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# Traffic safety culture within the safe system: developing a common definition of traffic safety culture

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This paper develops a common, theoretically grounded definition of traffic safety culture within a Safe System perspective. It provides the first triangulated, expert-informed, theoretically grounded unified definition of traffic safety culture applicable across actors in the transport system. Despite increasing use of the concept in research and policy, traffic safety culture is defined, measured and used in different ways, which may limit its usefulness for measurement and implementation. To address this gap, the study applies a three-step mixed-methods approach combining systematic literature reviews, two Delphi studies with international experts, and complementary focus group discussions. The literature reviews identified recurring conceptual elements across definitions of organisational safety culture and traffic safety culture, including shared values, beliefs, attitudes, norms, and patterns of behaviour. Two Delphi studies demonstrated strong expert consensus on the importance of these elements for both organisational contexts (e.g., drivers at work) and societal traffic contexts. Focus group discussions further highlighted the need for definitions that are practically applicable, sensitive to social context, and suitable for different actors within the transport system. Based on these findings, the paper proposes a unified definition of traffic safety culture that applies across meaningfully defined groups of actors, including road users, organisations, authorities, and other stakeholders. The definition emphasises shared cultural elements that shape how traffic safety is understood and enacted, while allowing for group-specific aspects in measurement and intervention.

### KEYWORDS

common definition, mixed methods, road transport, safe system, traffic safety culture

# 1 Introduction

## 1.1 Background

Every year, some 20,000 people die on roads in the EU and at least 100,000 are severely injured (European Commission, 2025). Despite the progress over the last decades, these numbers are still unacceptably high and a key challenge for all European countries. There are even signs that the trend of decreasing road fatalities is stagnating or reversing in some countries, and most European countries face great challenges with a large number of seriously injured pedestrians and cyclists. Whilst continued progress can still be expected through improved infrastructure, vehicle technology, traffic laws and enforcement, many road safety experts argue that lasting improvement require changes in the beliefs, values and social norms of all stakeholders involved in road safety, including road users (Nævestad et al., 2019a). These changes imply the need for a cultural change, which does not only apply to road user groups, but also—if not more—to those who are responsible for shaping the traffic system through their roles in organisations. This focus on safety culture and the crucial role of all stakeholders influencing the road traffic system is also underlined by the Academic Expert Group (AEG) of the Fourth Global Ministerial Conference on Road Safety in Marrakech in 2025 (STA, 2025). Leveraging a cultural change that may improve traffic safety culture across European countries requires, however, a well-developed definition of the traffic safety culture concept; describing what it is and what it is not; making it an effective tool for measurements and targeted interventions.

Focus has been directed to the concept of traffic safety culture, in recent years, both among policy makers and researchers. There has been an increasing number of studies on the topic, but the concept is not well developed in the sense that there is an agreed understanding of how the concept should be defined and operationalised, and not the least how the concept should be utilised by policy makers. There is also a great deal of confusion about traffic safety culture and even misuse (Hopkins, 2018). If we want to apply the concept to bring about real change (and not just unleash a new buzzword), it is of utmost importance to be precise with terminology. That means defining and operationalising traffic safety culture and its conceptual elements (such as beliefs, attitudes, norms, values etc.) according to best practices in social sciences. Therefore, defining and operationalising traffic safety culture in different contexts of traffic safety implementation is key.

The traffic safety culture concept is important, as it denotes shared ways of thinking and acting that are relevant to traffic safety. Previous research indicates that such shared ways of thinking and acting are related to individual road safety behaviour, and thus accident involvement (Nævestad et al., 2019a). Safe System has become the state-of-the-art approach for road safety management, and it is recommended to countries worldwide (WHO and United Nations Regional Commissions, 2021; ITF, 2022). Safe System policies need, however, to be coupled with a well-developed understanding of traffic safety culture to ensure effective implementation. While Safe System refers to the formal aspects of road safety management (e.g., formal laws and policies), traffic safety culture refers to the informal aspects, (i.e., what road users actually do). There is often a discrepancy between formal policies; strategies, rules and regulations; and what people actually do (Antonsen, 2009). Thus, a proper understanding of traffic safety

culture might address this implementation gap and provide new insights that may help improve road safety (Nævestad et al., 2025).

## 1.2 Aims

The overarching aim of this paper is to develop a definition of organisational safety culture for road users at work (“organisational level”) and a definition of traffic safety culture that can be applied to private road users in the society, e.g., at national, regional and local level. To fulfil this aim, the study has the following subgoals:

- (1) Search the research literature to identify and review definitions of organisational safety culture and traffic safety culture.
- (2) Based on the reviews, conduct Delphi studies among experts to identify common elements in definitions of organisational safety culture for road users at work and traffic safety culture for private road users.
- (3) Conduct complementary focus group discussions to discuss the definitions refined in the Delphi groups; including opportunities and barriers, further specifications and elements that should be included.

