Transportation Research Interdisciplinary Perspectives 37 (2026) 101986

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

Drivers and automation: a systematic review on road suitability for assisted and partially/conditionally automated vehicles

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ARTICLE INFO

Keywords:
Automated vehicle
Autonomous vehicle
Geometric road design
Driver behaviour
Driver performance
Road safety

ABSTRACT

Vehicle automation technology is advancing faster than our road system can adapt. It is vital to integrate automated vehicles effectively while ensuring drivers can safely and efficiently perform driving tasks when required. This systematic review examines vehicle automation's impact on driver behaviour and performance with respect to the suitability of existing roads. Focusing on guidance tasks influenced by road geometry and traffic, the review screens 1569 studies; forty met eligibility criteria. The results reveal a significant deterioration in driver behaviour and performance during guidance tasks, characterized by protracted decision-making and reaction times, longer durations for guidance tasks, and increased variability in gaze movement, lateral displacement, and longitudinal and traversal kinematic parameters. While some technological solutions have been suggested to alleviate these declines, the need for more research into how road design affects driver behaviour in automated settings remains evident. A key finding is the limited evidence on both road geometric variables and traffic-related factors; the latter appears more often but remains limited and heterogeneously reported. Significant gaps in knowledge persist regarding automation's impact on driving guidance in merging, diverging, weaving, and overtaking scenarios, especially on two-lane roads, requiring further study. Additionally, there are gaps related to environmental factors in the context of automation's impact on guidance tasks and coverage of older drivers and interactions with pedestrians/cyclists and heavy vehicles (including professional drivers) were limited or absent. These points identify the most critical gaps and outline concrete directions for future work on road suitability under assisted and partially/conditionally automated driving.

Introduction

Automated vehicles (AVs) are gradually being introduced onto roads. They are expected to change the nature of road transportation and improve safety and the quality of life by decreasing the number and severity of crashes, and by improving road network performances in terms of operation efficiency (Kyriakidis et al., 2019). According to the current classification for AVs (SAE, 2021), partially automated driving (PAD, SAE level 2), has been applied by many automobile producers to their high-end vehicles. However, the application of the next levels of automation to vehicles is slow and complex due to several factors involving (i) the significant improvement of in-vehicle technologies, and (ii) the different role that the driver must learn to play as they transition from active to passive driver, and vice versa when the vehicle encounters environmental and traffic conditions that are outside its operational capabilities. These restraining factors, notwithstanding current predictions and trends, indicate that about 50% of circulating vehicles will be fully AVs by 2050 (Liu et al., 2019). Despite the acceptance and availability of this technology, the path to full automation will be less than smooth.

With conditionally automated driving (CAD, SAE level 3), the driver's role changes from an active participant to a passive supervisor (Madigan et al., 2018), opening the door to the possibility that the driver's situational awareness of what is happening on the road may be reduced (Endsley, 2017), to the extent that drivers may even deal with dangerous out-of-the-loop situations (Madigan et al., 2018).

The major concern with CAD in the transition period is the need to understand driver behaviour and performance when interacting with existing roads and traffic. It is worth noting that the features of existing roads were designed on the basis of expected driver behaviour and

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https://doi.org/10.1016/j.trip.2026.101986
Received 3 February 2025; Received in revised form 17 November 2025; Accepted 7 April 2026
Available online 17 April 2026

performance in manual vehicles (Highway and Officials, 2011). For example, Madigan et al. (2018) found a significantly higher variation in speed and lateral position when drivers changed lane in PAD compared to manual driving. Similarly, excessive longitudinal and lateral behaviour beyond what was deemed necessary were also detected during lane changes in CAD (Tanshi and Soffker, 2022). Therefore, there is an urgent need to assess the suitability of existing roads for the automation era to come in order to understand what behavioural changes and adaptations can be expected.

Despite numerous reviews addressing various aspects of AVs, such as users' acceptance of AVs (Islam et al., 2022; Kaye et al., 2021; Lee et al., 2021; Milakis et al., 2017; Zhang et al., 2021), take-over control (Cao et al., 2021; Deniel and Navarro, 2022; Gasne et al., 2022; Jansen et al., 2022; Manchon et al., 2021; McDonald et al., 2019; Soares et al., 2021; Weaver and DeLucia, 2022; Zhang et al., 2019), applications of driving simulators (Rosique et al., 2019) and virtual reality (Riegler et al., 2021) for developing AVs, travel behaviour (Soteropoulos et al., 2018), environmental impacts (Silva et al., 2022) and the safety of AVs (Sohrabi et al., 2021; Wang et al., 2021; Xiao et al., 2021), the comprehensive review by (Tengilimoglu et al., 2023) stands out for its discussion on the suitability of the existing road and physical environment for AVs. However, Tengilimoglu et al. (2023) primarily focused on assessing the infrastructure requirements for automated vehicles at Levels 4 and 5, including the ability of AV systems such as sensors and onboard technologies to navigate and operate safely on existing roads. Their review emphasizes the interaction between AV technologies and road features, such as geometry, markings, and signage, which are necessary for safe automated driving, where the driver's role is significantly diminished or entirely absent, as in Level 5.

In contrast, the current research examines the suitability of existing roads for drivers whose responsibilities are still substantial under assisted manual driving through CAD (level 3). This includes situations where drivers remain responsible and roads are still designed around human capabilities (e.g., visibility, workload, reaction time). In this context, infrastructure and behaviour are interdependent; the same design choices that support manual driving also shape driver performance under assistance and CAD. This knowledge gap raises questions about the potential need for adjustments in current road designs to ensure a safe environment for performing evolving driving tasks. The main aim of this study is to fill this gap through a systematic literature review.

Of the three driving tasks (i.e., control, guidance, and navigation), it is guidance which is most influenced by traffic operations and road geometrics (AASHTO, 2011). In CAD and PAD, lane placement, road following, and car following can be entirely performed by the automated vehicles. However, in PAD, drivers are required to take control for other guidance activities, such as lane changing, merging/diverging, and overtaking, while CAD automates these guidance activities within its operational design domain. It is worth noting that current CAD systems have limitations on their out-of-design domain capabilities. Consequently, drivers must manage the guidance activities mentioned after taking over control from the system. Therefore, this systematic review focuses on the inclusion of lane changing, weaving, merging/diverging, and overtaking as guidance activities. While the primary focus is on the two main levels of automation, PAD and CAD, the study also extends its scope to include lower levels of automation, namely, Level 0 (manual driving) and Level 1 with Advanced Driver Assistance Systems (ADAS). This broader perspective aims to gain a deeper understanding of how automation impacts driver behaviour and performance on the existing road infrastructure.

The objectives of this systematic review are as follows:

- to study the impact of different levels of automation on driving behaviours and performance in lane changing, merging/diverging and overtaking manoeuvres;
- to evaluate whether the current road system, which was developed solely to enable manual driving, is ready for higher levels of vehicle automation or requires adaptation; and
- to identify the knowledge gaps to be bridged on driver-vehicle–road interaction studies in a context in which automated vehicles are increasingly prevalent.

Through a systematic analysis and synthesis of the existing literature, this study seeks to offer a nuanced understanding of how automation influences specific guidance tasks and its broader implications for road safety, human factors, and the overall driving experience. The anticipated findings of this review should make a valuable contribution to a better understanding of the interaction between automated driving technologies, drivers, and road dynamics. The insights gained, coupled with the identified gaps in this systematic review, have the potential to inform and enable relevant stakeholders – such as automotive manufacturers, policymakers, and road designers – to strategically optimize road infrastructure and elevate the safety and efficiency of automated driving systems in pursuit of their respective goals.

Methodology

The present study involved a systematic and comprehensive review of relevant literature, examining the effects of automation on guidance driving tasks across different levels of automation, ranging from manually assisted driving to CAD. To ensure a rigorous and transparent methodology, this systematic review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The PRISMA framework (see Appendix A1) provides a structured and reliable process for identifying, selecting, and analysing relevant studies in a systematic manner. By utilizing PRISMA, we aim to minimize bias, increase reproducibility, and present a clear and comprehensive synthesis of the available evidence related to the impact of automation on driving behaviours, performances, road infrastructure suitability, and potential future research directions in the context of automated driving systems.

Eligibility criteria

The eligibility criteria for the inclusion of studies in this systematic literature review were as follows:

1. *Automation Levels*: studies investigating the effects of automation at SAE Level 1, SAE Level 2 (PAD), and SAE Level 3 (CAD) were considered for inclusion in this review. Additionally, studies focusing on Advanced Driver Assistance Systems (ADAS) were included.
2. *Guidance Activities*: studies that examine the impact of automation on various guidance activities, including lane-changing, overtaking, merging, diverging, and weaving manoeuvres, were eligible for inclusion.
3. *Participants*: the selected studies had to involve participants (drivers) engaged in real-world driving or driving simulator experiments. Studies relying solely on questionnaires or video observation without involving actual driving tasks were excluded. This criterion ensures that the focus remains on studies in which drivers actively participated in driving scenarios, thereby providing more direct and relevant insights into the effects of automation on guidance tasks.
4. *Measurement of Driver Behaviour/Performance*: studies must have investigated at least one behavioural or performance related measurement concerning guidance activities under different levels of automation. Papers that only investigated the acceptance of automation by drivers were not considered for inclusion.
5. *Publication Types*: only full-text, peer-reviewed publications, including journal articles and book chapters, were included.
6. *Language*: only studies written in English were included to ensure consistency in data extraction and analysis.

Information sources and search strategy

The primary information sources for this systematic literature review were Scopus and Web of Science (WoS) databases, which provide a comprehensive collection of peer-reviewed academic journals and other scholarly publications. By utilizing Scopus and WoS, this review aimed to access a broad array of relevant studies on the effects of automation on guidance driving tasks across different levels of automation. The search was limited to studies published prior to October 14, 2024.

The search query (Table 1) was created using Boolean operators to ensure that the included studies were directly related to our research objectives and met the predefined inclusion criteria. This approach contributed significantly to the consistency and relevance of the findings presented. The search strings for Scopus and WoS are presented in Appendix A2.

Selection process

The selection process for this systematic review involved a series of rigorous steps to determine whether a study met the inclusion criteria. The initial search conducted in WoS and Scopus resulted in 1,049 and 1,341 records, respectively. Duplicate records were then identified and removed using the *revtools* (Westgate, 2019) package in R (Team, 2021), with the paper DOI as a control parameter. After the removal of duplicates, 1569 unique records remained for further evaluation.

Three independent reviewers, including a master's student, a Ph.D. student, and a postdoctoral research fellow, with similar educational backgrounds but with different levels of expertise and gender were actively involved in the screening process. They reviewed the title and abstract of each record using the *metagear* R package (Lajeunesse, 2016). Each reviewer worked independently to ensure unbiased decision-making and contributed unique perspectives to the selection process. The involvement of three reviewers further strengthened the comprehensiveness and objectivity of the study selection.

As shown in the PRISMA flowchart in Fig. 1, the selection process involved the following screening stages:

- *Title and Abstract Screening*: the independent reviewers screened the titles and abstracts. A total of 1461 records were excluded based on predefined criteria. If a record did not meet at least one of the eligibility criteria, it was excluded. However, not all reviewers consistently documented which specific criteria were not met for each excluded record. This inconsistency may affect the transparency of the review process, but it does not compromise the validity of the included studies and the overall conclusions drawn.
- *Full-Text Screening*: all reviewers participated in the full-text screening of the remaining 108 records. At this stage, 30 studies were directly included, and 42 studies were excluded with unanimous decisions from all reviewers.
- *Consensus Meeting*: for the remaining 36 studies, the reviewers had not same opinions as to whether they should be included or not; therefore, a meeting was conducted with all authors. During the meeting, the 36 records were thoroughly examined and discussed, resulting in a unanimous agreement to include 10 of them. It is noteworthy that 30% (3 out of 10) of the final inclusion decisions aligned with the choice of only one reviewer, underscoring the significance of conducting screenings with multiple reviewers. The reasons for excluding studies during the full-text review are shown in the PRISMA flowchart in Fig. 1.

