conducting scoping reviews (Tricco et al., 2018), published primary studies on AVTs that used any type of research design were considered for inclusion. While studies could be conducted in any country without any language limitation, we only extracted data from studies that were published in languages understood by members of the research team (i.e., English, German, French, Portuguese, Spanish). Studies had to include human drivers (i.e., healthy volunteers, persons without impairments) aged 16 years or older. We included studies evaluating AVTs from SAE levels 0–3 only (SAE, 2018) excluding the studies that investigated drivers' performance in taking over driving control from a Conditionally Automated Vehicle (CAVs, i.e., SAE Level 3). We excluded studies of Level 4–5 technologies because these types of technologies were not available to the public prior to this scoping review had started and have only been described by industry and academics.

Studies were included if reporting outcomes related to objective measures of driving safety and/or subjective experiences and perceptions of these technologies. Safety was defined as the influence of AVTs on driving performance (simulator and/or on-road), collisions, and infractions (including those based on insurance claims and/or other large databases). Subjective driver experiences and perceptions included, for example, perceived usefulness, workload, or trust of the technology.

Studies were excluded if the population consisted of commercial vehicle drivers (e.g., bus, trucks) or motorcycle drivers, or when drivers were, or had the potential to be, impaired (e.g. by alcohol, cannabis or prescription medications). We did not extract outcomes of surrogate measures of driving performance, such as the Useful Field of View (Ball et al., 1988), Test of Variables of Attention (T.O.V.A), Digit Symbol Substitution Test (DSST), and Choice Reaction Time (CRT).

Studies were also excluded if they were based on computer simulations only (i.e., AVTs were not tested with human drivers), pilot data, if the findings were preliminary, and if they were review articles, theoretical discussions (i.e., no empirical data), or thesis dissertations.

2.2. Databases searched

Comprehensive searches were conducted of the following databases: MEDLINE (Ovid), EMBASE (Ovid), PsycINFO (Ovid), CINAHL (EBSCO), The Cochrane Library, including the Cochrane Register of Controlled Trials, Cochrane Database of Systematic Reviews, Database of Abstracts of Reviews of Effects, Health Technology Assessments Database and NHS Economic Evaluation Database (Ovid), Social Science Abstracts (EBSCO), and Compendex (Engineering Village).

2.3. Search terms

The search strategy was developed by an information specialist with ongoing input from the research team, which included a second information specialist. Knowledge users including government and industry were also engaged in identifying relevant search terms during a stakeholder meeting on 4 October 2016. The search strategy included a combination of controlled vocabulary (e.g. MeSH, Emtree) and free-text word terms broadly related to: (1) drivers, motor vehicles or traffic collisions and (2) vehicle technology, automation, artificial intelligence or specific vehicle technologies. Searches were limited to humans and adults when possible in that specific database. See Appendix 1 for the full Medline search strategy and a detailed search narrative. All searches were conducted from database inception to December 2016 and were updated in March 2018. Search results were imported into Endnote (Clarivate Analytics, 2019).

2.4. Citation screening

After duplicates of studies were removed, search results were imported into Covidence to be screened (Covidence, 2019). Covidence was used to screen references at both title/abstract and full text stages based on the above inclusion criteria. To reduce the risk of bias, each reference was screened by two team members at both stages and any conflicts were discussed by the team or assigned to a third party. The first round of screening was completed in April 2017 and updated results were screened in April 2018.

2.5. Data extraction

A spreadsheet was developed using Microsoft Excel to extract data from each included study. Several rounds of piloting the data extraction spreadsheet were conducted where all team members extracted data from the same studies and the results were compared at team meetings to determine consistency in coding across members. Piloting the extraction process ensured all relevant data fields were captured and confirmed that coding of such fields were consistent across the entire research team. Once all team members were familiar with the data extraction process, studies were assigned to each member and corresponding information extracted independently. The following information was extracted from each included study when available: year; country; age range and mean age of participants; sample size recruited; sample size analyzed; environment (on-road vs. driving simulator); name of AVT; comparison group (if the AVT was compared to no AVT or to another AVT); if there were objective or subjective outcomes, and how they were measured; the results of the comparisons for each AVT and for each outcome; and main conclusions of the study made by the authors of the publication. Data extraction was completed in July 2018.

2.6. Data analyses

Age of drivers/users: If age of the participants was provided, the studies were categorized into the following groups: younger participants (30 years of age or under, or mean age below 25 if age range was not provided); older participants (65 years of age or older, or mean age above 65 if age range was not provided); mixed (middle age group or mixed younger and older); not reported (no age data provided). A study could be classified as younger and older when each group was analyzed separately in the same publication.

Types of AVTs: Categories were developed by the research team to classify the types of AVTs based on the categories used by Transport Canada (Table 1). These categories included: vehicle controls, warning and crash mitigation, visibility, and other driver assistance systems (Transport Canada, 2019).

Objective outcomes were extracted from all included studies in the manner that they were reported. These outcomes were then a posteriori categorized by the research team based on similarities among concepts being measured: reaction time, longitudinal and lateral control, eye movement, vehicle maneuvering, driver intervention, secondary tasks, collisions, infractions, and physiological responses.

Subjective outcomes were also extracted in the manner that they were reported in the publications, and then categorized based on similarities among concepts being measured: trust, functionality/preference, likeability/satisfaction, usability, workload, acceptability and usefulness. The definitions for each subjective outcome were extracted from the included studies and operationalized by consensus within our authorship team (Furlan et al., 2018).

The results of each outcome in terms of whether it was considered positive or negative with respect to safety were determined for each AVT by at least two members of the research team who reviewed the study results independently and categorized them as either: 1) Positive, if there was demonstration that the outcome was safer with the AVT than without it; 2) Negative, if there was demonstration that the outcome was less safe with the AVT than without it; 3) Mixed results when there were both positive and negative effects for the same AVT; 4) Neutral, if there was no difference with or without the AVT; 5) Unclear, if the results were unclear with regard to the positive or negative effect of the AVT; and 6) Not available if the results for that outcome was not available in the publication.

The safety-related outcomes for each AVT type were then considered across all studies to make an overall determination of safety. The authors' conclusions about the overall safety of the AVT were categorized by at least two members of our research team who reviewed the results from each study using the summary table. The overall safety was based on a global assessment of both objective and subjective outcomes in combination with the authors' conclusions. The categories were the same as above: positive (safer with the AVT), negative (less safe with the AVT), mixed (mixed of positive and negative outcomes for the same AVT), neutral, unclear, and not reported. Here, we give an example of how these terms were operationalized: in the included study by Bianchi Piccinini et al. (2014) the authors examined reaction to a critical situation during driving with Adaptive Cruise Control (ACC) for regular users and non-users of the system. The objective outcome was average time to collision (TTC) with and without the ACC. The results showed that when the ACC system was activated, both ACC users and non-users increased their risk of crash with the stationary vehicle compared to the baseline situation (driving manually). In our scoping review, this objective outcome was classified as "negative". The authors of this study also employed subjective outcomes of "trust" by assessing driver's trust before and after the trial, and the result showed that trust did not significantly change after the trial with ACC (compared to before) and that ACC users and non-users did not differ in regard to the trust placed in the system. In our scoping review, this subjective outcome was classified as "neutral". When combining objective results, subjective results and the author's conclusions in this scoping review, our team concluded in the study by Bianchi Picinini et al., safety was worse with ACC than without ACC. Therefore, this study had a negative global rating in relation to ACC.