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# 2 Methods

## 2.1 Literature review

A systematic literature review to identify definitions of organisational safety culture and traffic safety culture was conducted. We applied a simplified version of the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) approach (Page et al., 2021).<sup>1</sup>

### 2.1.1 Search strategy

We searched Web of Science and Scopus. Search strings were translated between databases to maintain conceptual consistency, while using database-specific features when this improved retrieval. Conceptual versions of the search strings are shown in Table 1, and full database-specific versions are available in Appendix 1.

The search for organisational safety culture was restricted to focus on studies relating to one of four transport sectors (road, maritime, air, rail including the nuclear sector). The traffic safety culture search was limited to the road sector.

All search hits were imported into Endnote. Duplicates were removed automatically, and then manually checked at the title and author level to identify duplicates caused by, e.g., spelling inconsistencies. Detailed search terms for two systematic literature searches and screening criteria for each search are provided in Appendix 1. Figure 1

<sup>1</sup> We have applied a simplified approach, which means that we have not followed all the steps in the PRISMA guidelines, e.g., full protocol registration, or formal risk-of-bias assessment. Cf. Appendix 1.

TABLE 1 Search strings, restrictions and total number of unique hits in databases for each of the two literature searches.

| Topic                         | Search string                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Restrictions                                                                                                                                                                                        | Hits* |
|-------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| Organisational safety culture | ("safety culture" OR "safety climate" OR "organisational culture" OR "company culture" OR "corporate culture" OR "workplace culture") AND (safety) AND ("air pilot" OR helicopter OR aviation OR airline seafarer OR maritime OR ship OR boat OR ferry OR offshore OR nautical rail OR railway OR subway OR metro OR tram OR subway OR road OR traffic OR street OR taxi OR cab OR "professional driver" OR "truck driver" OR lorry OR "bus driver" OR "work driver" OR nuclear OR IAEA) | Main search terms searched in titles and key words, sector terms in title, keyword and abstract.<br>Publication type: Article or review article.<br>English language<br>Publication date: 2010–2025 | 695   |
| Traffic safety culture        | (traffic OR road OR pedestrian OR cyclist OR bike OR car OR lorry OR moped OR motorcycle OR truck OR road user* OR bus OR taxi OR cab OR cyclist OR highway) AND safety AND (climate OR culture)                                                                                                                                                                                                                                                                                         | Searching title or key words. English language.<br>Publication type: Article or review article                                                                                                      | 654   |

Although not fully shown in this table, search terms were adapted to consider plural forms and alternative spellings. \*Hits are the total number of hits in Scopus and WoS, excluding duplicates. All searches were conducted early July 2025.

displays the flow chart from the traffic safety culture search, and Figure 2 from the organisational safety culture search.

As indicated in Figure 2, a total of 229 studies were included the literature search on organisational safety culture. References for all studies included in either literature search are available in Appendix 1.

## 2.2 Delphi approach

Based on the two literature reviews, two Delphi studies were carried out, one focusing on traffic safety culture in society, and one focusing on organisational safety culture for drivers at work.

The aim of the Delphi studies was to gather expert input on elements that should be included in definitions of (a) traffic safety culture in society and (b) organisational safety culture for drivers at work. Figure 2 illustrates the Delphi process. The literature review can be regarded as a preparatory phase for the Delphi study, informing the subsequent online survey steps. For each of the two Delphi studies, two survey rounds were conducted. In addition, a focus group discussion was held with some of the invited experts, which can be considered the final phase of the Delphi process.<sup>2</sup> In the following, we will describe how the surveys were conducted. The approach used for the focus group discussions is presented in section 2.3.

Two unique questionnaires were developed, based on the summaries from the two literature reviews, drawing on the cultural elements and aspects identified. The questionnaires were programmed and distributed using Walr platform, and the experts received an invitation, including a link to the survey, via email. Each survey took approximately 8–10 min to complete. The first survey round was conducted in September–October 2025, while round two was carried out in October–November 2025 (Figure 3).

### 2.2.1 Recruitment of experts

In this study, we operate with two expert subgroups in the Delphi studies, one for traffic safety culture and one for organisational safety culture. Experts were recruited among both researchers and stakeholders with demonstrated expertise in traffic safety and safety culture. Identification was based on publication records (e.g., authors of relevant scientific papers), professional networks, and project

consortium knowledge. Invitations were sent to a large pool of potential participants, and several rounds of reminders were issued to increase participation. We generally identified participants' e-mail addresses in previously published papers. The experts were allocated to one of the two surveys. Those who indicated competence in both traffic safety culture in society and organisational safety culture were randomly assigned to one of the surveys.

Figure 4 shows an overview of the Delphi process for both surveys.