Table 1
Search strategy.

Automation	"automated" OR "autonomous" OR "partially automation" OR "conditionally automation" OR "self-driving" OR "Assisted Driving Automation" OR "advanced driving assistance system" OR "ADAS" OR "Level 1" OR "Level 2" OR "Level 3" OR "driverless" OR "intelligent" OR "level of automation" AND
System	"vehicle" OR "car" OR "automobile" AND
Driver	"driver" OR "participant" OR "driving" AND
Guidance activity	"lane change" OR "lane changing" OR "overtaking" OR "passing" OR "merge" OR "cut in" OR "merging" OR "diverge" OR "diverging" OR "weaving" AND
Measurement	"behaviour" OR "behavior" OR "attitudes" OR "performance" OR "decision" OR "reaction" OR "response"

A total of 40 records meeting all the predefined inclusion criteria were included in the final analysis. These 40 records, which were the subject of rigorous scrutiny and achieved the consensus of all the reviewers, became the focus of a comprehensive evaluation and synthesis in the systematic review.

Data extraction

The data extraction process was conducted systematically, following the list in Table 2 to capture bibliographic details, study characteristics, methodology/experiment characteristics, participant characteristics, study outcomes, and main findings. This rigorous and structured approach ensured the consistency and accuracy of data collection. One of the reviewers extracted the data while another checked the quality of same.

Risk of bias assessment

In systematic reviews, evaluating the risk of bias in included studies is crucial for ensuring the reliability and validity of the review's conclusions. The Cochrane Collaboration's Risk of Bias Tool, ROB2 (Sterne et al., 2019) was used to assess systematic errors in study design, conduct, or analysis that may distort outcomes. ROB2 evaluates bias across several domains: (i) the randomization process, (ii) deviations from intended interventions, (iii) missing outcome data, (iv) measurement of the outcome, and (v) selection of reported results. Each domain is analysed through signalling questions, which help classify the risk of bias as "low," "some concerns," or "high". This assessment framework is applied to each paper included in the review, providing a comprehensive evaluation of the evidence and supporting informed decisions based on the accumulated data.

The risk of bias associated with this systematic review was assessed using the ROBIS tool (Whiting et al., 2016), which provided a structured approach to evaluating potential biases across various stages of the review process. It identifies concerns with the review process in four distinct domains, including (i) study eligibility criteria, (ii) identification and selection of studies, (iii) data collection and (iv) study appraisal, synthesis and findings.

Data synthesis and analysis

The extracted data from the studies is presented in the results section. Initially, the selected records underwent bibliometric analysis to comprehend the landscape of the research field. This analysis involved processing the data retrieved from the two databases automatically. The tools presented by Zygomatic (2024) and Van Eck and Waltman (2010) were employed to generate the keyword cloud and co-occurrence network of title terms in Fig. 3 and Fig. 4, respectively. Additionally, Fig. 2 depicts publication trends to provide insights into the level of research in this field.

The characteristics of the studies, including (i) the experimental environment, (ii) participant details such as the number, age, and gender distribution, (iii) levels of automation, and (iv) the investigated

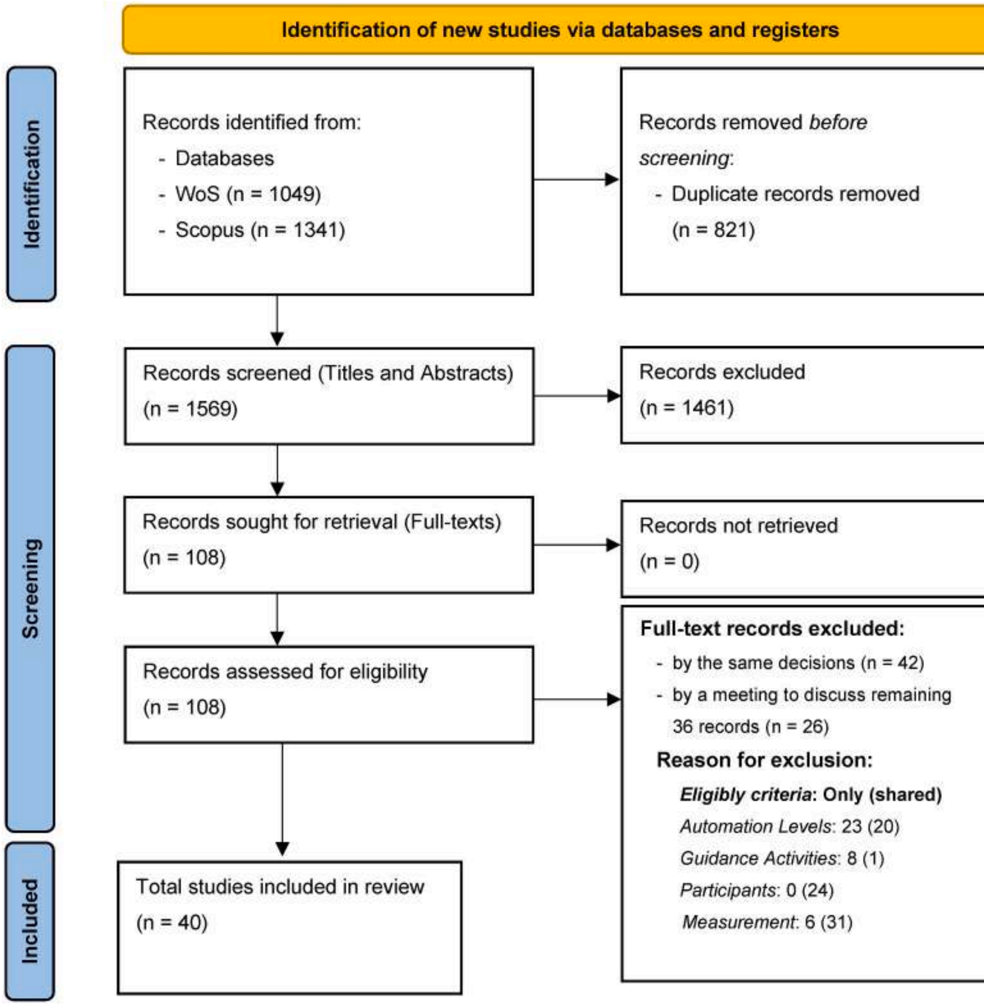


Fig. 1. PRISMA flowchart.

Table 2
Information extracted from included records.

Information Category	Details
Bibliographic information	Title, Author(s), Year of publication, Country of origin, Journal characteristics
Information about the study	Main research objective(s), Level(s) of automation, Guidance activity type(s)
Methodology/Experiment characteristics	Design of experiment method, Factors considered in design of experiment (e.g., road geometrics, traffic characteristics, …), Type of vehicle or simulator used, Driving simulator validity, Experiment duration per participant, Investigated factors (e.g., road characteristics, driving environment (urban/ rural), lighting conditions, weather conditions, automation state during guidance activities (active/immediately after take-over (manual)/a lower level of automation/ …)
Participant characteristics	Number of participants, Gender, Age, Driver professionality, Driving experience of the participants
Study outcomes	Driver behaviour measurements, Driving Performance measurements, Safety-related measurements
Main findings	Based on the objective of this systematic review

driving manoeuvres, were extracted and presented using tables and graphs designed to illustrate similarities and differences. Notably, a three-field plot based on an alluvial Sankey diagram was employed to visually depict these relationships (Flourish, 2024).

Results

Bibliometric analysis

Table 3 presents the list of included records. As illustrated in Fig. 2, the initial study in this field was published in 2009. However, there has been an evident and significant increase in interest in the effect of automation on the specific guidance activities considered in this research since 2017, with a notable surge in the number of published studies which reflects the increasing awareness of the transformative impact of automation on driving behaviours and the need to comprehensively understand its implications. This surge in research activity reflects the urgent need to address the critical questions and challenges posed by the integration of automation with existing infrastructures.

The word cloud of Fig. 3 visually captures the most prominent themes and topics identified across the studies included in this systematic review. Fig. 3a illustrates the prevalence of the keyword ‘driver behavior’, which implies that studies predominantly focused on understanding and examining driver behaviour as a central point of interest in AVs. The highlighted keywords associated with AVs include ‘vehicle automation’ and ‘automated driving’. Fig. 3a shows that most of the studies centre around lane change manoeuvres, with driving simulators being used as the main tool. In contrast, Fig. 3b provides a more detailed perspective by breaking down multi-word keywords into individual terms, highlighting the foundational concepts driving the research. The prominence of ‘driving’, ‘driver’, ‘automation’, and ‘automated’ highlights the combined emphasis on human interactions

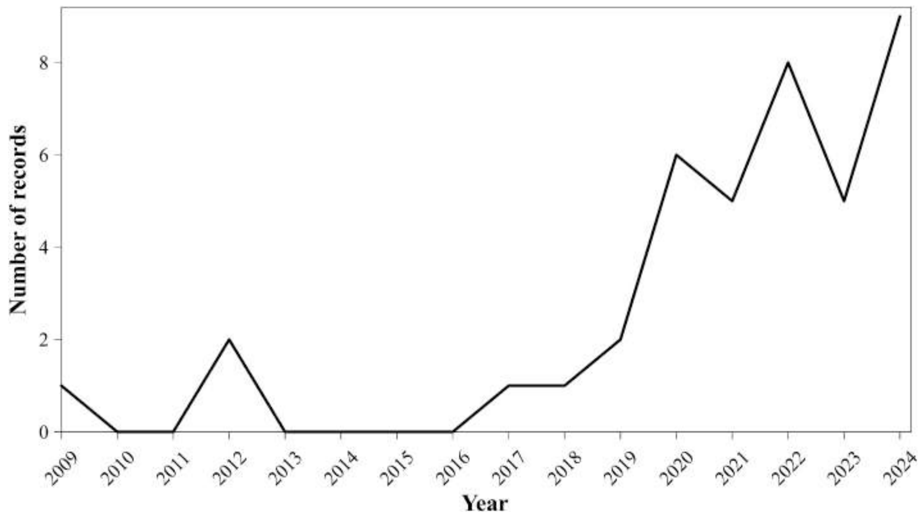


Fig. 2. Trend of published studies over time.