2.7. Data summary

Pivot tables and charts were created to capture the frequency and distributions of the evidence. Descriptive statistics were used to report absolute numbers, means, and proportions of the included studies, where possible.

3. Results

The initial search yielded 10,808 references. Once duplicates were removed, there were a total of 9395 titles and abstracts screened from which 910 studies underwent full text review. A total of 324 studies met the inclusion criteria and were included in the analyses (see Fig. 1 for the PRISMA flow diagram). The 324 included studies were conducted in 25 countries and 50 % of the studies (n = 160) were published within the past five years (from 2013 onwards; Fig. 2). The references from all 324 included studies can be found in Appendix 2.

3.1. Driver populations

Participant ages in the studies were categorized into five distinct groups: younger only, older only, two groups where younger and older participants were compared, and mixed ages (i.e., all ages), as well as those that did not report participant ages (Fig. 3). Of the 324 studies, 51 % were mixed ages, 23 % had only younger drivers, 3% had only older drivers, and 6% included younger and older drivers. A total of 51 studies (16 %) did not report the drivers' ages.

3.2. Types of AVTs

The types of AVTs reported included: blind spot detection, forward collision warning, forward collision mitigation, lane departure warning, lane departure mitigation, adaptive cruise control, intelligent speed adaptation, non-forward collision warning and mitigation, parking aids, adaptive headlights, driver monitoring systems, night vision systems, and in-vehicle information systems (Fig. 4). The AVTs that did not fit within these categories were classified as "other" (e.g. electronic stability control). The majority of studies focused on a single AVT (n = 237 studies), while 64 studies examined two AVTs, 12 studies examined three AVTs, five studies examined four AVTs, three studies examined five AVTs and three studies examined six AVTs.

As illustrated in Fig. 2, there has been an increase in the number of studies focused on multiple AVTs (combinations) in the past 5 years (i.e., since 2013). The combinations of AVTs involved studies where two or more AVTs were examined with 40 unique combinations of AVTs studied. Lane departure mitigation with ACC was the most common combination (n = 25), followed by LDW with ACC (n = 4), forward collision warning with lane departure mitigation (n = 4), and LDW with lane departure mitigation (n = 4).

3.3. Testing environments

As summarized in Fig. 5, studies were conducted in four types of experimental environments: driving simulators, on-road driving, mixed (both simulator and on-road), andmodelling/computer simulations using large databases (e.g., insurance company databases). The majority (55 %; n = 177) of studies were done in a driving simulator, whereas 21 % of the studies were conducted on-road (i.e., naturalistic or closed course; 69 studies), 15 % of studies used mixed environments, and 9% were done using other methods such as computational statistical modelling using large databases (e.g. National Automotive Sampling System General Estimates System (NASS GES)) and the Fatality Analysis

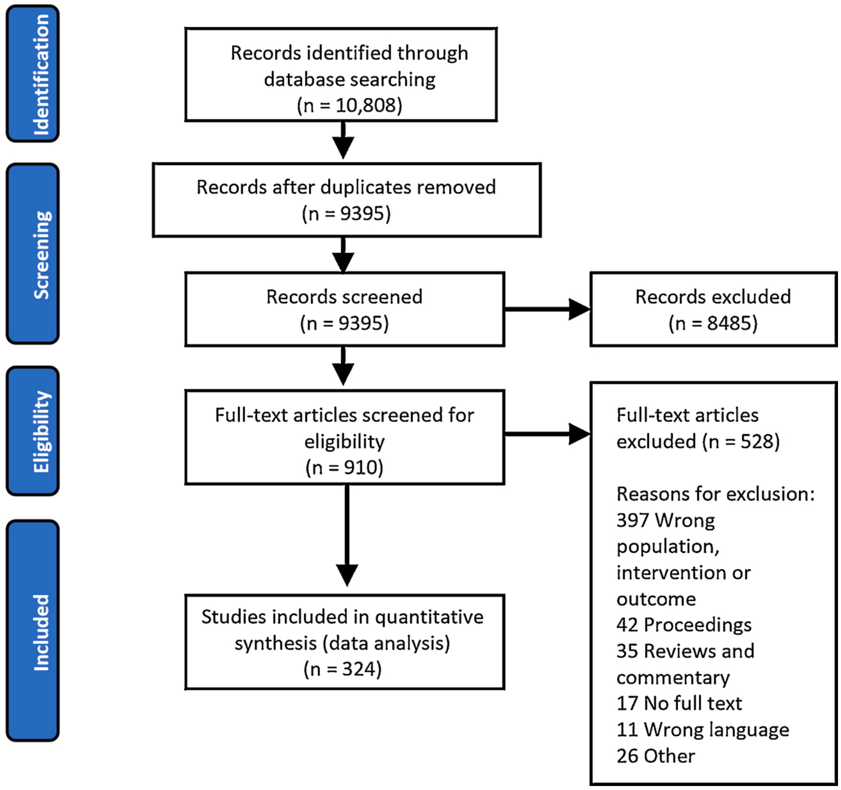

Fig. 1. PRISMA flow diagram.

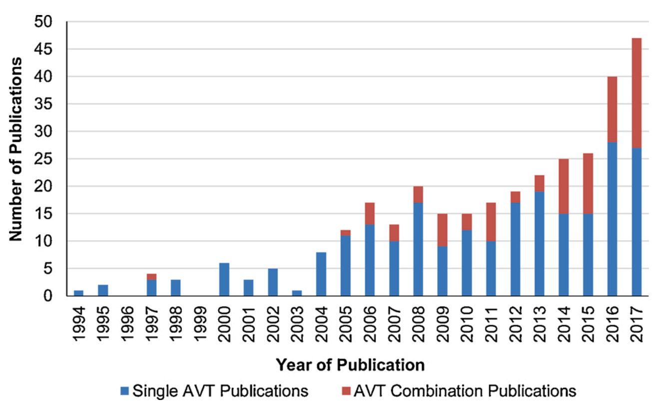

Fig. 2. Year of Publication for 321 publications that assessed a single AVT and for combination of multiple AVTs. One study was not included in this figure because it was published in 2008 but the studies reported in the publication were conducted between 2000 and 2003. Two other studies were not included in this figure because they were published in 2018, and since we did not have full data for 2018 we excluded them from this figure.