For the traffic safety culture survey, 87 experts were invited to participate in the survey by email with a link to the survey. Thirty-six experts completed the first survey round, corresponding to a response rate of 41%. For organisational safety culture, 144 e-mail invitations were sent out. Twenty-eight experts completed the first survey round, which corresponds to a response rate of 19%. In Round 2, invitations were then sent to 28 in the organisational safety culture survey and 36 in the traffic safety culture survey. We received 21 responses for the organisational safety culture survey, and 20 for traffic safety culture. This corresponds to a 75% Round 2 response rate for organisational safety culture and 56% for traffic safety culture.

A total of 28 experts completed the first organisational safety culture survey round, and 21 experts completed both rounds. To ensure that all comparisons are based on the same individuals and to provide more reliable measurement of changes over time, results are primarily based on the experts who participated in both survey rounds.

Among the organisational safety culture experts ( $n = 21$ ) included in the analysis, the majority were male (62%). Most experts had an academic background in the social sciences (76%), followed by technical/engineering/natural sciences and others. In terms of age (assessed in intervals), the largest share was aged 60 years or older (43%), followed by those aged 40–49 years (29%) and 50–59 years (24%). The remaining experts were younger (30–39). The sample reflects relatively broad geographic spread, with 12 countries from four continents. Most respondents (62%) stated research or academic institution as primary profession/organisation, and the remaining ones worked for private companies (14%), public body or policy institutions (14%) and road or transport authorities (10%).

Among the experts ( $n = 20$ ) included in the traffic safety culture analysis, the majority were male (55%). Most experts had an academic background in the social sciences (80%), followed by technical/engineering/natural sciences and others. In terms of age, the largest share was aged 40–49 years (45%), followed by the 50–59 and 60+ age groups (each 25%). The remaining experts were

<sup>2</sup> We do not actually know if the focus group experts participated in the Delphi study, but they were invited to do so.

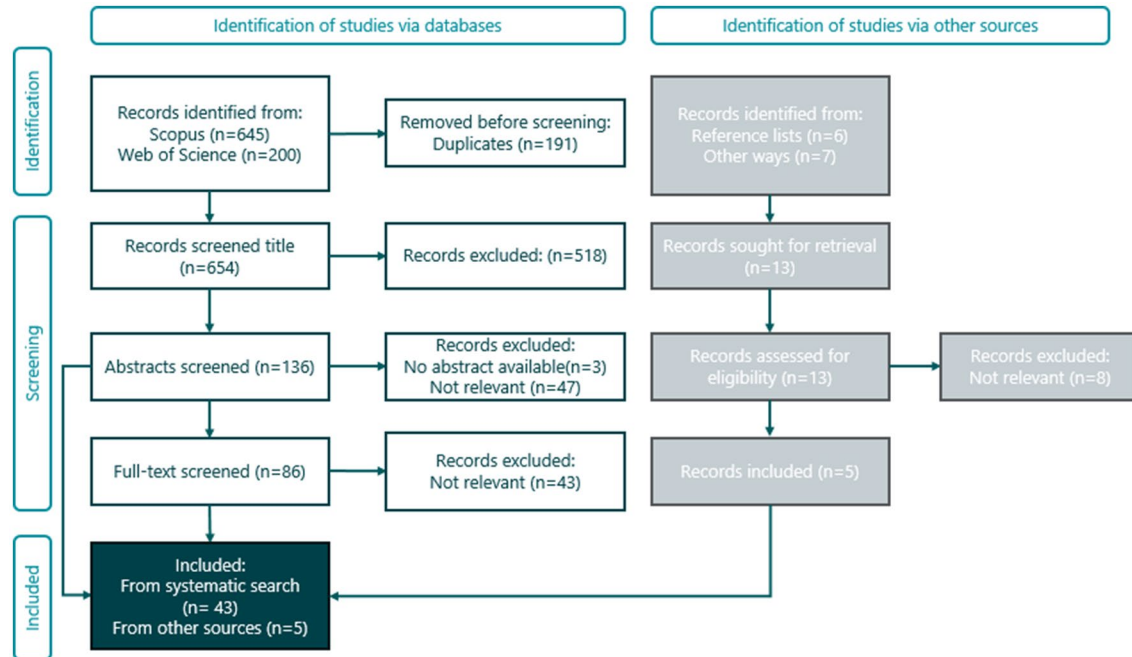


FIGURE 1  
PRISMA flow diagram for literature search for traffic safety culture.