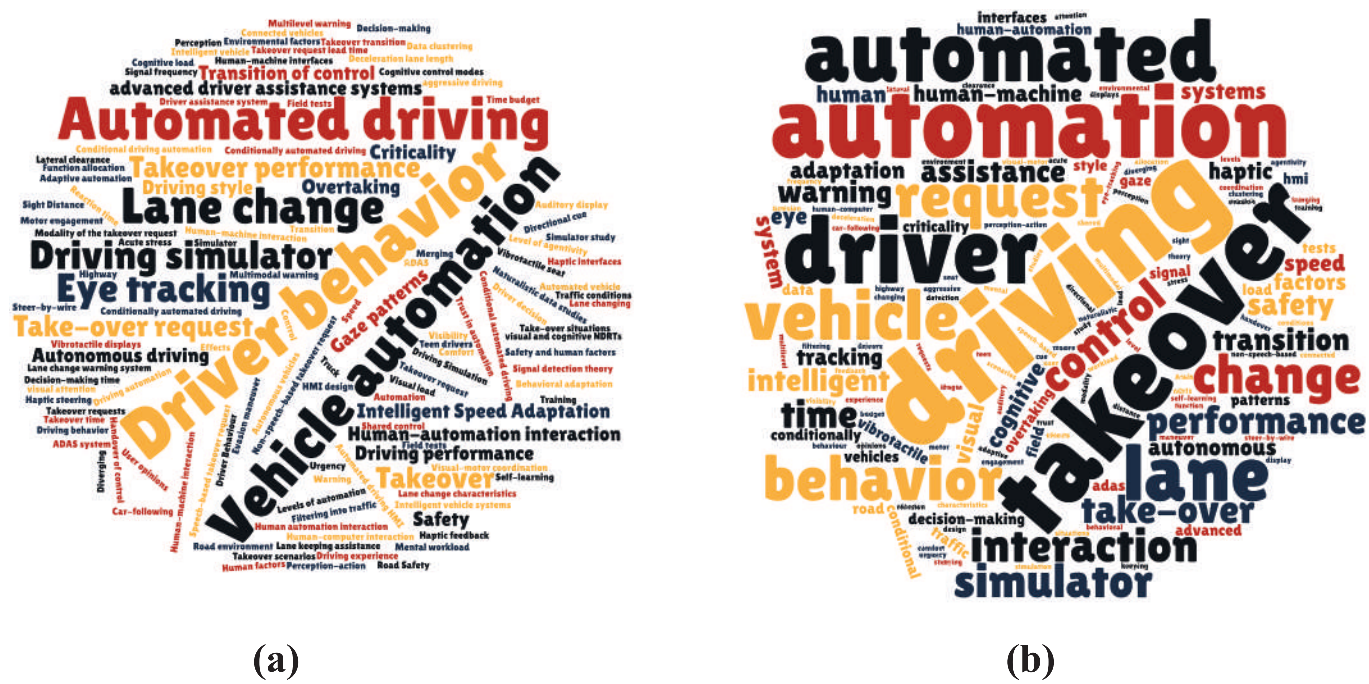


Fig. 3. Keyword cloud of included studies: (a) original multi-word phrases; (b) individual keywords after splitting multi-word phrases into single terms.

within the context of automated driving systems. A key area of this interaction is the transition of control from the automated system to the driver, which is prominently reflected in the term 'takeover'. This highlights the critical importance of studying how drivers respond to takeover requests, manage control transitions, and ensure safety during these moments in automated driving scenarios.

Fig. 4 illustrates the co-occurrence network of title terms extracted from the included studies. It provides a comprehensive overview of the key research themes and their interconnections. The central position of the term 'effect', with strong links to 'takeover performance', 'level', and 'advanced driver assistance system', emphasises a significant focus on evaluating the impacts of various automation levels and ADAS on driver performance. Closely connected to this are terms like 'driver', 'control', and 'takeover' which form a driver-centred cluster, highlighting the role of human interaction with automation, particularly during transitions of control. Another cluster includes 'design', 'evaluation', and 'lane', and reflects research on specific driving scenarios, such as lane changes, and the design and assessment of systems to enhance safety and efficiency of automated vehicles.

Risk of bias in studies

Fig. 5 presents the results of the risk assessment for the included studies using the ROB2 method. In the first domain, which addresses the randomization process, all studies were generally well-handled, except for (Ammar et al., 2023; Chauvin et al., 2020; Du et al., 2024; Sun et al., 2019). There is high risk of bias for (Sun et al., 2019) due to an excessively small sample size. There is no evidence of randomization for (Chauvin et al., 2020). Du et al. (2024) were not able to conduct tests in a random manner, which could raise some concerns. Finally, the naturalistic study of Ammar et al. (2023) was not a controlled experiment and did not follow randomization. For all studies except (Dillmann et al., 2021), the allocation sequence was not concealed, as the nature of the interventions required disclosure. This is often the case in studies

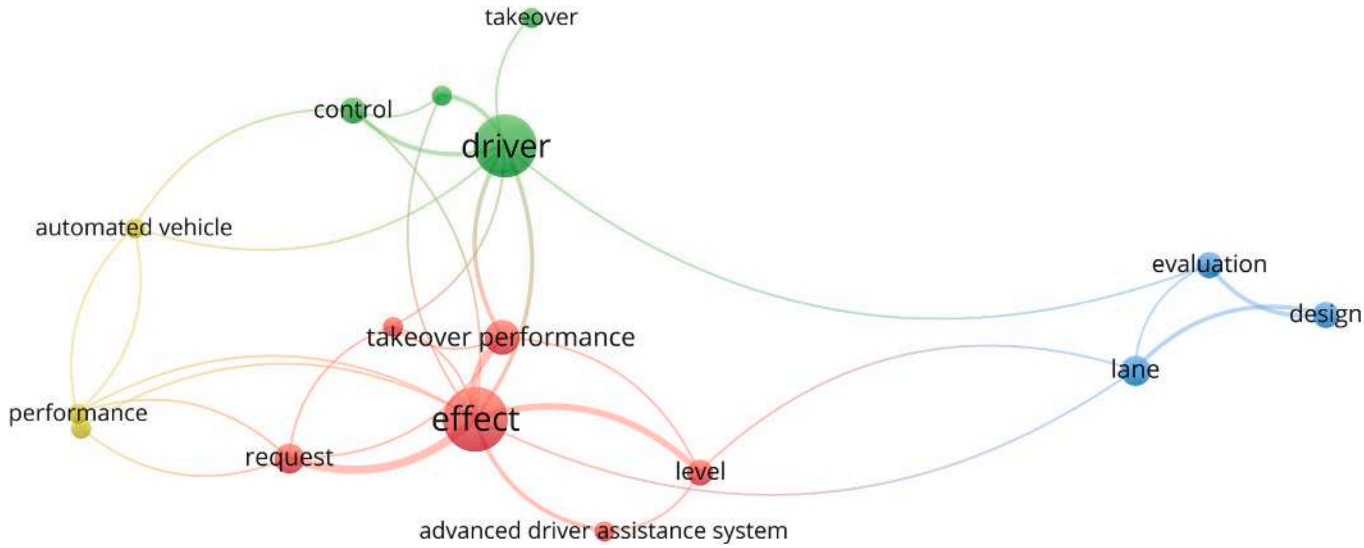


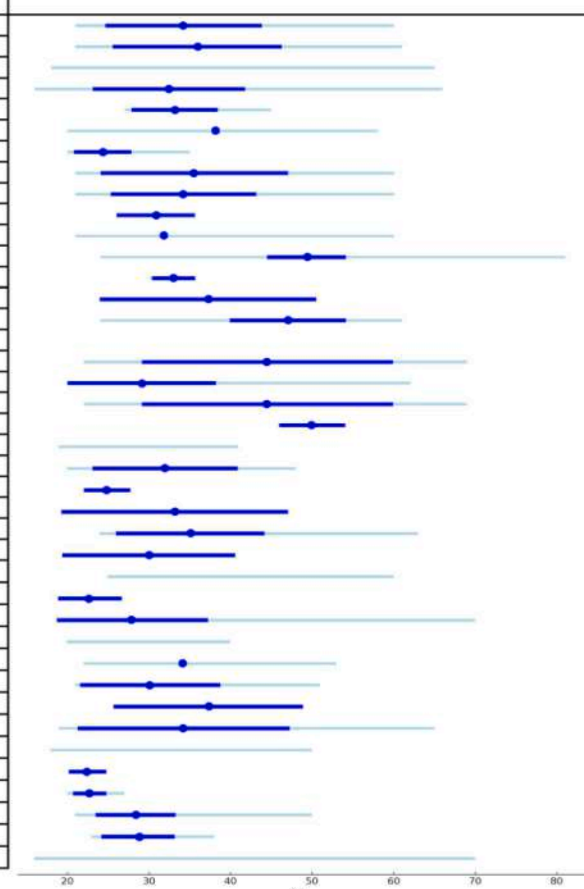
Fig. 4. Co-occurrence network of title terms.

Table 3

Experimental environment and participant characteristics of included studies. Note. Rightmost panel: dark-blue segment = minimum–maximum age range; light-blue band = ±1 SD around the mean age (dot). Elements are omitted when the corresponding statistics were not reported. Table 4. Overview of automation levels explored in the included studies.

Study ID	Author(s)	Experimental Environment	# Participants	Percentage of females (%)
1	Madigan et al. (2018)	DS	29	48.28
2	Dillmann et al. (2021)	DS	85	29.41
3	Várhelyi et al. (2020)	RV	27	55.56
4	Brijs et al. (2022)	DS	48	43.75
5	Maggi et al. (2022)	DS	16	56.25
6	Hazoor et al. (2023)	DS	32	37.50
7	Yan et al. (2021)	DS	12	16.67
8	Goncalves et al. (2022)	DS	30	43.33
9	Goncalves et al. (2020)	DS	29	48.00
10	Maag et al. (2012)	DS	16	37.50
11	Doubek et al. (2020)	DS	25	52.00
12	de Waard et al. (2009)	DS	33	18.18
13	Sun et al. (2019)	RV	3	0.00
14	Choi et al. (2020)	DS	60	51.00
15	Chauvin et al. (2020)	DS	36	-
16	Hu et al. (2020)	DS	156	-
17	Muslim et al. (2021)	DS	40	50.00
18	Roche et al. (2022)	DS	60	46.67
19	Muslim et al. (2022)	DS	40	50.00
20	Peng et al. (2022)	DS	70	41.43
21	Tanshi and Soffker (2022)	DS	70	14.29
22	Chen et al. (2021)	DS	30	30.00
23	Heo, et al. (2022)	DS	33	42.42
24	Muslim and Itoh (2021)	DS	42	28.57
25	Cramer and Klohr (2019)	RV	39	48.72
26	Telpaz et al. (2017)	DS	26	46.15
27	Jamson et al. (2012)	DS	26	53.85
28	Du et al. (2024)	DS	40	50.00
29	Leitner et al. (2023)	PC-DS	37	73.00
30	de Winter et al. (2024)	DS	38	39.47
31	Yang et al. (2023)	DS	46	50.00
32	Lin and Chen (2024)	DS	30	40.00
33	Muslim (2023)	DS	80	45.00
34	Zhao et al. (2024)	RV	51	13.73
35	Deniel et al. (2024)	DS	31	58.06
36	Hu and Hu (2024)	DS	16	25.00
37	Chai et al. (2024)	DS	32	18.75
38	Talukder et al. (2024)	DS	60	36.67
39	Pan et al. (2024)	PC-DS	75	36.00
40	Ammar et al. (2023)	RV	148	-

Minimum, standard deviation, mean, and maximum of participants age



DS = Driving Simulator, PC-DS = Low-fidelity, desktop PC driving simulator, RV = Real Vehicle

Fig. 5. Risk assessment results for individual studies (D = Domain).

involving distinct systems or procedures that must be explained to participants for ethical, safety, or practical reasons, making complete concealment of allocation unfeasible. Given these considerations, we assigned a low risk of bias for this signalling question to these studies.