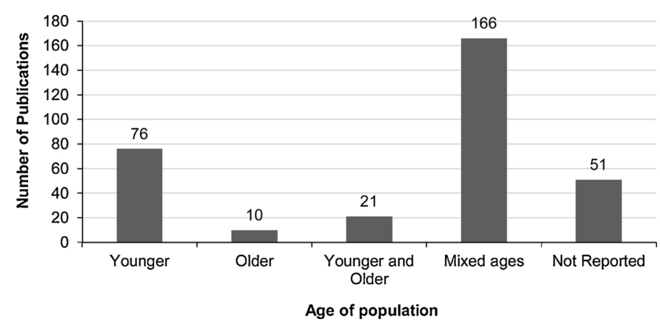

Fig. 3. AVT studies by age of population, where the "younger and older" category includes when each group was analyzed separately in the same publication, and the "mixed ages" category identifies where it is not possible to analyze the data from younger and older age groups separately within the same publication.

Reporting System (FARS) (e.g., Jermakian, 2011).

Fig. 6 shows the type of AVTs by type of testing environment. Some AVTs were predominantly studied in driving simulators environments (e.g. forward collision warning, lane departure warning, adaptive cruise control, non-forward collision warning/mitigation), while other types of AVTs were studied predominantly on-road (e.g. intelligent speed adaptation).

3.4. Outcome measures

3.4.1. Objective outcome measures

Based on the evidence, objective outcomes were sub-categorized into: 1) driver reaction time (e.g., braking); 2) longitudinal control (e.g., speed); 3) lateral position (e.g., lane deviation); 4) measures of eye movements; 5) vehicle maneuvering; 6) driver's interaction with AVT (e.g., driver activation and deactivation of the AVT or ignoring warnings); 7) secondary task performance (e.g., proportion of tasks skipped (Blanco et al., 2006)); 8) number of collisions; 9) number of driver violations or infractions; and 10) physiological responses (e.g. heart rate) (Fig. 7). Based on our analysis, the most studied objective outcomes were longitudinal control (50 % of studies), reaction time (40 %), and lateral position (23 %). The remaining outcomes were measured in less than 16 % of the included studies.

From the 91 publications that assessed objective outcomes of a single AVT (not all the same AVT), there were 15 studies that measured driver reaction time with mixed results. Specifically, one study demonstrated neutral results (i.e., no change), eight studies demonstrated positive results (i.e., faster reaction time), three studies were unclear, and three

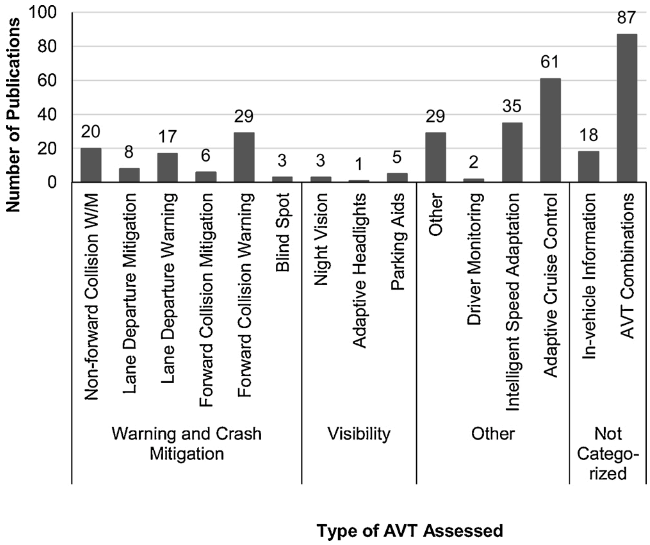

Fig. 4. Number of publications for each type of AVT.

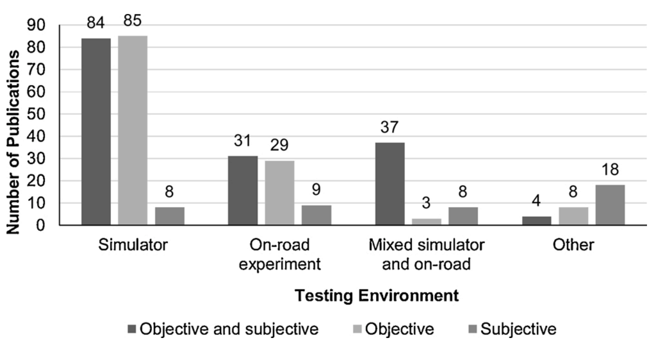

Fig. 5. Number of publications by type of environment and type of outcome.

studies did not report. There were 35 studies that assessed longitudinal control, of which four demonstrated negative outcomes, four neutral, 22 positive, three unclear, and two were not reported. There were 12 studies on lateral position; two studies demonstrated negative outcomes, six positive, two unclear, and two were not reported. There were three studies that mentioned eye movement measures in the methods, but the results were not reported in any of the publications. There were two studies that assessed vehicle maneuvering (e.g. the extent to which surrounding traffic that had right-of-way had to decelerate when the participant was passing the intersection), and both studies were positive in favour of the AVT. There were 11 studies that assessed how the driver interacted with the AVT, such as activation/deactivation or ignoring warnings, and the results demonstrated one negative, one neutral, five positive, two unclear and two not reported results. There was only one study assessing the performance of a secondary task (i.e., cognitive processing demand) related to operating an in-vehicle information system, which was found to be detrimental, as it demonstrated that the presence of multiple decision-making elements in a task had a negative impact on driving performance compared to conventional tasks with only one decision-making element. There were nine studies on collisions with results demonstrating two neutral outcomes, and six positive

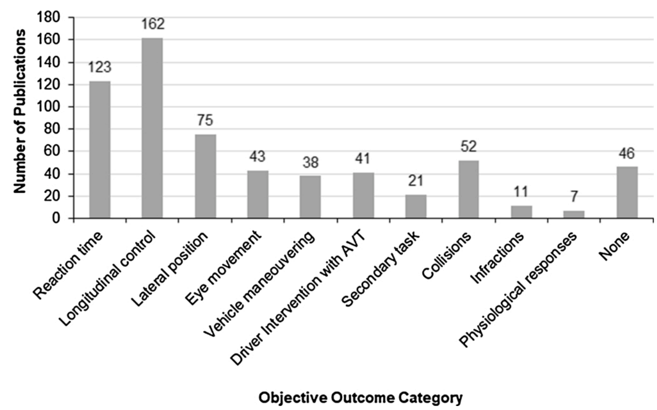

Fig. 7. Objective outcomes used in AVT studies.