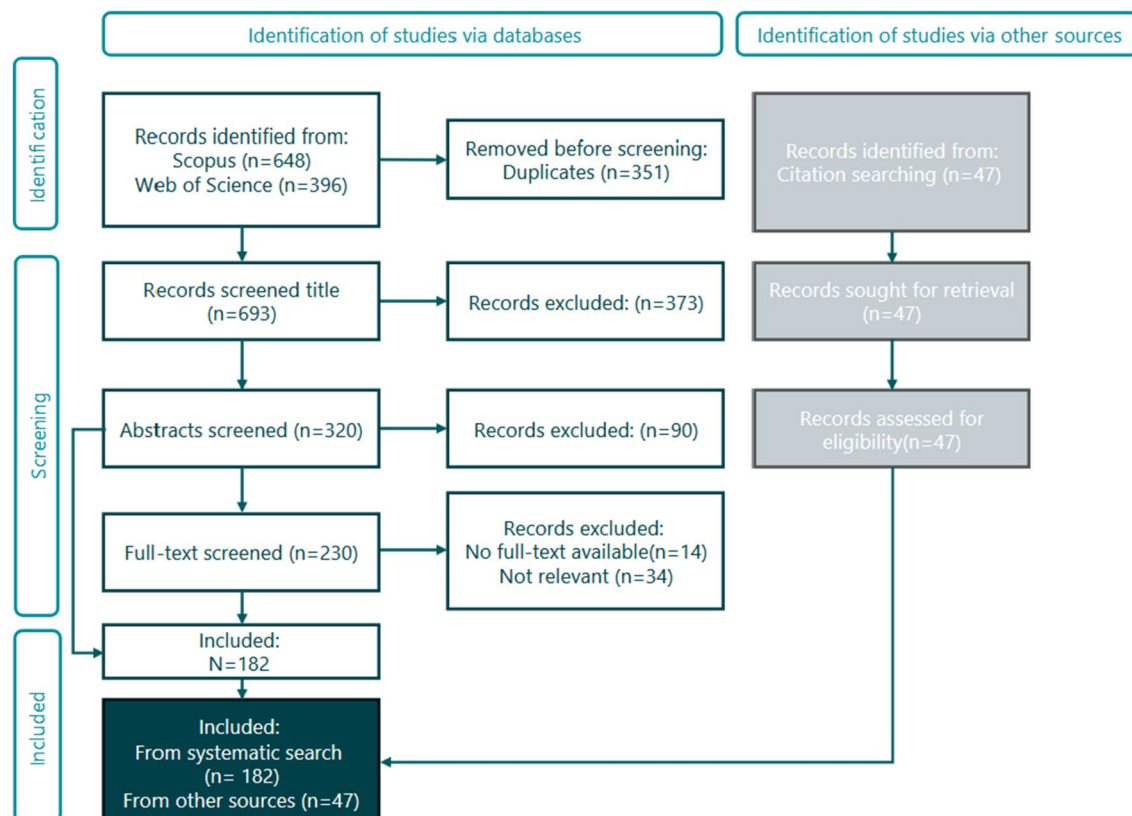
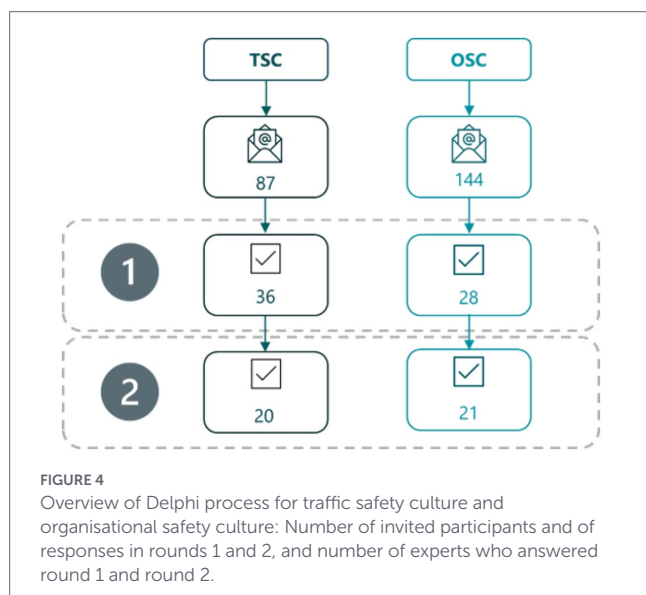
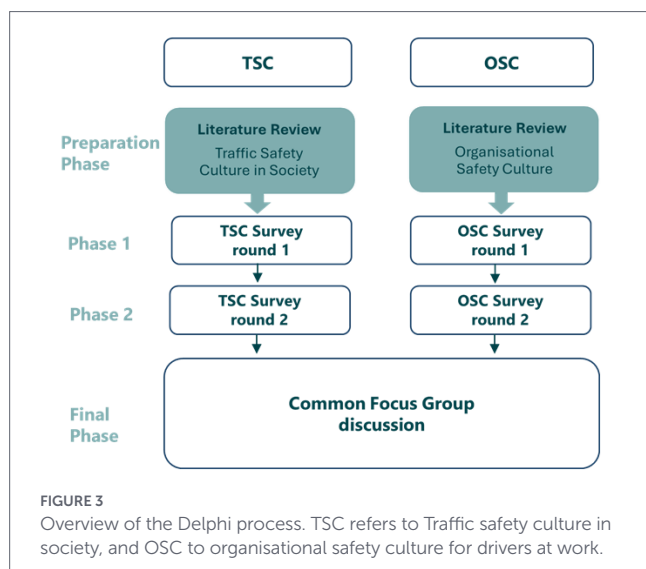