In the second domain, concerns are more pronounced compared to other domains, primarily due to the methods used for analysing the outcomes. In (de Winter et al., 2024; Maag et al., 2012; Muslim et al., 2021; Tanshi and Soffker, 2022), each participant was involved in multiple scenarios. The authors employed ANOVA and Spearman correlations to analyse the data. However, these methods assume independence between groups, which may not hold when multiple observations are collected from the same participants. Prior studies, such as (Lioi et al., 2024), have demonstrated that observations from the same participants are often correlated, potentially violating this assumption. Therefore, using ANOVA without accounting for these correlations may increase the risk of biased results. The risk of bias in this domain for these studies was deemed high. Furthermore, Sun et al. (2019), with only three participants, is considered to be at high risk due to insufficient statistical power. Statistical power is directly related to sample size, and a small sample reduces the ability to detect true effects or differences, if they exist. Studies with very few participants are more likely to produce results that are unreliable or not generalizable to a larger population. In this case, the extremely small sample size limits the robustness of any conclusions drawn and increases the likelihood of Type II errors, where true effects may go undetected. There were some concerns related to some studies (Chen et al., 2021; Choi et al., 2020; Doubek et al., 2020; Du et al., 2024; Goncalves et al., 2022; Heo et al., 2022; Hu and Hu, 2024; Lin and Chen, 2024; Madigan et al., 2018; Maggi et al., 2022; Muslim, 2023; Muslim and Itoh, 2021; Peng et al., 2022; Talukder et al., 2024; Telpaz et al., 2017; Yan et al., 2021) since authors used repeated-measure ANOVA or linear random/mixed effects models for time-dependent measurements. However, for time-dependent data characterized largely by asymmetric and non-normal distributions (Cleves, 2008), as well as censored time data, time duration models, also known as survival analysis, are generally more suitable than linear regression or ANOVA. These studies did not report the validity of the assumptions for the models they used. Time duration models are specifically designed to estimate event timing and to explore factors influencing the event's occurrence. Survival analysis is advantageous because it effectively manages data with non-normal distributions and handles censoring, a common challenge in time-to-event analyses (Cleves, 2008). For example, Muslim (2023) and Talukder et al. (2024) removed the censored time data because of collisions; however, eliminating this data can lead to bias in the results.

In the third domain, which addresses missing outcome data, (Chauvin et al., 2020; Choi et al., 2020; Doubek et al., 2020; Talukder et al., 2024; Várhelyi et al., 2020) were deemed to have a high risk of bias. These studies experienced significant data loss during the experiments, and the missingness appeared to depend on the actual values of the outcomes. Additionally, these studies failed to implement any methods to correct for biases or conduct sensitivity analyses that could demonstrate how the missing data might have affected the outcomes, especially given the potential relationship between the missingness and the true values of the outcomes.

Studies generally demonstrated minimal risk concerns for domains 4 and 5. However, there were some concerns regarding the lack of a predefined analysis plan in (Sun et al., 2019). Although questions arose in Domain 4 about the validity of the driving simulators used in most studies, these concerns were assigned a low risk. These concerns will be further discussed in the subsequent sections.

Experimental attributes in included studies

Driving environment and participants

Table 3 provides an overview of the participant groups included in the studies under consideration. Notably, about 13% of the studies included 16 or fewer participants, highlighting their limited sample sizes. These small samples pose a challenge when it comes to generalizing the results obtained. In the majority of studies, the percentage of females was below 50%, and in some studies, the percentage was very low. The age distribution is also presented in Table 3, revealing a distinct inclination towards younger drivers in the studies included. In addition, the presence of a narrow age range or a small standard deviation in certain studies, coupled with others lacking age distribution information, diminishes the robustness of the results for practical application. The majority of studies utilized a driving simulator as the experimental environment, while only five investigations (Ammar et al., 2023; Cramer and Klohr, 2019; Sun et al., 2019; Várhelyi et al., 2020; Zhao et al., 2024) opted for real-world settings, including actual roads and real vehicles.

Experimental design factors and conditions

In this section, we delve into the critical aspects of the included studies' experimental designs, shedding light on the nuanced factors and conditions that underpin the investigation of human-automation interaction in driving contexts. A robust understanding of these elements is pivotal for discerning the intricacies of research methodologies and drawing meaningful insights from the diverse body of literature under review.

Exploring the spectrum of automation levels and driving manoeuvres. Exploring the data related to the levels of automation investigated in the considered studies offers valuable insights into the research emphasis on automation and driver assistance technologies. Table 4 displays the IDs of studies that investigated various levels of automation. While this systematic review primarily focused on assisted manual driving up to Level 3, certain studies also explored other automation levels (i.e., Levels 4 and 5), as highlighted in Table 4. Among all the included studies, only seventeen followed the standard definitions of SAE (2021) or its earlier versions, while one adhered to the NHTSA (National Highway Traffic Safety Administration) (2013) guidelines when specifying the automation levels examined. However, the findings indicate that the use of standardized definitions has become more common in recent years.

Fig. 6 concurrently illustrates the levels of automation and the associated driving manoeuvres considered in this review. The graph indicates that, among the included studies, Level 3 automation is the primary focus of investigation, with 24 studies out of 40. Subsequently, ADAS emerges as the next most studied aspect, with 11 studies. Of significance, only seven studies devoted attention to manual driving while also exploring various levels of automation. This is noteworthy because including manual driving in these studies allows for meaningful comparisons between higher automation levels and a foundational reference

Table 4
Overview of automation levels explored in the included studies.

Level of Automation	Study ID
Level 0	(1_a) (3_a) (6) (9) (22_a) (30) (35_a)
Level 1	(5) (35_a)
Level 2	(1_a) (2_a) (5) (9) (14_a) (25_a) (33) (35_a)
Level 3	(1_a) (2_a) (3_a) (8_a) (11_c) (15_a) (17_c) (18_a) (19_c) (20) (21) (22_a) (23) (26_b) (28_a) (29_a) (30) (31_a) (32_a) (35_a) (36) (37_a) (38_a) (39_a)
Level 4	(5)
Level 5	(9)
ADAS	(4) (6) (7) (10) (12) (13) (16_c) (24) (27) (34) (40)

a. SAE definition of level of automation explicitly reported.
b. NHTSA definition of level of automation explicitly reported.
c. Level of automation not clear nor assigned using common definitions.
* Several studies lacked specific subscript details in the Study ID; the level of automation in these studies was reported by the authors without adhering to any standard.

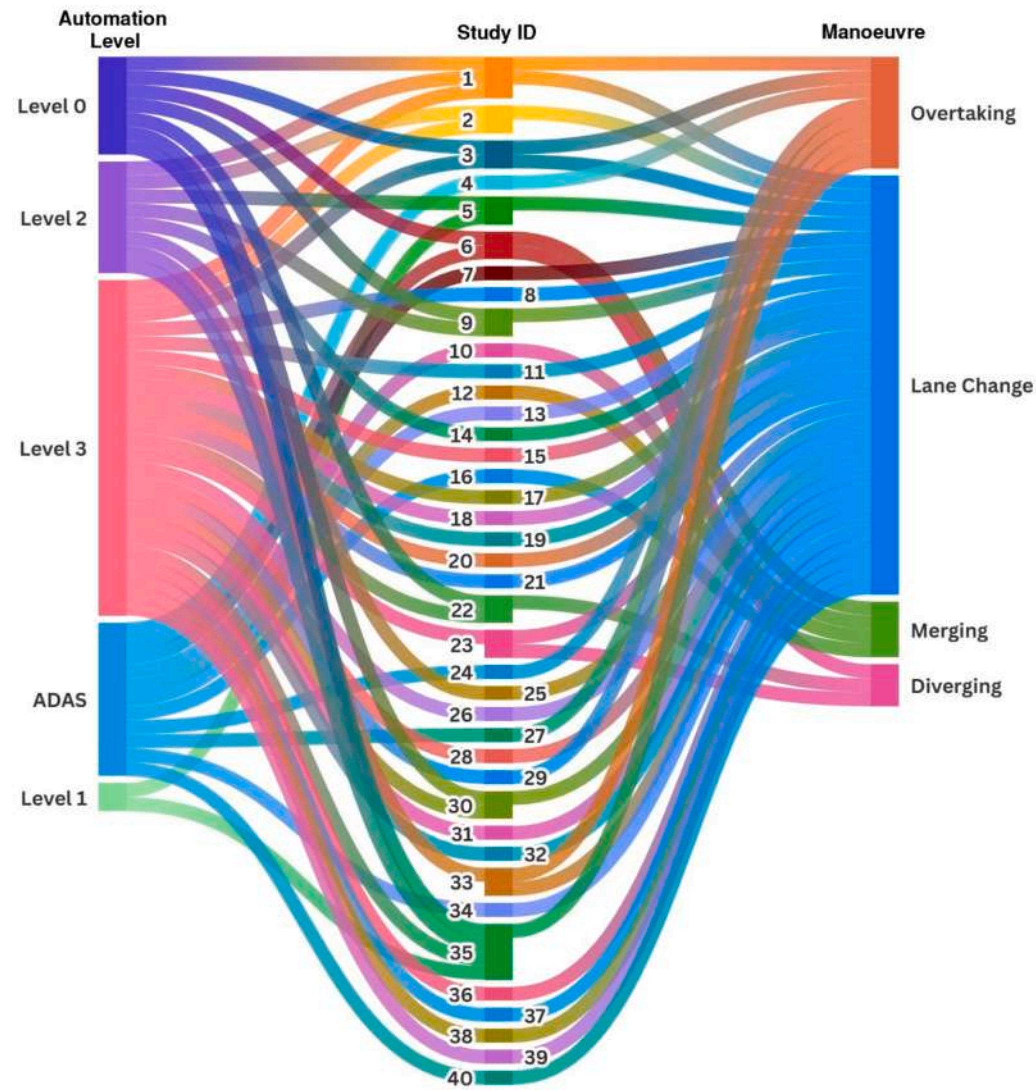


Fig. 6. Investigated automation levels and guidance activities.

point aligned with the current road infrastructure, helping determine if adaptations are needed for future automation.

Examining the studies, lane change and overtaking manoeuvres emerge as the most frequently investigated. In Fig. 6, most entries fall in the combination of Level 3 with lane change and Level 3 with overtaking, with a smaller cluster for ADAS with lane change. Notably, the weaving manoeuvre was not addressed at any level of automation. Additionally, it is noteworthy that all studies addressing merging manoeuvres specifically investigated the impact of ADAS; there are no Level 2 and 3 entries for merging. Studies that included manual driving in Fig. 6 are limited and spread across lane change, overtaking, merging, and diverging. This dispersion makes it difficult to draw robust cross-level comparisons for each manoeuvre.

Examination of road geometric and traffic-related factors. The success and safety of automated vehicles hinge not only on advanced technological capabilities but also on a profound understanding of the dynamic environments in which they operate. Fig. 7 summarises the coverage of the included studies by factor type (road-geometry elements, traffic-related factors, or both) and by driving manoeuvre (lane change, merging, overtaking, diverging). In this figure, traffic-focused studies are the most frequent, but still scarce overall, and analyses that consider traffic and geometry together are rarer; only two. Traffic variables appear only for merging, lane changing and overtaking, with no entries for diverging, while road-geometry variables are absent for lane changing. Overall, coverage is concentrated in a small number of factor–manoeuvre combinations, with several combinations showing no entries, indicating specific gaps in the evidence base.

As illustrated in Fig. 7, four studies focused on road geometrics, while seven delved into traffic-related factors, with (de Waard et al., 2009; Hazoor et al., 2023) examining both aspects. Notably, these two studies specifically investigated the impact of an ADAS during merging manoeuvres. The surrounding environment of the road (i.e., rural, urban, or suburban) affects its design and layout, which can significantly influence drivers' behaviours and their ability to respond to various traffic situations effectively. Only (Du et al., 2024) examined the impact of the road environment (i.e., rural versus urban) on safety and driver behaviour. Six studies (Brijs et al., 2022; de Winter et al., 2024; Deniel et al., 2024; Jamson et al., 2012; Leitner et al., 2023; Roche et al., 2022) explicitly identified the road environment as rural, while (Pan et al., 2024) specified it as urban. Most other studies mentioned only the type of road, such as highways or motorways, without specifying the environment. Additionally, three studies (Ammar et al., 2023; Maggi et al., 2022; Sun et al., 2019) did not provide explicit information about either the road type or the environment.