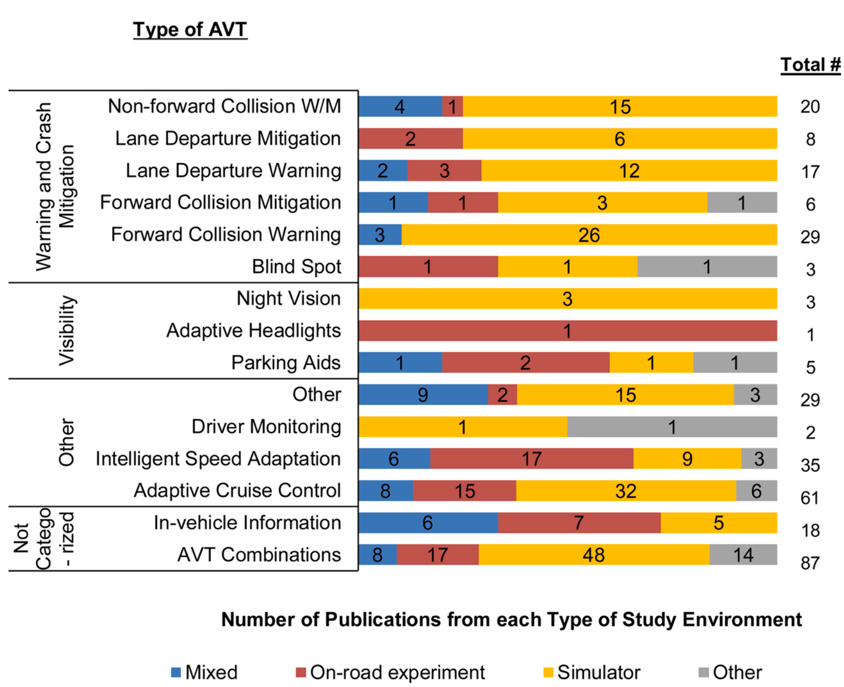

Fig. 6. Type of AVT by type of environment.

outcomes that were in favour of the AVT. There was only one publication on infractions, with a positive result in favour of the AVT (i.e., fewer infractions). There were two studies assessing physiological responses, one showed that stress levels following assisted parking were lower, and the other was neutral. (Fig. 8).

Blind spot detection was studied as a single AVT in three studies, two showed positive results for blind spots in terms of safety, and one study did not report the results specific to safety. The results of objective outcomes by each AVT are shown in Fig. 8. Some AVTs were studied in isolation while others were studied in combination. For example, there were eight studies that assessed blind spot technology in combination with other AVTs; one was positive, one was neutral, one unclear, and five did not report their effect on safety.

We also assessed the results of the objective outcomes by type of AVT in two separate age groups: younger and older drivers (Fig. 9). We found more studies involving younger drivers (76 studies) than older drivers (10 studies), and within the younger age group, combinations of AVTs (23 studies) were the most studied followed by adaptive cruise control (12 studies).

3.4.2. *Subjective outcome measures*

One hundred ninety-six studies (60 %) reported at least one subjective outcome. The most studied subjective outcomes were trust (n = 86, 27 % of studies), perceived workload (n = 65, 20 %), and likability/satisfaction/acceptability (n = 54, 17 %). The remaining subjective outcomes comprised less than 16 % of the 196 studies (Fig. 10).

There were 71 studies that assessed subjective outcomes of a single AVT (not all AVTs were the same). Of these, there were 30 studies that measured trust with mixed results in terms of safety; 12 positive outcomes (meaning higher trust, safer outcomes), three neutral, four unclear, and nine where the safety outcome was not reported. There were eight studies that assessed functionality with the results demonstrating one positive outcome (meaning higher user preference, safer outcomes), one unclear and six not reported. There were three studies on likeability/satisfaction with results demonstrating one positive outcome (meaning higher satisfaction, safer outcomes), one unclear, and one that was not reported. There were three studies on usability with one positive outcome (meaning easier to use, safer outcomes) and two that were not reported. There were 18 studies that assessed mental workload with two positive outcomes (meaning less stressful, safer outcomes), one negative, six neutral, three unclear, and five studies that were not reported.

There were six studies that assessed acceptability, which had two positive outcomes (meaning willingness to keep using it, safer outcomes), two neutral, and two were unclear. There were three studies that assessed usefulness; all of which reported positive outcomes (meaning a high degree of perceived value, safer outcomes). (Fig. 11)

Many studies that assessed at least one of the subjective outcomes did not report the findings in relation to safety (Fig. 12).

We also assessed the results of the subjective outcomes by type of AVT in two separate age groups: younger and older drivers (Fig. 13). We found more studies involving younger drivers (76 studies) than older drivers (10 studies), and within the younger age group, combinations of AVTs (23 studies) were the most studied followed by adaptive cruise control (12 studies).

3.5. *Effect of AVTs on safety*

The overall safety consideration for each AVT is shown in Fig. 14. For sixty-two percent of the AVTs, we determined the findings to be generally positive across most AVTs with regard to their impact on road safety. The results of this scoping review showed that the types of AVTs with highest proportion of studies with positive results were parking aids (4 of 5 studies, 80 %), non-forward collision warning/mitigation systems (15 of 20 studies, 75 %), intelligent speed adaptation (23 of 35, 66 %), blind spot detection (2 of 3, 66 %), night vision assistance (2 of 3, 66 %), lane departure warning (11 of 17, 65 %), forward collision warning (16 of 29, 55 %). The remaining AVTs had proportion of positive studies in 50 % or less of the studies (lane departure mitigation, forward collision mitigation, driver monitoring, adaptive cruise control, in-vehicle information systems, and combinations of various AVTs). There was only one study for adaptive headlight and the results of this study was considered unclear.

4. Discussion

4.1. *General summary*

Results from this scoping review highlight the exponential growth of AVT-related research in SAE levels 0–3, as reflected in the recent and rapid rise in the number of studies. Based on our findings, over half of the included studies have been published in the past five years alone. Congruent with the methods for conducting such a review (Arksey and

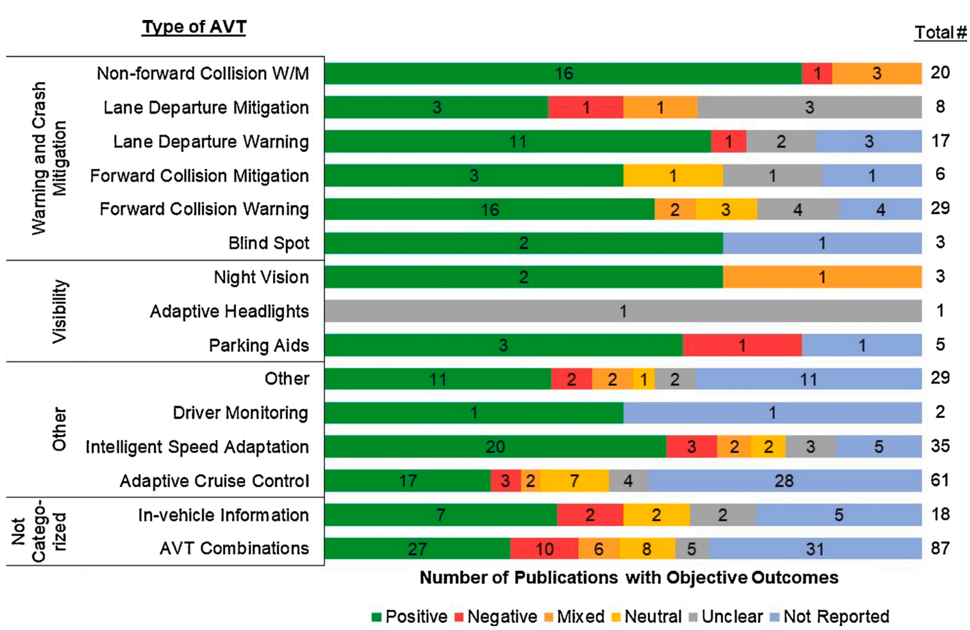

Fig. 8. Direction of results of each study (positive, negative, mixed, neutral, unclear, and not reported) in relation to the objective outcome measured.