FIGURE 2  
PRISMA flow diagram for literature search for organisational safety culture.

younger (30–39). The sample reflects relatively broad geographic spread, with 14 different countries of work represented. Most respondents ( $n = 14$ ) work in a European country. Most respondents (60%) worked with research or in academic institutions.

Other participants reported to work in private companies (10%), public body or policy institutions (10%), road or transport authority (5%), non-profit working with traffic safety (5%) or other places of work (10%).



## 2.2.2 Surveys and procedure

In the first round of the Delphi survey, experts in traffic safety culture and organisational safety culture were asked to rate the importance of various conceptual elements related to each type of culture. *Conceptual elements* refer to broad, overarching components of culture such as values, norms, and beliefs, identified in the literature. Each item was rated on a scale from 1 (not important) to 10 (very important), using a slider bar. Example items are provided in [Appendix 2](#).

Because the surveys were based on the literature reviews, and because organisational safety culture is a more mature research field than traffic safety culture, the survey targeting organisational safety culture included an additional section in which experts were asked to rate the importance of various aspects of organisational safety culture for drivers at work (e.g., management commitment to safety, learning culture, just culture). The aspects were also based on the literature review. Finally, the Round 1 surveys also included open-ended questions to capture experts' reflections on the elements presented. Here,

experts could suggest additional elements or aspects they felt were missing, or share any further thoughts.

In the second survey round, experts were asked to rate the same elements (and aspects) as they did in Round 1. For each item, they were presented with the mean score from the ratings in Round 1, as well as their own previous answers, indicated on the same slider bars. The items were introduced with the following text: Please use the slider to record your rating for this round, taking into account the group average and your own professional judgement. In the second round, new open-ended questions were added that were informed by the findings from the previous rounds. Consequently, the content of the new questions differed between the two surveys. In the organisational safety culture questionnaire, experts were presented with a summary of the qualitative feedback from Round 1, and asked to share their reflections on that summary, and to provide additional input. The traffic safety culture-questionnaire concluded with a set of open-ended questions aimed at capturing experts' reflections regarding the conceptualisation of traffic safety culture.

## 2.3 Focus group discussions

The aim of the focus group discussions was to get more detailed elaborations and viewpoints on the different culture concepts. Thus, the focus group discussions can be viewed as the third and last step in our Delphi approach.

Two focus group interviews were conducted. The first one was conducted with seven experts online on the 14th of November 2025, and the second one was conducted with five experts onsite in Athens, Greece on the 18th of November 2025. The focus group discussions followed a semi-structured approach. The experts were first asked for their views on the definitions derived from the literature review and the Delphi surveys. The order, number, and content of subsequent questions were guided by the direction of the discussion.

The focus group discussions involved international experts in traffic safety and safety culture, recruited from the same pool as the Delphi study participants, including both researchers and practitioners. In total, two focus groups were conducted ( $n = 12$ ), representing a range of professional backgrounds and geographical contexts, although with a predominance of European and US-based experts.

## 3 Results

### 3.1 Results of the literature review

The following sections summarise how organisational safety culture and traffic safety culture are defined and discussed in the literature, highlighting common elements, conceptual distinctions, and points of disagreement relevant for operationalisation.

#### 3.1.1 Organisational safety culture

Organisational safety culture is commonly viewed as a subset of organisational culture focusing on safety-related values and norms, while its closely related concept, safety climate refers to more immediate, measurable shared perceptions of safety at a given point in time (Zohar, 1980; Cox and Flin, 1998).

Elements of organisational safety culture: Despite the conceptual ambiguity reflecting the wide diversity of disciplines in which the concept is used, the definitions provided in Table 2 indicate that most definitions are grounded in certain common elements. Safety culture is typically described in terms of shared values, beliefs, norms, attitudes, perceptions, competencies, and patterns of behaviour that shape how safety is understood and enacted within organisations (Altinpinar and Başar, 2022; Badia et al., 2021; Fernández-Muñiz et al., 2007; García-Herrero et al., 2013; Glesner et al., 2020; Mearns et al., 1998). At a theoretical level, however, fundamental debates persist. One key distinction is between an interpretive view, in which safety culture is something an organisation *is*—an emergent property grounded in tacit assumptions and collective sense-making—and a functionalist view, in which safety culture is something an organisation *has*—a set of tangible practices, structures, and policies that can be actively shaped and managed (Choudhry et al., 2007; Cooper, 2000; Guldenmund, 2000; Reason, 1998; Schein, 1983).