Most of the studies included in this systematic review analysed

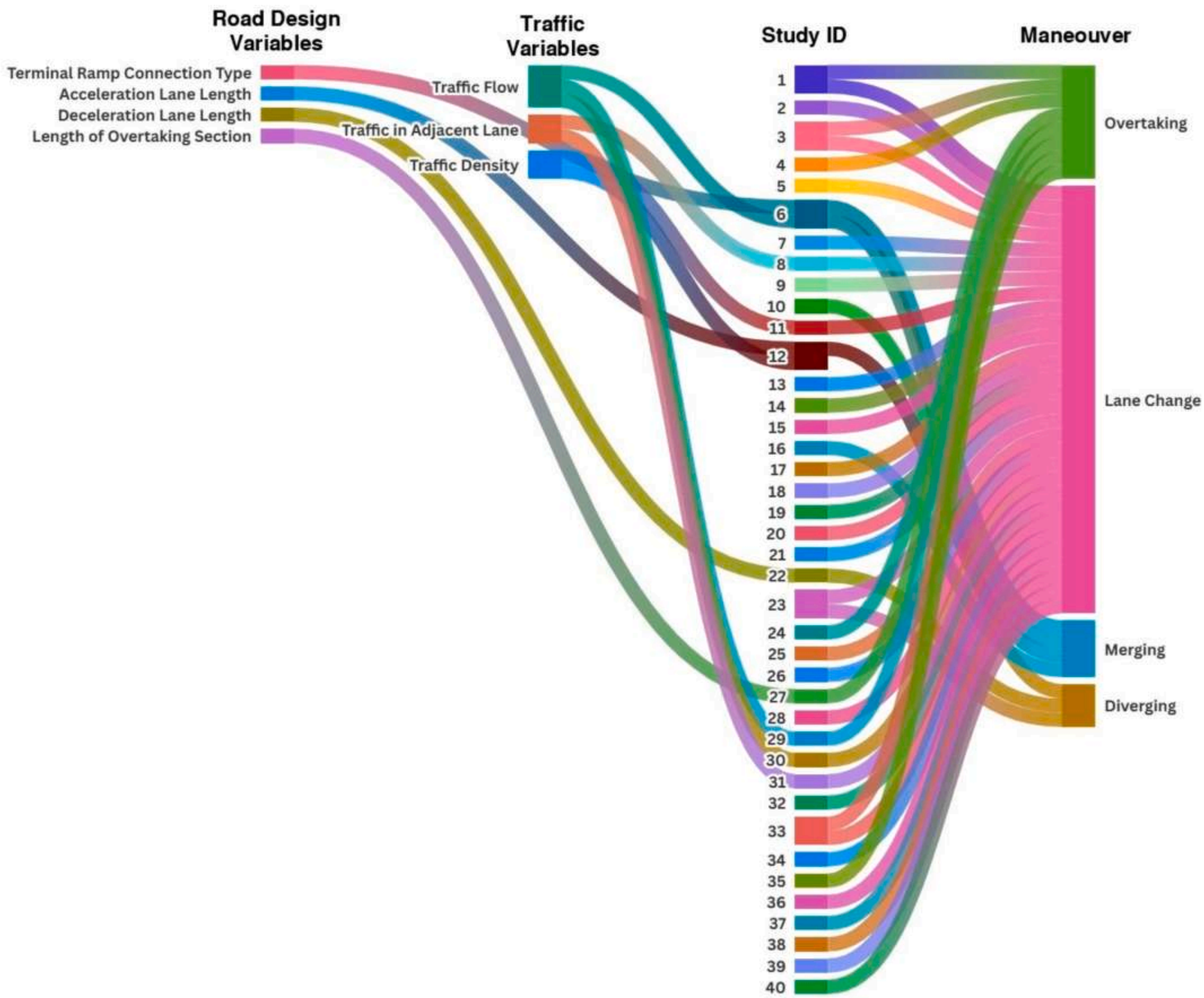


Fig. 7. Investigated road geometric and traffic-related variables.

vehicle–vehicle interactions within guidance tasks. Two studies involved vulnerable road users: (i) a study of car–cyclist overtaking involving three cyclist behaviours (Brijs et al., 2022), and (ii) a takeover scenario at a country road junction incorporating a pedestrian crossing and a cyclist turning right (Tanshi and Soffker, 2022). Evidence on heavy vehicles was also limited: one simulator study systematically varied the presence of heavy vehicles on a motorway (de Waard et al., 2009). Several other papers only considered trucks as static hazards (e.g., broken-down or accident vehicles), with no analysis of moving interactions (de Winter et al., 2024; Deniel et al., 2024; Peng et al., 2022). None of the included papers analysed professional heavy-vehicle drivers as a separate group.

Metrics exploration in driving analysis

The included papers examined the impact of various automation levels or ADAS on guidance activities using diverse metrics. The measurements calculated in each study are detailed in Appendix A3 and categorized into four groups as illustrated in Table 5: (i) performance and behavioural, (ii) safety-related, (iii) biometrical, and (iv) subjective measurements. The performance and behavioural category are further divided into three sub-categories: longitudinal, transversal, and temporal measurements. The longitudinal and transversal sub-categories primarily focus on vehicle dynamics and trajectories, such as speed, acceleration, and vehicle displacements. In contrast, the temporal subcategory relates to the time required to execute driving tasks or decisions, including manoeuvre durations, take-over control time, and driver decision-making time. As indicated in Table 5, the majority of studies (31 out of 40) used the measurements of this category. The safety-related metrics examined in the reviewed papers were classified into (i) temporal measurements such as time to danger, time headway, and time to collision; and (ii) frequency measurements such as lane departure frequency, number of conflicts, and collision frequency. The biometrical category related to the driver's state and behaviour. This category includes metrics obtained through eye-tracking, which measures gaze direction, fixation points, and pupil dilation to understand driver attention and behaviour. Eye-tracking was employed in thirteen studies. However, in some recent works, electrodermal activity (EDA), which measures skin conductance to assess stress or emotional arousal, was explored in (Du et al., 2024; Hu and Hu, 2024), and cardiovascular activity (CVA), which evaluates heart rate or variability to gauge stress or workload, was examined in (de Waard et al., 2009; Hu and Hu, 2024). Three studies reported physiological indices with mixed results. Hu and Hu (2024) estimated acute stress using phasic EDA, heart rate, and heart-rate indicators, and found a significant relationship with

Table 5
Examined metrics in the included studies.

Measurement categories	Study ID	# of Papers
Performance and Behavioural		
(i) longitudinal	(1) (2) (3) (4) (6) (10) (11) (12) (15) (16) (18) (21) (22) (23) (26) (27) (28) (30) (31) (32) (34) (37) (38) (40)	24
(ii) transversal	(1) (2) (3) (4) (5) (7) (11) (12) (14) (15) (17) (18) (19) (20) (21) (23) (24) (25) (26) (27) (28) (29) (31) (32) (33) (36) (37) (38) (39) (40)	30
(iii) temporal	(1) (2) (5) (7) (8) (11) (12) (14) (15) (16) (17) (18) (19) (21) (22) (23) (24) (25) (26) (27) (28) (29) (30) (31) (32) (33) (34) (36) (37) (38) (39)	31
Safety-related		
(i) temporal	(1) (4) (10) (11) (12) (13) (15) (20) (23) (24) (27) (28) (30) (31) (32) (33) (37) (38) (39)	19
(ii) frequency	(3) (5) (11) (15) (18) (27)	6
Biometrical		
(i) eye-tracking	(2) (5) (8) (9) (11) (12) (15) (19) (22) (26) (28) (35) (39)	13
(ii) electrodermal activity (EDA)	(28) (36)	2
(iii) cardiovascular activity (CVA)	(12) (36)	2
Subjective		
(i) workload or mental effort	(3) (5) (7) (12) (21) (23) (27) (37) (38)	9
(ii) driver awareness	(21) (25)	2
(iii) system rating	(1) (2) (3) (4) (5) (10) (12) (19) (24) (25) (26) (27)	12
(iv) risk and criticality perception	(12) (18)	2

perceived urgency but not with takeover time, information-processing time, or steering-wheel speed. de Waard et al. (2009) observed heart-rate increases around lane-change manoeuvres, with lower heart rate variability in the 0.10 Hz band for younger drivers. Du et al. (2024) found that phasic EDA varied by road type and driving task, with higher values on rural highways relative to urban areas during lane change, but lower values on highways during lane keeping. Overall, these findings indicate sensitivity to arousal/workload while showing inconsistent correspondence with behavioural performance across the available studies.

The subjective category involves driver-reported or perceived assessments, divided into four sub-categories: (i) workload or mental effort, (ii) driver awareness, (iii) system rating, and (iv) risk or criticality perception. Workload or mental effort, studied in nine papers, evaluates the cognitive and physical demands placed on the driver. Driver awareness, assessed in two studies, captures the driver's level of alertness or attentiveness. System rating, the most frequently studied sub-category in this group with twelve papers, involves drivers' evaluations of the system's usability and performance. Finally, risk and criticality perception, investigated in two papers, reflects the driver's perceived level of danger or criticality in various scenarios.

Risk analysis of the systematic review

The self-assessment of risk of bias was conducted using the ROBIS method (Whiting et al., 2016). The eligibility criteria were fully aligned with the study objectives and were clearly defined to ensure that the study's aims were met. To verify that all reviewers had a consistent understanding of these criteria, a pre-screening phase was conducted with a limited set of records. The eligibility criteria and restrictions applied were clearly described as provided in Methodology section. As no major concerns related to the risk of bias in the eligibility criteria were identified, the first domain of ROBIS (i.e., study eligibility criteria) was deemed to have a low risk of bias.

Although the study utilized an appropriate range of databases for published studies, including Scopus and WOS, the exclusion of conferences and reports introduces a potential risk of publication bias, particularly concerning unpublished studies. As a result, some concerns about publication bias exist in Domain 2 (identification and selection of studies), representing a limitation of this study. However, the use of a structured and comprehensive search strategy, along with the involvement of three independent reviewers, helped to minimize errors in the selection of studies. Furthermore, the extraction of data from forty studies by applying a formal risk assessment tool (i.e., ROB2) suggests a low risk of bias in Domain 3 (data collection and study appraisal) of the ROBIS assessment. By employing predefined methods for presenting the results, which account for potential between-study variations that could affect the conclusions, the risk of bias in Domain 4 (synthesis and findings) was minimized, allowing readers to be fully aware of these variations.

Discussion

This study conducted a systematic literature review with a specific focus on exploring the impact of varying automation levels on guidance activities associated with driving manoeuvres. These manoeuvres include lane changing, merging, and diverging, weaving, and overtaking. The examined automation levels range from manually assisted driving with ADAS to Level 1, Level 2 (PAD), and Level 3 (CAD) automation. The investigation examined the effects of these automation levels on driving behaviour and performance, together with their compatibility with existing road geometrics which were originally designed for manual driving. Additionally, the resulting safety implications associated with these effects were considered within the scope of this review.

The research findings highlight the relative scarcity of publications on the examined topics. Following a thorough screening of records in the Scopus and WoS databases, only 40 published research papers meeting the inclusion criteria were identified. Notably, these selected articles were predominantly published post-2009, with a discernible surge in scientific works observed post-2017. This surge suggests a growing interest in comprehending the impact of automation on driving behaviour. The heightened interest aligns with current predictions and trends, which anticipate that 12% of new passenger cars sold by 2030 will be with Level 3 automation or higher, with this figure projected to increase to 37% with advanced autonomous driving technologies by 2035 (Deichmann, 2023).