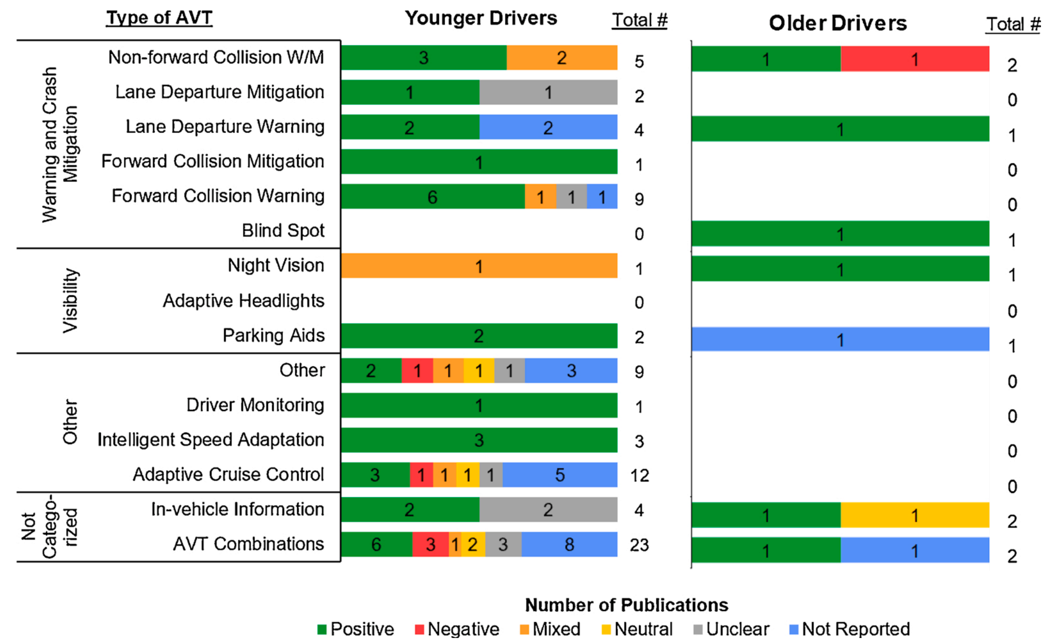

Fig. 9. Objective outcomes by type of AVT and driver's age.

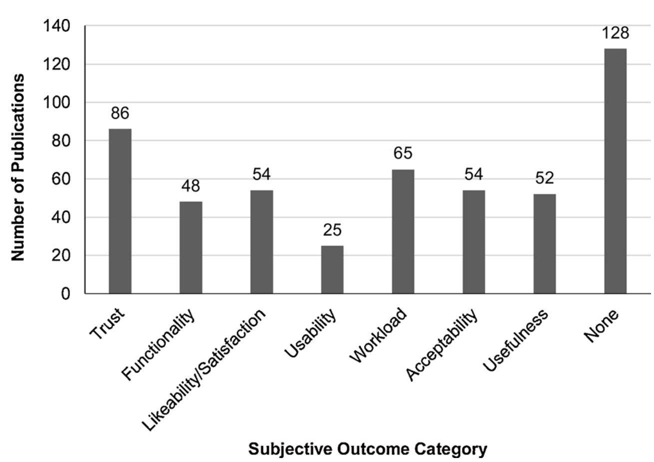

Fig. 10. Number of subjective outcomes across studies.

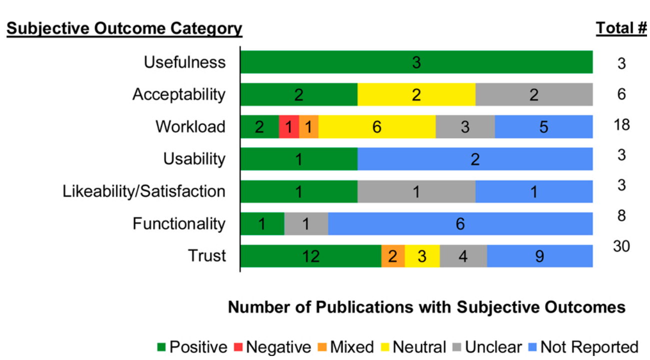

Fig. 11. Direction of results of subjective outcomes across studies.

O'Malley, 2005), our scoping review aimed to first, describe the nature of evidence with respect to the types of AVTs, the driver populations, testing environments, and outcome measures that have been previously studied, and secondly, to provide an overview of their overall impact on road safety. Our findings as related to both of these objectives are discussed below.

4.2. Driver populations and AVTs

Our findings suggest that some AVT-related studies did not report participant characteristics, such as drivers' age. For example, 114 (35 %) of the 324 studies did not report mean age of participants and 49 (15 %) did not include participants' age at all. Additionally, differential analysis of younger and older drivers in such studies were not always conducted, which may be due, in part, to challenges with recruitment. It is important to include both young and older driver demographics in studies of AVT safety given that novice and older drivers are known to have higher crash risks (Tefft, 2017). Similarly, in a scoping review on the impact of AVT on older drivers, Classen et al. (2019) also found that studies on AVT safety reported insufficient detail about participants' age.. In this way, pooling the results across age groups could mask the differential effects of AVTs on safety. In other words, while the effect of an AVT may seem generally positive, but it may actually be negative or positive for certain groups of drivers. However, it is important to acknowledge that differentiating results by age groups could be quite costly, as it would require the statistical power to realize the differentiation, which could increase the sample size, and, in turn, the costs of running the study in question. Hence, striking a balance with regard to the pragmatics of running a study that is also feasible in terms of participant recruitment is important. Researchers should account for age when curating the study eligibility criteria, report detailed information on participants age and other graphics, and provide the statistical power of their analysis when possible. As it will enable meta-analyses where the safety of AVTs with more high-risk driver populations (i.e., younger and older drivers) can be evaluated.