Table 2 presents some of the most influential definitions (based on how much the articles were cited).

Aspects of organisational safety culture. Organisational safety culture is widely understood as a complex and multi-dimensional construct, encompassing multiple interacting elements rather than a single trait (Choudhry et al., 2007; Cooper, 2000; Edwards et al., 2013; Mearns and Flin, 1999). For example, Reason (1998, p. 196) describes a safe culture as an “informed culture” supported by reporting, just, flexible, and learning cultures, while Guldenmund’s (2010) model, building on Schein (2010), conceptualises safety culture as layered, spanning from underlying basic assumptions, to espoused values at the middle layer, and observable artefacts at the most artificial layer.

Across studies, commonly identified aspects for organisational safety culture and safety climate include management commitment and leadership, safety systems and procedures, communication, training and competence, risk perception, employee involvement and behaviours, and the overall work environment (Choudhry et al., 2007; Clarke, 1999; Cooper, 2000; Griffin and Curcuruto, 2016; Griffin and Neal, 2000; Mearns et al., 2003; Zohar, 2002, 2010). Flin et al. (2000) further suggest a hierarchy among these aspects, highlighting management commitment to safety as the most central, followed by perceptions of safety management systems and risk. At the same time, there is no consensus regarding the number, structure, or labelling of safety culture dimensions, with proposed models ranging from as few as two to as many as 19 dimensions and substantial overlap in terminology (Guldenmund, 2000, 2010; Kath et al., 2010). Moreover, despite the dominant multi-dimensional perspective, some research, particularly within the safety climate literature, has found empirical support for more unidimensional interpretations, either for specific measurement tools or analytical purposes (Neal et al., 2000; Hahn and Murphy, 2008; López De Castro et al., 2013).

This combination of recurring core elements and persistent disagreement regarding dimensional structure underscores the need for a systematic, expert-driven approach to identifying and prioritising the most relevant elements and aspects of safety culture, providing a clear rationale for the use of a Delphi methodology in the present study.

### 3.1.2 Traffic safety culture

Defining Traffic Safety Culture. This systematic literature search was conducted with the aim of reviewing proposed definitions and the

TABLE 2 Key definitions of organisational safety culture.

| Author                                                            | Year | Definition of organisational safety culture                                                                                                                                                                                                                                                                                                                           |
|-------------------------------------------------------------------|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Uttal (cited in Reason, 1997, p. 192)                             | 1983 | “Shared values (what is important) and beliefs (how things work) that interact with an organization’s structures and control systems to produce behavioural norms (the way we do things around here).”                                                                                                                                                                |
| Turner, Pidgeon et al. (p. 4)                                     | 1989 | “The set of beliefs, norms, attitudes, roles, and social and technical practices that are concerned with minimizing the exposure of employees, managers, customers, and members of the public to conditions considered dangerous or injurious.”                                                                                                                       |
| Pidgeon (p. 135)                                                  | 1991 | “The constructed system of meanings through which a given worker, or group of workers, understands the hazards of their world.” He also suggested that a “good safety culture” can be characterized by three attributes: “norms and rules for handling hazards, attitudes toward safety, and reflexivity on safety practice.”                                         |
| International Atomic Energy Agency (p. 1)                         | 1991 | “That assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance.”                                                                                                                                               |
| Advisory Committee on the Safety of Nuclear Installations (p. 23) | 1993 | “The product of individual and group values, attitudes, perceptions, competencies, and patterns of behaviour that determine the commitment to, and the style and proficiency of, an organization’s health and safety management.”                                                                                                                                     |
| Reason (p. 196)                                                   | 1997 | A safety culture is “an informed culture” characterized by reporting, just, flexible, and learning cultures that collectively enhance an organization’s ability to manage risk.                                                                                                                                                                                       |
| Guldenmund (p. 250)                                               | 2000 | “Those aspects of the organisational culture which will impact on attitudes and behaviour related to increasing or decreasing risk.” He also proposed a framework where safety culture consists of three layers: basic assumptions (the core), espoused values (operationalized as attitudes, equated with safety climate), and artefacts (manifestations/behaviour). |
| Choudhry et al. (p. 1008)                                         | 2007 | “The product of individual and group behaviours, attitudes, norms and values, perceptions and thoughts that determine the commitment to, and style and proficiency of, an organization’s system and how its personnel act and react in terms of the company’s on-going safety performance within construction site environments.”                                     |
| Edwards and Davey (p. 77)                                         | 2013 | “The assembly of underlying assumptions, beliefs, values and attitudes shared by members of an organization, which interact with an organization’s structures and systems and the broader contextual setting to result in those external, readily-visible, practices that influence safety.”                                                                          |

application of the concept of Traffic Safety Culture, also referred to as Road Safety Culture, and related terms such Traffic Culture and Traffic Safety Climate.