Bibliometric analysis revealed that over 75% of the included studies are concentrated in four developed and industrial countries (China 27.5%, Japan 17.5%, Germany 17.5%, and the United Kingdom 12.5%). Previous research has demonstrated that global variations in driver behaviour originate from diverse cultural norms (Suzuki et al., 2022), socio-economic factors (Machado-León et al., 2016), infrastructure, and law enforcement differences (Solmazer et al., 2016). Hence, future studies should aim for broader geographical representation beyond the countries mentioned above, particularly for the purpose of assessing the transferability of results to contexts where different traffic rules and environmental settings apply. Additionally, the primary researchers hailed from the fields of psychology, industrial and automotive disciplines, with approximately 78% of corresponding authors falling within these domains. This underscores the importance of integrating infrastructure engineering considerations when evaluating the suitability of current roads for advanced automation levels.

The results highlight the diversity in the size and composition of study participant samples. Some studies had a limited number of participants, with 13% comprising 16 individuals or fewer. These small sample sizes pose a challenge for generalizing study results, emphasizing the importance of careful consideration of statistical experimental design in future studies. Ensuring an adequate number of participants serves to strengthen the reliability of findings. However, it should be noted that the number 16 served here as a rough indicator; ensuring an adequate sample size requires a power analysis tailored to the specific experimental design. In most cases (~70%), the percentage of females in the participants was below 50%, and the percentage was even lower in some studies. Future research should aim for a more representative gender distribution, aligning with the demographic composition of the driving population, to ensure a comprehensive understanding of the impact of automation on the real-world driver population.

The results on age distributions of participants in included studies revealed a distinct bias toward younger drivers. In addition, the presence of a narrow age range or a small standard deviation in certain studies, coupled with others lacking age distribution information, diminishes the robustness of the results for practical application. The global population is aging significantly (Grinin et al., 2023) and including older participants in research studies becomes crucial for obtaining reliable results that accurately reflect the demographics of the future population. One potential reason for the greater representation of young participants in research studies may be the accessibility of this demographic within university settings, where many studies are conducted. In these environments, the education level of participants is higher than that of the general population, which may introduce bias in the results (Youssef et al., 2023), particularly in the context of gaining insights into new technologies such as automated vehicles.

An examination of the experimental settings for the 40 included articles outlined in Table 3 reveals that only five of them employed real vehicles for testing. This highlights the significant role of driving simulators in facilitating research of this nature. To ensure measurements are comparable to real-world driving scenarios, the validation of simulators is paramount. A crucial aspect for a driving simulator study is the comprehensive reporting of the validation evidence for the driving simulators used, including specific details on the fidelity of the measurements employed (Wynne et al., 2019). However, only Hazoor et al. (2023) explicitly reported the validation of the driving simulator used, stating that it had been previously validated for driver speed decisions, lateral manoeuvres, and operations. This means that only 2.5% of the included studies mention this crucial information. Two of the studies (Leitner et al., 2023; Pan et al., 2024) employed a low-fidelity, desktop PC driving simulator (single-screen display and consumer-grade steering wheel) with very low fidelity and no accompanying validation studies, making it difficult to rely on their findings. In a related context, Maag et al. (2012) noticed that the use of a cost-efficient driving simulator may not be appropriate for measuring all driving variables, such as decelerations, in a valid way. For other manoeuvres, including overtaking, merging, and diverging, simulators may also be inappropriate for studying some measurements (Karimi et al., 2020a; Mao et al., 2025).

Furthermore, most of the screened records and more than half of included studies did not explicitly report the level of automation considered based on the standards. This omission could give rise to misunderstandings, thus increasing the risk of error and/or bias in both the screening process and the interpretation of results. As presented in Table 4, 17 studies adhered to the SAE standard definition of automation levels, while only one (Telpaz et al., 2017) aligned with the NHTSA (2013) standard. When evaluating ADAS, including features like Adaptive Cruise Control (ACC) and Lane Keeping/Lane Centring Assistance, it is important to acknowledge that they could fall under Level 1 automation according to SAE levels of automation definitions. However, in the absence of an explicit mention of this automation level by the authors, they were categorized as ADAS in this review study. Consequently, it is highly advisable for future works addressing autonomous vehicles to provide a clear definition of the level of automation, by referencing recognized standards such as SAE (2021) or NHTSA (2013).

How does the level of automation influence driver behaviours, performances, and safety in the context of guidance activities?

Evolving driver roles

The impact of various levels of automation on driver behaviour and performance is a multifaceted dynamic that is evolving with advancements in automotive technology. As automation increases, drivers may shift from actively engaging in driving tasks to relying more on automated systems. The level of automation determines the division of responsibilities between the driver and the vehicle and influences the degree to which drivers are engaged with the driving task. While lower levels of automation may prompt drivers to remain actively involved, higher levels can lead to reduced situational awareness and slower reaction times as individuals may become more accustomed to the automated assistance. Addressing these considerations is crucial for fostering a safe driving environment, and this systematic review specifically explores the impact of automation on drivers, particularly in the context of driving guidance tasks.

Madigan et al. (2018) observed that in PAD, speed variance, lateral accelerations, and variation in lateral position during lane-changing were significantly higher compared to manual driving. Furthermore, the study noted a slight delay in the initiation of overtaking manoeuvres in PAD compared to manual driving. These findings suggest a decrease in driver performance after automation in PAD with respect to the manual driving mode. The reason for this decline in performance is explained by Goncalves et al. (2020). They found that with the escalation of automation levels, drivers tended to pay less attention to the road centre as they started to cede physical control of the car, especially when they were not actively involved in the lane-changing process. Roche et al. (2022) determined that drivers exhibited more extreme deceleration and steering behaviours than required when regaining control from a CAD system during critical lane change manoeuvres.

Deniel et al. (2024) investigated the effect of different levels of automation (i.e., manual, SAE level 1, SAE level 2, SAE level 3 with hands on the steering wheel, and SAE level 3) on drivers' gaze behaviour during a take-over scenario when overtaking a potential collision zone. Their findings indicated that for most areas of interest, gaze percentage time remained relatively consistent across different levels of automation. However, they identified two exceptions, as under SAE Level 3 conditions there was an increase in gaze percentage time directed toward the Human-Machine Interface (HMI) and a decrease in gaze percentage time directed toward the far-road area, compared to the other automation levels. However, the number of visits to the area of interests including speedometer, obstacle, far and near roads, by increasing in the level of automation. This suggests that drivers need to more actively gather and interpret relevant information to fully regain their understanding of the situation before taking control. Finally, once drivers took back control and began overtaking in the collision zone, their eye-related measures generally returned to baseline. However, high automation levels (i.e., SAE Level 3 automation with and without hands on the steering wheel) still exhibited some residual effects. Along the same lines, Chen et al. (2021) noted a significant rise in gaze fluctuation among drivers immediately after regaining control for the purposes of executing a diverging manoeuvre, when compared to manual driving. The pronounced increase in gaze fluctuation while retaking control of the vehicle likely stems from the restoration of situation awareness. Notably, the maximum longitudinal deceleration after assuming control for executing a diverging manoeuvre was significantly greater, particularly in systems with constrained time budgets, than in manual driving. It is important to note that (Chen et al., 2021; Deniel et al., 2024; Goncalves et al., 2020; Madigan et al., 2018; Roche et al., 2022) primarily involved younger participants with average age <34.5 years. The age range in these studies may not fully capture the potential differences among older drivers, who are likely to exhibit different cognitive and motor responses under automated conditions. This demographic limitation suggests that the findings may not be entirely representative of the broader driving population.

Dillmann et al. (2021) examined drivers' critical reactions following three scenarios: lane change manoeuvres conducted automatically at Level 3, lane-changing automatically with hands on the steering wheel (transitioning from Level 3 to Level 2, semi-automated lane change), and taking over control to conduct the lane change manually (switching from Level 3 to manual mode). Dillmann et al. (2021) noted a slower maximum deceleration following automated lane changes compared to semi-automated and manual lane changes. Moreover, automated lane changes adversely affected the quality of takeovers by significantly increasing the standard deviation of the steering wheel angle. Drivers involved in automated lane changes exhibited prolonged braking reactions compared to manual driving, with the longest reactions observed during semi-automated lane changes. Utilizing eye-tracking technology, they discovered that the percentage of fixation on the road was significantly lower during automated lane-changing compared to both semi-automated and manual lane-changing, which exhibited similar fixation percentages.

Muslim et al. (2021) examined four distinct scenarios within a CAD system during traffic situations that required lane changes: (i) reducing speed in response to traffic congestion, (ii) a manual lane change request, (iii) automatic lane change with driver approval, and (iv) an automatic lane change without driver approval. The interaction of driver demographic factors with various system conditions and capabilities resulted in a notable variation in drivers' decision-making and reaction times. Despite the non-time-critical nature of the examined scenarios, the safety-critical dimension of drivers' decision-making emerged, particularly the need to scan the adjacent lane before initiating a lane change manoeuvre. This inherent safety consideration contributed to a longer reaction time in the first situations compared to the subsequent three. In a follow-up study (Muslim et al., 2022), the authors found that, within the same systems, lane changes were perceived as more critical in the last two system conditions where the lane change was automated, as opposed to manually changing lanes in the first two system conditions.

The discussed works suggest that at high levels of automation, when drivers are required to take control and participate in both critical and non-critical situations, performing tasks manually may decrease driver performance, potentially leading to unsafe conditions. Choi et al. (2020) further demonstrated that the decrease in driver performance escalates with an increase in both cognitive and visual load. Pan et al. (2024) identified that visual non-driving related tasks (NDRTs) drastically reduce attention to essential areas like the road ahead and mirrors, leading to significantly diminished control during takeovers, whereas cognitive tasks constrain focus and impair a comprehensive understanding of traffic conditions. Among the reviewed papers, some studies suggested various interventions to enhance driver performance following the resumption of manual control.

Enhancing driver performance through targeted intervention

Several works (Chai et al., 2024; Goncalves et al., 2022; Hu and Hu, 2024; Talukder et al., 2024; Yang et al., 2023; Zhao et al., 2024) have sought to enhance driver behaviour and performance through improved design of HMIs. Goncalves et al. (2022) explored the impact of HMI information as a means to enhance driver performance when resuming control in CAD, particularly during lane-changing manoeuvres. Their findings highlighted a robust correlation between drivers' gaze on the HMI information and the decision-making time required for lane changes. Yang et al. (2023) found no significant differences between HMI systems with both visual and auditory modalities and those with only the auditory modality in terms of their impact on factors such as acceleration, lane change speed, and lane change rate during taking over the control in CAD. Hu and Hu (2024) evaluated the effects of auditory signal frequencies on drivers' lane-change performance after regaining control. Their results showed a significant impact on steering wheel control but not on temporal parameters such as takeover time and information-processing time. Chai et al. (2024) compared speech-based and auditory takeover requests, finding that auditory requests offered advantages in terms of takeover time, lane change time, and minimum time-to-collision. However, drivers expressed a preference for speech-based takeover requests. Talukder et al. (2024) found that integrated TORs, which combined simulator and tablet alerts, led to faster takeovers and better driving stability compared to conventional TORs. The addition of headphones to integrated TORs showed no further performance improvement, though participants rated the integrated TOR higher for comfort and safety. Zhao et al. (2024) found that, in comparison with visual HMI alone for integrated ADAS, presenting three messages through both visual and auditory channels improved performance during lane changes; conversely, performance decreased when four messages were presented visually.