4.3. Types of AVTs

Seventy-three percent of the studies examined a single AVT, and some AVTs were studied much more than others. For example, there were 61 studies of ACC and only 3 for blind spot warning systems. This finding may reflect the fact that ACC is more nuanced in terms of the level of intervention and oversight required from the driver, whereas blind spot warning is seemingly more natural and intuitive. Hence, perhaps it is not surprising that Wang et al. (2020) found the level of

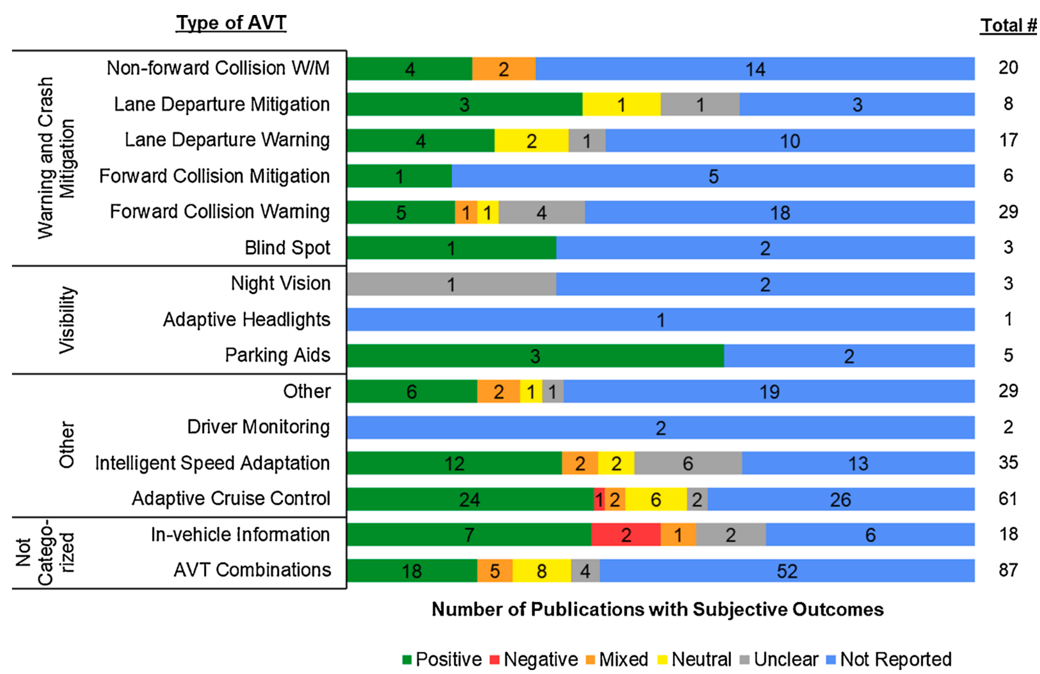

Fig. 12. Direction of results of each AVT study (positive, negative or neutral) in relation to the subjective outcome measured.

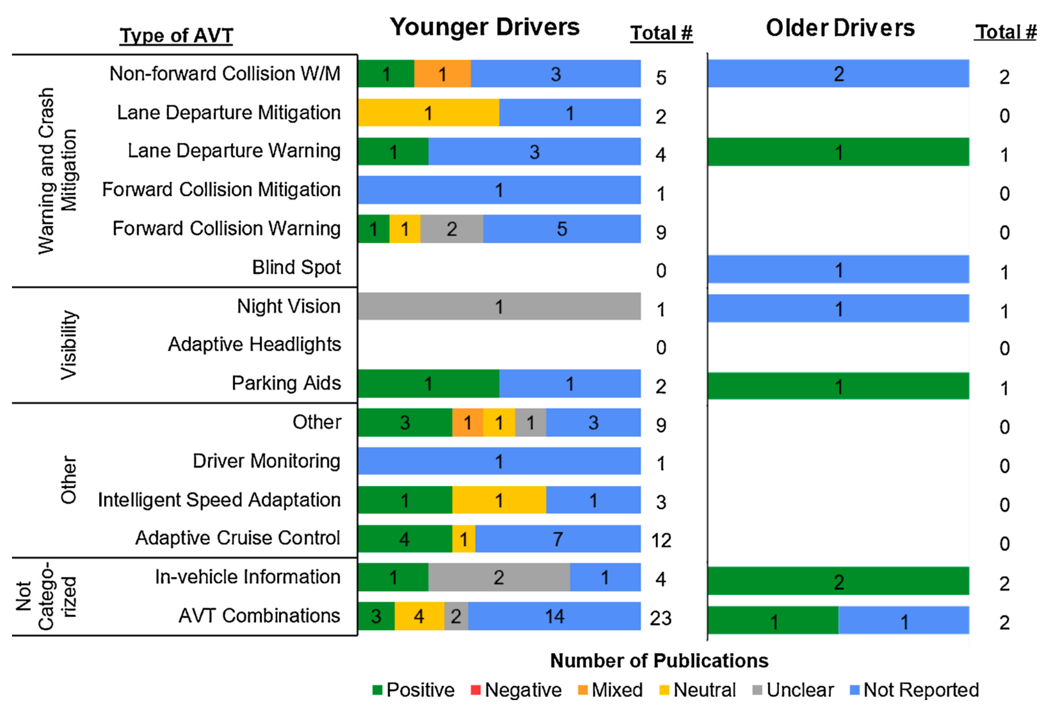

Fig. 13. Subjective outcomes by type of AVT and driver's age.

safety effectiveness of particular AVTs depended on the type of crash in question, i.e., head-on collision or lateral collision. However, the question remains as to how (experimental conditions) and with whom (i.e., drivers) such AVT study is being conducted.

Interestingly, our review also noted a rapid rise in research where the effects of combinations of AVTs on driving safety are being studied. In fact, our review is the first to track the number of studies where two or more AVTs were tested concurrently in the same study. This trend may also reflect what is happening in the automotive industry where more technologies are being offered in combinations within new vehicles models (i.e., safety packages). The challenge is that the current classification frameworks for AVTs, such as the SAE levels of automation, specify the level of automation provided by the AVT to perform driving tasks, however, it does not specify the safety implication of this increasing automotive automation, and is therefore not analogous to a categorization of AVTs in term of their safety. Hancock et al. (2020) recently raised the potential challenges for human drivers in an automobile where its technological capacity is rapidly evolving and "…the vehicle acts to 'assist' the human to drive" (p. 316). While current classifications of AVTs remain helpful to delineate levels of automation, such frameworks may need to evolve, as more complex technologies emerge that are expected to require differential degrees of input from