The concept of Traffic Safety Culture is a relatively new and evolving field of research, with its roots in the broader concept of organisational safety culture. The complexity of transferring the knowledge accumulated from organisational safety culture research to traffic safety culture becomes apparent when looking at the group of people it is supposed to be applied to. While organisational safety culture can be studied in a tightly defined set of people (e.g., members of a company or corporation, fleet managers of a company, all truck drivers of a carrier) (e.g., Nævestad and Bjørnskau, 2012; Pietrek, 2023), private “road users” on the contrary are—in some cases—unified only by their means of transport and the jurisdiction they are subject to. Thus, more meaningful and unifying social units need to be chosen for making statements about the traffic safety culture of specific groups, such as families, peer groups, schools, communities (e.g., Edwards et al., 2014). Traffic safety culture has been applied, however, also to entire nations or other administrative and legal units which determine important factors assumed to shape a traffic safety culture such as law and enforcement, education or transport infrastructure (e.g., Nævestad, 2021).

Elements of traffic safety culture. From all reviewed papers, 25 definitions for “Traffic Safety Culture” or “Road Safety Culture” were extracted, which were either postulated or cited by the corresponding author(s). It is highlighted, however, that 12 of the definitions alone stem from two research groups, who proposed similar definitions which seemed to evolve over time or were finetuned for particular research purposes. Three definitions are very broad without apparent intention to provide explanatory value (Table 3). Twenty-two definitions include further elements, which are either postulated to be traffic safety culture, to be relevant dimensions influenced by culture Table 4.

These broad definitions facilitate grasping traffic safety culture as a concept. They are, however, not suitable for operationalisation and measurement. Most of the identified definitions, on the other hand, consist of a break-down into further 1–5 elements of mainly cognitive but also behavioural and motivational nature (see Table 5). There seems to be agreement that traffic safety culture is in people’s minds and mere observation of common behaviour is insufficient.

Nævestad et al. (2019b) for example, define road safety culture as “shared norms prescribing certain road safety behaviours, and thus shared expectations regarding the behaviours of others” (p. 324)—a definition assuming road safety culture to be reflected in another construct: common norms. Another definition, proposed by McDonald & Arthur (cited by Coogan et al., 2014), lists a series of constructs as crucial to understand the traffic safety culture paradigm: “the attitudes, beliefs, values, and knowledge about safe driving behaviour shared within a meaningfully defined group” (p. 12).

A few authors included an *implicit* definition of traffic safety culture by describing how they understand it. For example, the symbol exchange approach emphasises how symbols (gestures, signs, rituals and behaviour, all of which carry symbolic meaning) are exchanged within a community to shape behaviour and social norms. These forms vary across cultures and are suggested to be taken into account when studying culture in order to capture both broad cultural patterns and smaller subcultures (Rundmo et al., 2012).

All definitions identified are displayed in Tables 4, 5. This includes publications providing an explicit definition.

Social units of application. Regarding the social unit the proposed definitions refer to, e.g., “road users,” “groups,” “members of a

TABLE 3 General definitions of traffic safety culture extracted from the literature review.

| Studies                      | Concept                         | Definition                                                                                                                                                                                                                                                                                                                             |
|------------------------------|---------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Girasek (2012, pp. 37, 40)   | Positive Traffic Safety Culture | “A social climate in which traffic safety is highly valued and rigorously pursued. ... The factors that explained the most variance in TSC were support for increased government attention to traffic safety, strict monitoring and control of alcohol-impaired drivers, disapproval of speeding, and avoidance of aggressive driving” |
| Jadaan et al. (2022, p. 590) | Road Safety Culture             | “... how people behave when no one is watching.”                                                                                                                                                                                                                                                                                       |
| Ward et al. (2014, p. 42)    | Traffic Safety Culture          | “... the aspect of society that influences behavioural choices that affect traffic safety”                                                                                                                                                                                                                                             |

community,” “meaningful defined group” or do not indicate a social unit for application, making all the definitions applicable in various contexts. Two groups of authors explicitly include stakeholders in their definitions (Otto et al., 2016; National Academies of Sciences, Engineering, and Medicine, 2018), some authors keep their definitions broad enough to be applicable to not only road users but also other groups of people in a Safe System.

Nævestad and Bjørnskau (2012) investigated how the concept of Safety Culture can best be transferred to road users in general and concluded that local communities and nations are heterogeneous groups while peer groups seem less heterogeneous.