Telpaz et al. (2017) determined that the use of a vibrotactile seat contributed to enhanced speed and efficiency in reactions, particularly in scenarios demanding lane changes immediately after regaining control. Cramer and Klohr (2019) proposed that vehicle roll motions could enhance drivers' situation awareness, thereby improving their performance when lane-changing after regaining control. Muslim (2023) four steering interventions in a PAD system, including no intervention, haptic resistance to unsafe lane changes, autonomous steering away from hazards, and combined interventions with variable haptic and automatic control. All three types of assistance significantly reduced lane-change collisions compared to no intervention, though occasional hazardous manoeuvres still occurred. Maggi et al. (2022) examined the potential improvement in performance of drivers when assisted for a brief period after taking control from an autonomous vehicle in non-critical situations. The study looked specifically at scenarios where a lane change was requested after a delay following the driver's full resumption of control. The findings indicated that, in the initial seconds, between 2 and 7 s after taking over control from the system, drivers heightened their situation awareness and scanned their surroundings. Moreover, the study revealed that drivers derived benefits from lateral assistance, particularly if it remained active for at least 7 s after regaining control. However, there is a potential bias in the positive effects of the interventions proposed in these studies (Cramer and Klohr, 2019; Goncalves et al., 2022; Maggi et al., 2022; Muslim, 2023; Talukder et al., 2024; Telpaz et al., 2017; Yang et al., 2023) as the samples skewed significantly toward younger drivers, who are generally more familiar with and can adapt more quickly to new technologies compared to older drivers. This demographic skew suggests that the findings may not fully apply to older drivers, who might respond differently to these interventions. Despite this, a suitable gender balance was maintained across these studies, providing some confidence in the generalizability of the results across genders.

Influence of driver demographics and individual differences

Chauvin et al. (2020) categorized drivers into three distinct behavioural groups when resuming control in CAD for lane changing. Consistent with the findings of Muslim et al. (2021), which emphasized a notable interaction between driver demographics and automation conditions, Peng et al. (2022) discovered a correlation between age-related differences in executive functions and lane-changing performance after receiving a takeover request. Ammar et al. (2023), who explored the effect of ADAS activation on driving style, found that driving style varied across age groups, with teenagers being the most aggressive drivers. These findings highlight the need to consider driver demographics and characteristics if we wish to understand and improve driver behaviour in automated driving scenarios.

However, it is important to acknowledge the heterogeneity among the studies, particularly in terms of participant demographics. For example, Várhelyi et al. (2020) found no discernible differences in subjective workload while driving between CAD and manual modes when they conducted their field test. Despite noting the superior performance of the automated system vis-à-vis human drivers, the study did not delve into the impact of automation on drivers' performance during the crucial transition of responsibility from the system to the driver. Moreover, the limited representation of women in the study samples across the reviewed literature, such as in Tanshi and Soffker (2022), where only a small percentage of participants were female, underscores a potential bias in understanding the full spectrum of driver responses. This underrepresentation of women could lead to gaps in understanding how gender-specific factors influence driver behaviour in automated driving scenarios.

Despite these challenges, Tanshi and Soffker (2022) reported that different driving scenarios, such as encountering obstacles and vehicles ahead on highways and exiting highways, had no significant effect on the subjective workload and situation awareness of drivers after they had taken over control in CAD. However, further research is required to fully elucidate the complex interplay between driver-related factors, such as gender and age, and automation during various guidance tasks. A more balanced representation in future studies will be crucial to address these gaps and improve the robustness and generalizability of the findings. Despite the degradation in driving behaviours and performance as automation levels increase, de Winter et al. (2024) and Ammar et al. (2023) showed that demonstrated that manual driving style persisted after taking over control in CAD and after ADAS activation, respectively. Moreover, driving behaviour can be predicted based on one’s manual driving style.

As evidenced in this section, the majority of studies have indicated that drivers may face challenges executing guidance tasks (Chen et al., 2021; Deniel et al., 2024; Dillmann et al., 2021; Goncalves et al., 2020; Madigan et al., 2018; Muslim et al., 2021; Muslim et al., 2022; Roche et al., 2022), particularly lane changes, after periods of prolonged engagement with automation. This has prompted researchers to investigate technological interventions as potential remedies. However, there persists a substantial void in comprehending how automation impacts driver behaviour and performance across a diverse range of guidance tasks and driving scenarios. To address the challenges associated with automation, another potential intervention involves modifying road geometries. This approach will be explored in the subsequent sections.

Are current road designs, primarily developed for manual driving, suitable and ready for higher levels of automation?

While road infrastructure has evolved over the years to address the needs of human drivers, the emergence of automated driving systems introduces a new dimension to road design considerations. The dynamics of driving behaviour in manual and automated modes in different road geometrics (driver-road-vehicle system) play a pivotal role in answering the main question of this section.

As shown in Fig. 7, only four studies (Chen et al., 2021; de Waard et al., 2009; Hazoor et al., 2023; Jamson et al., 2012) investigated the effects of road geometric variables on the wide range of automation levels from assisted manual to CAD during guidance activities including lane changing, overtaking, merging, diverging, and weaving manoeuvres. Both studies, conducted by Hazoor et al. (2023) and Jamson et al. (2012), examined the influence of different Intelligent Speed Adaptation (ISA) systems on merging/diverging and overtaking scenarios, respectively. Hazoor et al. (2023) discovered that the terminal-ramp connection type had a significant impact on merging and diverging distances. However, they did not identify any interaction effects between the different variants of their developed ISA system and road geometrics. Consequently, they concluded that their ISA system does not have any adverse effects on safety. Nevertheless, Jamson et al. (2012) concluded that the mandatory ISA system had a significant impact on overtaking behaviour and performance across various lengths of overtaking sections. This resulted in decreased safety, with a noticeable increase in the frequency of abandoned overtaking manoeuvres observed.

In another study conducted by de Waard et al. (2009), the impact of a driver support system that encourages drivers to accelerate across various lengths of the acceleration lane was investigated, specifically focusing on elderly individuals. They found that the support system, combined with an extended acceleration lane (longer than standard), facilitated smoother merging. Chen et al. (2021) uniquely examined the impact of a road geometric factor, specifically deceleration lane length, on driver performance and behaviour immediately after the transition from level 3 automation (CAD) when drivers assumed control. In their study, under takeover conditions, drivers showed increased gaze dispersion and higher mainline deceleration, diverging later into the deceleration lane. A longer deceleration lane positively impacted vehicle control, with a diminishing marginal effect as lane length increased.

A broad spectrum of road geometric factors was found to have a significant impact on driver behaviour, performance, and safety during guidance activities in manual driving mode. Numerous studies have identified road geometric factors, including lane width (Farah et al., 2009; Karimi and Boroujerdian, 2020; Karimi et al., 2020b), passing zone length (Karimi and Boroujerdian, 2020; Mwesige et al., 2017; Mwesige et al., 2016), vertical grade (Hansen and Chang, 2019; Karimi and Boroujerdian, 2020; Karimi et al., 2020b; Mwesige et al., 2017; Mwesige et al., 2016), horizontal curvature (Farah et al., 2009; Hansen and Chang, 2019; Toledo and Farah, 2011), and vertical curvature (Hansen and Chang, 2019), that significantly impact overtaking-related measurements. These measurements encompass gap acceptance, overtaking duration, overtaking rate, and safety on two-lane roads. For lane changing/overtaking manoeuvres on multilane highways and freeways, several investigations into the impact of road geometric factors (including curve radius, number of lanes, curve length, presence of curve) (Ahmed et al., 2021; Das et al., 2020), have also been conducted to gain a better understanding of their impact on driver behaviour and performance, and safety in general. Merging, diverging, and weaving manoeuvres are other types of driving manoeuvres which are affected by road geometric factors. Several factors including freeway radius, terminal length, connection type, weaving length (Calvi and De Blasiis, 2011; Portera and Bassani, 2020; Portera and Bassani, 2021; Yuan et al., 2019) have been found to be significant for these manoeuvres.

As demonstrated, there is a substantial gap in our understanding, particularly in testing road geometric factors, in the presence of various ADAS systems installed in modern cars. This knowledge gap includes not only advanced ADAS technologies but also extends to the currently prevalent Level 1 and Level 2 automation systems that are already integrated into public roads. Furthermore, addressing this gap becomes even more crucial when considering the advent of Level 3 automation systems. These systems pose unique challenges, given the transformation in the role and contribution of the driver. Bridging this gap is imperative for a comprehensive evaluation of how road design interacts with the diverse spectrum of ADAS technologies, spanning from commonly used to cutting-edge systems, and for enhancing automotive safety and automation.

Furthermore, environmental factors exert a significant impact on road safety (Papadimitriou et al., 2019) and these factors exhibit noteworthy interactions with road geometric factors (Wen et al., 2019). Du et al. (2024) found no significant difference in take-over time for lane changing between rural and urban environments. In urban settings, drivers had smaller maximum resulting acceleration, smaller standard error of road offset, and wider horizontal gaze dispersion. The effect of road environment (i.e., rural vs urban) on the standard error of steering angle was not significant. However, drivers showed significantly higher mean EDA phasic activation on highways compared to that in urban areas. Heo et al. (2022) delved into the effects of environmental conditions (i.e., various weather and lighting conditions). Their findings highlight the substantial influence of environmental conditions on various parameters, including take-over time, lane-changing time immediately after take-over, maximum acceleration, time-to-collision, and subjective workload. Lin and Chen (2024) found an increased crash rate when drivers changed lanes after taking over control under low-visibility conditions (foggy vs. clear). However, a considerable gap exists in the examination of how environmental conditions affect driver behaviour and performance when it comes to different levels of automation, diverse driving manoeuvres, and their interactions with road geometrics. This gap underscores the need for future studies to address these multifaceted aspects comprehensively.

Understanding the consideration of traffic variables' impact in studies

As indicated in Fig. 7, a few of the studies included in this systematic review explore crucial traffic-related variables, providing insights into the intricate dynamics influencing drivers' behaviour under varying traffic conditions. Doubek et al. (2020) concentrate on traffic density, distinguishing between low and medium levels. In medium traffic density, their observations revealed a concerning pattern: upon regaining control from the automated system, numerous participants failed to decelerate before executing a lane change. This behaviour led to hazardous emergency braking situations for the vehicle in the left lane. In a comparable scenario involving lane-changing post take-over, Goncalves et al. (2022) discovered that drivers took longer to decide whether to change lane when the vehicle in the adjacent lane was in close proximity. In a scenario involving traffic in adjacent lanes, Yang et al. (2023) found that a majority of drivers preferred to remain in their current lane and brake more sharply; in this situation, it took more time for drivers to regain control. Yang et al. (2023) also demonstrated a significantly higher variation in driving performance among drivers when traffic was present in adjacent lanes. Leitner et al. (2023) found that when there was a smaller gap (i.e., higher traffic flow) in the opposing direction of a two-lane highway, participants were less likely to accept the automated overtaking of a CAD system, and their decision times were longer.

Hazoor et al. (2023) specifically examined the repercussions of traffic flow conditions classified as high and low. Although they found that traffic flow had a significant effect on driver performance, they could not find a significant interaction effect between traffic flow and their ISA system. de Waard et al. (2009) investigated the impact of heavy goods vehicles and ADAS designed to encourage speed on driver merging behaviours. Their findings suggest that an increased presence of heavy vehicles increases the mental effort required for merging and poses greater risks, particularly for elderly drivers. In contrast, using an ADAS system reduced the mental workload experienced when merging into heavy motorway traffic.

In a limited number of discussed studies, the presence of surrounding vehicles had a significant interaction effect on driver behaviour and performance when certain levels of automation were involved in guidance tasks. However, several traffic-related variables significantly influence driver behaviour and performance during merging. These variables encompass factors like the relative speed and distance between the subject vehicle and others (Chu et al., 2017; Li et al., 2023; Marczak et al., 2013), the traffic speed on the main road (Ahammed et al., 2008), and the type of vehicle involved (Li et al., 2023). Similarly, in the context of lane-changing, drivers' actions are intricately tied to variables such as the speeds of the leading and lagging vehicles in the target lane, relative speed, and the acceleration of the following vehicle (Moridpour et al., 2010; Wang et al., 2019). When it comes to overtaking, the dynamics are shaped by factors like the following gap and the speeds of the subject, front, and opposing vehicles (Farah et al., 2009; Karimi et al., 2021; Toledo and Farah, 2011). The intricate interplay of these multiple variables highlights the multifaceted nature of driver decision-making in various traffic scenarios. Therefore, it is crucial to consider a comprehensive range of traffic scenarios and factors in future studies.