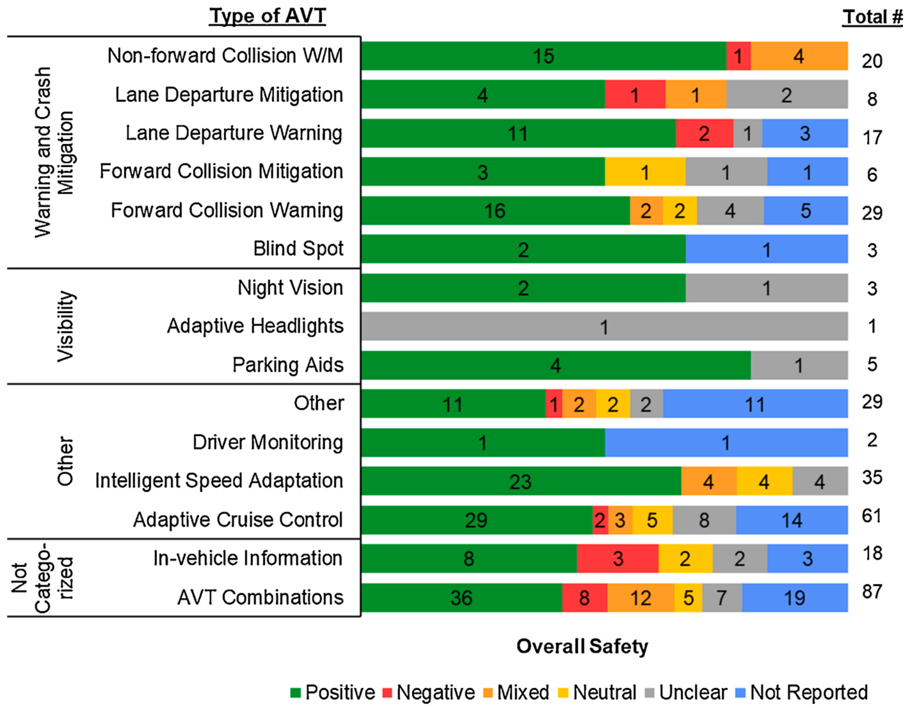

Fig. 14. Direction of results of the overall safety considering all outcomes (objective and subjective).

drivers.

4.4. Testing environments for AVTs

Evidence from the current review highlights the range of experimental conditions, including advanced analytical techniques that have been undertaken to investigate the safety of AVTs. Much of this research has occurred in high- and in low-fidelity driving simulators as well as naturalistic driving conditions, including open and closed driving circuits. A few studies have used large databases that contain crash records and fatalities to model predictive estimates of the effectiveness of certain technologies. The range of approaches is not surprising given the number and types of technologies available and their associated differences in functionality. When conducting AVT-related research, it is critical to weigh the advantages and disadvantages of each testing environment. While research using advanced driving simulators is highly valuable for its ability to capture behind-the-wheel behaviour in a tightly controlled and safe testing context, Ljung Aust and Engström (2011) cautioned that results from such experimentation do not always translate to real-world settings, especially for emergency situations. In addition, repeated exposure of participants to critical events in driving simulators, for example, may influence results, so caution is warranted when interpreting findings with regard to safety.

Analyzing the effectiveness of AVTs using existing, large databases that track crashes and fatalities, for example, is another promising approach for examining the impact of this technology on safety and usability. For example, Jermakian (2011) analyzed crash records from the National Automotive Sampling System General Estimates System (NASS GES) and the Fatality Analysis Reporting System (FARS) to examine combinations of four collision avoidance technologies, namely, forward collision warning/mitigation, lane departure warning/mitigation, side view assist and adaptive headlights. Analysis of NASS GES and FARS data indicated, when combined, these AVTs might prevent up to 1, 866,000 crashes each year including preventing 149,000 serious to moderate injuries and 10,238 fatal crashes, which was almost 600,000 higher than if any of these AVTs were used alone. While such analysis is helpful when considering the potential impact of AVTs, Jermakian (2011) also emphasized the importance of investigating effectiveness in testing environments that reflect real-world demands when behind-the-wheel. Studies using advanced virtual modelling techniques are also increasing, which provides another important way to assess the safety of AVTs. While our review did not include such studies, computer simulation-based approaches enable iterative testing of AVTs that are at various stages of development (Thorn et al., 2018), which aim to improve their safety and functionality prior to their evaluation in real-world environments with human drivers. Virtual simulation may be helpful to further specify the testing conditions in which these technologies should be evaluated, whether in simulator or naturalistic driving studies.

4.5. Impact of AVTs on road safety

Determinations concerning the impact of AVTs on road safety was captured in a myriad of ways across included studies. Both objective and subjective measures were considered. Objective measures ranged from estimates of their influence on crash risk to estimates of changes in driver behaviour and vehicular control. In their recent scoping review of AVTs, Classen et al. (2019) also used absence of behind-the-wheel errors and crashes when considering the evidence specific to the safety of AVTs with older drivers. Based on the 28 studies that met their inclusion criteria, they found AVTs enhanced safety and mitigated age-related declines. Our scoping review reported similar results but for drivers of all age groups. As well, our review also captured the ways in which ‘safety’ of AVTs was measured across studies. While reducing or preventing the occurrence of a crash is an outcome of key importance in road safety research, few included studies, other than simulator-based research, can track this outcome without putting drivers and other road users at risk. However, most naturalistic studies measured behind-the-wheel behaviours, such as reaction time, as well as lateral and longitudinal control of the vehicle. In this context, details concerning the operation of the AVT are critical to interpret the safety of the system. For example, when lateral position is controlled by an AVT, any errors (variability) or crashes would be attributed to the system, whereas for certain lane departure warning systems, the onus is on the human to take corrective action.

For subjective measures, self-report surveys using Likert scales, and/

or open-ended, qualitative responses were the predominant means of tracking the experiences and perspectives of drivers. We found substantial differences between studies in how they weighed these scales and framed scale questions, which may be due, in part, to the fact that each technology delegates differential levels of responsibility to the driver as per the SAE Levels of Automation. As previously noted, subjective outcomes, such as acceptance and usefulness, have been captured using a range of definitions with corresponding measures lacking standardization in AVT studies (Adell et al., 2018; Zoellick et al., 2019). This lack of standardization has also been found in measures of usability (Hornbæk, 2006; Forster et al., 2018), and attitudes towards human-machine interfaces in driving automation (Forster et al., 2019). As such, further studies are needed to devise and validate universal tools that can capture individual's subjective opinions of AVTs in different levels and to further investigate whether such subjective outcomes are comparable across AVTs of different types or levels given the suitability of such measures continues to be questioned (Forster et al., 2018, 2019; Zoellick et al., 2019).

Our scoping review provides a guideline for a core set of key subjective measures that could be considered in the design and development of AVTs. We have previously published a criticism of this literature by pointing to the lack of consistency with regard to both the definition as well as the processes by which key subjective outcomes were captured across studies. We showed that there are multiple interpretations of the same subjective outcomes (Furlan et al., 2018).

4.6. Limitations

Our review of the literature included a large number and range of studies; the largest such review undertaken to our knowledge to date. Other such reviews have reported large numbers of publications as well, although they were narrower in their focus. For example, Eby et al. (2016) included 271 studies that focused on the impact of AVTs on aging drivers and 70 studies were included in a review on haptic support systems (Petermeijer et al., 2015). Despite our best efforts at developing comprehensive search strategies, we recognize that the search terms we selected to define AVTs may be limited, which may be due, in part, to a lack of a common lexicon for vehicle technologies among the automotive industry, safety organizations, and legislators (American Automobile Association, 2019). Further, while our search strategies were not limited by language restrictions, we excluded 11 full text articles that were published in languages that were not translated (two in Korean, five in Chinese, and four in Japanese). Although some relevant studies may have been missed, which may have limited the generalizability of our results, only a small portion of the identified literature (<1%) was excluded for this reason.