Relationship between road design and drivers' behaviour and performance, and suggestions for improvement through road design changes

Road infrastructure has traditionally been designed based on the behaviour and performance of human drivers operating manual vehicles. This design approach considers factors such as reaction times, decision-making processes, visual perception, and physical capabilities of drivers to ensure safety and efficiency (AASHTO, 2011). The previous sections discussed how the level of automation influences driver behaviours, performance, and safety based on the included studies. Here, the aim is to demonstrate how road design is dependent on driver behaviour and performance through specific cases, and to propose suggestions for road design modifications to mitigate the decline in driver behaviour and performance due to automation, which should be studied in future research.

Diverging manoeuvres

To design diverging terminals and ramps, it is assumed that deceleration begins when the driver removes the foot from the accelerator pedal and changes gear, which takes about 3 s. Following this, the driver decelerates at a comfortable rate by applying the brake. The manner of deceleration and the driver's speed choices when manoeuvring onto and after traversing the deceleration lane are the inputs for calculating the deceleration lane length. These two speeds are assumed to be equal to the average running speed of the highway and the limiting speed on the ramp, respectively, which are functions of the design speed and are lower than it (AASHTO, 2011; Torbic et al., 2012). (Chen et al., 2021). Even after regaining control, as indicated by Chen et al. (2021), the maximum longitudinal deceleration for executing a diverging manoeuvre was significantly greater in CAD respect to the manual mode before entering the deceleration lane; however, after entering, drivers experienced lower maximum longitudinal deceleration. Therefore, most of the assumptions used for calculating deceleration lane length need to be reconsidered. Furthermore, this higher deceleration in the through lane of highway increase the risk of rear-end collision which make it unsafe situation. In CAD, drivers remain in the through lane for a longer distance compared to manual driving, as they need time to regain situational awareness. Chen et al. (2021) found that a longer deceleration lane is needed to achieve acceptable driver behaviour and performance in CAD compared to manual mode, though their study focused on the tapered design. Alamry and Hassan (2023) showed that drivers tended to start deceleration on the freeway through lane, a behaviour not observed with the parallel design. This tendency may also occur in CAD systems, which warrants further investigation.

Merging manoeuvres

Merging manoeuvres rely on certain assumptions about acceleration lane length, which are typically based on three factors: (i) the initial speed on the ramp, assuming drivers exit the curve at an average running speed lower than the design speed; (ii) the merging speed, assumed to be 5 mi/h less than the average running speed of highway traffic; and (iii) the manner of acceleration, assumed to be constant (AASHTO, 2011; Torbic et al., 2012). While these assumptions may hold in manual driving, their validity becomes increasingly uncertain with higher levels of automation, particularly in PAD and CAD. To date of this systematic review, no studies have examined merging behaviour in PAD scenarios. Furthermore, the time required to take over control could necessitate a longer acceleration lane, as studies show that most drivers prefer to brake when taking control, which is counterproductive for merging. Additionally, the diminished situational awareness caused by automation, the challenge of re-engaging in the driving process, and the difficulty of finding an adequate gap for highway entry all complicate speed selection and acceleration behaviour. The type of merging ramp, whether parallel or tapered, and the length of the taper in parallel designs may also significantly influence driver behaviour and performance, highlighting the urgent need for further investigation.

Overtaking manoeuvres

Overtaking manoeuvres on two-lane rural highways can be safely executed in passing zones that provide adequate passing sight distance. The design of these highways relies on several key assumptions about driver behaviour and performance, as outlined in AASHTO Green Book (AASHTO, 2011). These assumptions include: (i) both the passing and opposing vehicles are assumed to be traveling at the design speed; (ii) the speed difference between the passing and passed vehicles is assumed to be 19 km/h, with the passed vehicle maintaining a constant speed; (iii) the passing vehicle is assumed to have sufficient acceleration capability to achieve the required speed difference up to the critical point of overtaking; (iv) if the driver decides to abort the pass before reaching the critical point, a perception-reaction time of 1 s is considered; (v) in the event of an aborted pass, the passing vehicle is expected to decelerate at a rate of 3.4 m/s^2; (vi) the time headway between the passing and passed vehicles when an aborted pass is completed is assumed to be 1 s; and (vii) a minimum clearance of 1 s is assumed between the passing and opposing vehicles when the overtaking manoeuvre is completed. Although there is no specific study on overtaking manoeuvres on two-lane rural highways involving CAD and PAD compared to manual driving, findings from a study conducted by Madigan et al. (2018) indicate a delay in initiating overtaking manoeuvres on freeways due to PAD automation. This delay could be more pronounced on two-lane highways, where the risk from oncoming traffic is greater, requiring drivers to carefully assess the opposing lane. The study also observed significant changes in speed variance, lateral accelerations, and lateral position variation. These findings suggest that the assumptions used in calculating passing sight distance may need to be revisited, warranting new studies to reassess these calculations. None of the included studies tested the overtaking manoeuvre when the passing vehicle or the vehicle being passed was a heavy vehicle. Heavy vehicles mainly appeared as static obstacles (e.g., broken-down or accident trucks) in the scenarios. This gap is important because heavy vehicles accelerate more slowly, are longer and have a higher driver eye height. These factors can affect how far ahead drivers can see and judge gaps in oncoming traffic. Together, these factors can increase the time spent in the opposing lane and may require a greater passing sight distance than that assumed from data on passenger cars.

Conclusion

This systematic review, conducted using the PRISMA method, provides insights into the evolving impact of automation on driver behaviour and performance during driving guidance tasks. By meticulously reviewing 40 selected papers, its overarching goal is to deepen our understanding of the compatibility of existing roads with automated vehicles. The paramount insights and considerations gleaned from this systematic review are summarized as follows:

- The size and composition of participant samples in the reviewed studies varied, with some having limited sample sizes, highlighting the importance of robust statistical experimental design and appropriate statistical power to control Type I and Type II error rates and to obtain effect estimates with adequate precision in future research. Otherwise, observed effects may be confounded by uncontrolled covariates and yield biased or unstable estimates. Addressing the absence of gender information or a small proportion of female participants is crucial for a more comprehensive understanding of automation's impact on drivers. Additionally, the emphasis on younger participants in current studies calls for the inclusion of older individuals in future research to reflect the evolving demographics of the driving population;
- In exploring experimental settings, most studies adopted driving simulators to real vehicles, highlighting the necessity for thorough reporting on simulator validation, especially that relative to the specific situations investigated. Unfortunately, only one research paper explicitly provided this crucial information;
- A significant gap in the reviewed studies was the absence of explicit reporting on the level of automation considered, increasing the risk of misunderstandings and bias. Future research on autonomous vehicles should offer clear definitions, referencing recognized standards i.e., SAE and NHTSA;
- Studies comparing driver behaviour and performance at higher automation levels with that of manual driving consistently noted a decline in the performance of the latter, especially when drivers resumed control for guidance tasks. Certain interventions, including vibrotactile seats, vehicle roll motions, and HMI information, have been proposed as a remedy;
- The redesign of existing roads to render them safer for the automation era is certainly a sustainable intervention warranting further investigation. While a limited number of studies delved into the interaction between road geometrics and ADAS systems, only one study, which concentrated on conditionally automated driving (CAD) (Level 3), demonstrated that increasing the length of the deceleration lane could counter the degradation induced by automation. Failure to pay attention to one of the components of the human-road-vehicle system can hinder the safe and seamless integration of automated technologies into the driving environment;
- Research on driver performance in various guidance tasks under automation should focus on diverse and challenging traffic scenarios, particularly by examining the influence of traffic-related factors such as speed, which have been largely overlooked to date. Moreover, the interaction of vehicles with varying levels of automation in mixed levels of traffic congestion can give rise to diverse driving behaviours, necessitating thorough evaluation in future studies;
- A notable knowledge gap exists in understanding the impact of automation on driving guidance activities, especially in merging and diverging scenarios in which the driver is not fully attentive. Overtaking on two-lane rural roads (only one study) and weaving manoeuvres remain understudied and should receive more attention in future research;
- Biometric evidence remains limited overall. Eye-tracking was used more frequently across the studies, whereas electrodermal activity and cardiovascular measures appeared in only a few, and sensors such as respiration or Electroencephalography were essentially absent. Evidence based on electrodermal- and cardiovascular-related indices remains preliminary due to the small number of studies and mixed results. We therefore interpreted the current physiological evidence cautiously and encourage future work to include biometrics where they are clearly justified by the research question;
- Evidence on vulnerable road users (pedestrians and cyclists) and heavy vehicles/professional drivers was limited in the included studies. Interactions with pedestrians or cyclists were rarely analysed, and heavy vehicles were seldom modelled as active participants in merging, diverging or overtaking. Professional drivers were not examined as a separate group. As vehicle dynamics, driver eye height and interaction patterns can differ from those in passenger car contexts, the findings may not be fully applicable. Future research should include scenarios involving pedestrians, cyclists and heavy vehicles/professional drivers across key guidance manoeuvres and report common behavioural and safety outcomes, enabling comparison and informing design guidance under Levels 1–3;
- The review highlights possible implications for road design in the context of automation in three areas: diverging, merging and overtaking manoeuvres. As only some elements were directly tested in the included studies (e.g., deceleration-lane length for diverging under CAD), these indications are suggestive rather than definitive. Many other design features were not examined, including curve geometry, vertical alignment, shoulder width/offset, merge–diverge tapers, and signing/marking placement. Targeted studies across Levels 1–3 are needed, using realistic scenarios (including heavy vehicles and vulnerable road users) and a range of visibility and weather conditions. These studies should report common behavioural and safety outcomes so that results can be compared across studies and design values updated where appropriate.

This systematic review focused on guidance activities, such as lane changing, merging/diverging, weaving, and overtaking, which are primarily influenced by road geometry and traffic conditions and typically fall under the driver's responsibility when the limits of automation are breached, thus, future research should expand its scope to encompass other driving tasks (i.e., control and navigation). Another limitation of this study is that it relied solely on Scopus and WoS databases as sources. Private-sector studies and internal reports were not accessible and are not represented in this review. Consequently, the evidence base reflects only the published literature and may miss findings that companies use to design and test their systems. By expanding the search to include additional databases, a broader range of relevant studies could be identified, potentially leading to a more comprehensive understanding of the topic.

CRediT authorship contribution statement

Arastoo Karimi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Suyi Mao:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Giorgio Lotto:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Jaeyoung Jay Lee:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Marco Bassani:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

Acknowledgments

This research was made possible thanks to the support of the European Commission through the call “MSCA PF”, which funded the project “GENIUS – next generation driver-vehicle interaction: real-time multimodal take-over control System” (Grant Agreement ID: 101150414), and Compagnia di Sanpaolo Foundation (No. 2021.2146) through the call: “Trapezio - Linea 2 MSCA Seal of Excellence - European Individual Fellowships H2020 e Postdoctoral Fellowships Horizon Europe”, which funded the project: “DIRECTIONS - driver road interaction on future road infrastructures”, by the China Scholarship Council under Grant No. 202106370107, by the Natural Science Foundation of China under Grant No. 72471249, and by Natural Science Foundation of Changsha under Grant No. kq2402221.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2026.101986.

Data availability

Data will be made available on request.

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