Many studies lacked critical details about their research methodology or specified their results. For many outcome measures, there were a number that were "unclear" or "unavailable". While we did not set out to critically appraise the methodological quality of individual studies, as per best practices for conducting a scoping review (Munn et al., 2018), we did categorize studies in terms of safety (i.e., positive, negative, neutral, unclear). However, our conclusions should be interpreted with caution given they indicate the general direction of the effect and given that a systematic review or meta-analyses of this evidence was not completed. As well, our review did not include studies of commercial vehicles, which limits the generalizability of our results to the safety and acceptability of AVT systems in this vehicle fleet. We also excluded studies of SAE level 4 and 5 where driver responsibility for vehicle control is removed. While the objective measures reported in our review aimed to capture how the safety of such systems was quantified, certain measures, such as near-crashes, were not tracked across the included studies. In their seminal 100-car naturalistic driving study, Klauer et al. (2006) defined a 'near-crash' as a "conflict situation requiring a rapid, severe, evasive maneuver in order to avoid a crash" whereas a 'crash' was defined as "any physical contact with another vehicle, fixed object, pedestrian, cyclist, animal, etc." (as cited in Fisher et al., 2017, p. 18−8). Based on these definitions, number of near-crash incidents, as a safety outcome, is more ambiguous than number of crashes, but might still be better than setting subjective safety thresholds on objective measures of lane departure, such as standard deviation of lane positioning. More recently, machine learning models were used to predict near-crash incidents from vehicle kinematic data. Although such predictions are still based on a priori definition of near-crash incidents, such developments and models can help future studies to quantify the characteristics of near-crash incidents and validate these characteristics against the data of crash incidents. (Osman et al., 2019)

Our review also excluded studies based only on computer (virtual) simulations, where actual human drivers were not involved. Our exclusion of this type of research was not because we do not see this work as important, rather the purpose was to narrow our search and keep our review of the evidence focused on the safety implications of AVT use by human drivers, which naturally does not include computer simulation studies. Similar to other reviews of this nature, a major challenge is to ensure the evidence reflects the most up-to-date research given the pace with which new studies are published. As noted in our methods, our team re-ran the search to include the latest research in this burgeoning field.

4.7. Directions for future AVT research

There are a number of important and timely opportunities with regard to future AVT-related research that emerged from this review. Our findings suggest that there is sufficient evidence on specific technologies, such as ACC, where systematic reviews and meta-analyses could be undertaken to determine their efficacy using evidence from a range of different testing environments (e.g., test-track closed course, on-road experiment, naturalistic driving, simulator, modelling). For example, Ziakopoulos et al. (2019) recently conducted a meta-analysis on the impacts of operating in-vehicle information systems on road safety. With increasing research and prevalence of AVTs, particularly those at SAE level 0–3, combining research findings on such AVTs using meta-analytic techniques will become even more critical. It is also important to highlight that AVTs need to be tested in different environments (e.g. driving simulators, on-road, test-track, naturalistic).

Results from our review also indicated that combinations of AVTs should be studied, as to which combinations are most effective with a focus on determining those singular technologies that may have reached a point of diminishing return in terms of safety. Our review also found many studies did not specify the demographics of the drivers with whom they were being tested. This finding was surprising given the known impact of age and other factors on behind-the-wheel behaviour and how differential levels of familiarity with technology can impact safety and comfort of AVTs (Zhan et al., 2013). For example, differentiation of study participants by level of driving experience and/or technology expertise, alongside age, gender, and other demographics should be considered when conducting future research on AVTs. Currently, standards for the design and testing of AVTs, as outlined by the NHTSA, do not make any recommendations concerning the type of demographics and how they should be identified in AVT research. Given AVTs hold much potential to reduce crash risk and that certain driver cohorts, such as younger and older drivers, who, given their collision profiles, stand to benefit from such advancements, differential analysis in certain demographics should be encouraged, where possible. As well, standardized naming and framing of the types of AVTs alongside associated objective and subjective outcome measures are all important considerations for research going forward. The categories outlined in Table 1 might be helpful for future studies.

There may come a point of diminishing returns where more technology does not necessarily lead to improved safety and driver comfort or could even have a negative impact by increasing the demands on the driver. For example, recent efforts have been made to improve the design of devices in a way that reduces or even prevents driver distraction (NHTSA 2014b). In fact, NHTSA recently changed its regulations on AVTs to enable testing on everyday roadways, including vehicles that do not have steering wheels, pedals, or mirrors (U.S. Department of Transportation, 2018). While it is exciting to consider the transformational impact of new and emerging AVTs on vehicle operation and safety, caution is warranted in their early adoption without sufficient evidence from well-designed studies.

5. Conclusion

There is much enthusiasm regarding the infusion of technology into the automobile cockpit and the potential for road safety to be improved as a result. Findings from our scoping review highlight the importance of considering the experimental context of studies when evaluating the safety implication of AVTs for potential widespread on-road use. This experimental context includes the study's population, testing environment (e.g., on-road, simulator, naturalistic driving), and outcomes used to evaluate the safety of AVTs. In fact, our results highlight some of the key factors pertaining to participants' demographics, such as age and level of driving and technology experience, that should be considered in the design of studies aiming to evaluate AVT safety where appropriate and feasible.

The results also signify a changing dynamic in the design of AVTs with regard to studying the effectiveness of combinations of different technologies and how computational modelling and other advanced statistical techniques can be used to inform and complement existing testing protocols where drivers are included in the experimental design (i.e., simulator and naturalistic driving). With the emergence of new technologies in the automotive marketplace and many of which being expected to become standard in the very near future, our timely review emphasizes key factors, including the populations being studied, that should be integrated in the design and development of AVTs. Such studies will be critical to determine those AVTs that are most effective in preventing collisions and optimizing driving performance where the ultimate aim is to improve road safety for all.

Funding

This work was supported by a Canadian Institutes for Health Research - Knowledge Synthesis grant (grant #147996).

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

The authors would like to acknowledge the Canadian Institutes for Health Research (CIHR) for funding this scoping review. The authors are grateful to the following individuals who helped in various stages of this review: Israel Souza (article selection), Keean Nanji (article selection), Hana Abbas (article selection and data extraction), Achyut Suri (data extraction), and Maria Vo (data extraction). We acknowledge the following people for input in the protocol design of this scoping review: Kristine D'Arbelles from the Canadian Automobile Association, Kim Gould from Canada Post, Garry Drouin and Roy Hulli from the Ministry of Transportation of Ontario, Dr. Geoff Fernie from the Toronto Rehabilitation Institute, Drs. Peter Burns and Joanne Harbluk from Transport Canada, and Dr. Lisa J. Molnar from the University of Michigan Transportation Research Institute.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.aap.2020.105741.

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