### 3.1.3 Elements and aspects of culture

In order to structure the synthesis of the literature and inform the subsequent Delphi process, we distinguish between elements and aspects of safety culture. Elements refer to the underlying, abstract cultural constructs that characterise how safety is collectively understood and prioritised within a group, such as shared values, norms, attitudes, beliefs, and patterns of behaviour. Aspects, in contrast, refer to more concrete, observable, and potentially measurable features through which these elements are expressed in practice, such as management commitment, communication, safety systems, and employee involvement.

This distinction allows us to differentiate between the conceptual building blocks of safety culture and their operational manifestations, thereby supporting both theoretical clarity and empirical applicability. It emerges from the literature synthesis and has guided the design of the Delphi study. The distinction provides a conceptual bridge between the identification of core cultural components and their subsequent operationalisation in empirical research.

## 3.2 Results of the Delphi study

To ensure that all comparisons are based on the same individuals and to provide more reliable measurement of changes over time, results are primarily based on the experts who participated in both

TABLE 4 Definitions of traffic safety culture (TSC) and road safety culture (RSC) identified based on literature review, which provide information on what TSC is in the context of traffic safety; SC, Safety Culture.

| Author(s)                                                               | Name of construct                         | Definition                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|-------------------------------------------------------------------------|-------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Chen et al. (2012, p. 139)                                              | TSC                                       | "When immigrants came to this country, they brought with them the attitudes and perceived social norms of their countries of origin toward risky traffic behaviour as pedestrians and cyclists, as well as habits and expectations of behaviour when driving. These 'attitudes, beliefs, perceptions, and values that (people) share in relation to traffic safety' are broadly referred to as (traffic) safety culture."                                                                                                              |
| Edwards et al., 2014 (p. 300)                                           | TSC                                       | "TSC can be defined as the assembly of underlying assumptions, beliefs, values and attitudes shared by members of a community, which interact with a community's structures and systems to influence road safety related behaviours."                                                                                                                                                                                                                                                                                                  |
| Lajunen et al. (2017, p. 11)                                            | TSC                                       | "The sum of all factors that affect the skills, safety attitudes, and safety behaviour of road users"                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| McDonald and Arthur (cited from Coogan et al., 2014, p. 314)            | TSC                                       | "The development of a new paradigm of a traffic safety culture to better understand 'the attitudes, beliefs, values, and knowledge about safe driving behaviour shared within a meaningfully defined group' ..."                                                                                                                                                                                                                                                                                                                       |
| Mishra and Mehran (2022, p. 82)                                         | TSC                                       | "... is a shared belief, assumption, and perception by a group of people towards traffic safety-related matters."                                                                                                                                                                                                                                                                                                                                                                                                                      |
| Myers et al. (2014, p. 26)                                              | n.a.                                      | "... we suggest that the utility of this "new" understanding of culture could be improved if researchers more clearly delineated the ideological—the socially constructed abstract systems of meaning, norms, beliefs and values (which we refer to as culture)—from concrete behaviours, social relations and other properties of workplaces (e.g., organisational structures) and of society itself."                                                                                                                                |
| Nævestad (2021, p. 557)                                                 | TSC (SC among nonprofessional road users) | "Thus, we may, for example, define safety culture among nonprofessional road users as, for example, shared norms, beliefs, and assumptions that provide frames of reference that guide individuals' interpretations of actions, hazards, and their identities, and which motivate and legitimize behaviours that have an impact on safety, and which are created through interaction within groups. We may hypothesize that this definition also can be applied to the national level, the community level, peer groups, and families" |
| Nævestad and Bjørnskau (2012, p. 146)                                   | TSC                                       | "... an interrelated set of perceptions of risk related to traffic safety, attitudes to traffic safety measures, and traffic safety behaviours shared by members of particular groups."                                                                                                                                                                                                                                                                                                                                                |
| Nævestad et al. (2019a, p. 3)                                           | RSC                                       | "... we define road safety culture (RSC) as shared patterns of behaviour, shared norms prescribing certain road safety behaviours and thus shared expectations regarding the behaviours of others."                                                                                                                                                                                                                                                                                                                                    |
| Nævestad et al. (2019b, p. 324)                                         | RSC                                       | "... as shared norms prescribing certain road safety behaviours, and thus shared expectations regarding the behaviours of others."                                                                                                                                                                                                                                                                                                                                                                                                     |
| Nævestad et al. (2022, p. 376)                                          | RSC                                       | "... shared values and attitudes signifying what is important (e.g., safety, mobility, respect, politeness), shared norms prescribing certain road safety behaviours, and thus shared patterns of behaviour and shared expectations regarding the behaviours of others."                                                                                                                                                                                                                                                               |
| National Academies of Sciences, Engineering, and Medicine (2018, p. 11) | TSC                                       | "... define traffic safety culture as the values and beliefs shared among groups of road users and stakeholders that influence their decisions to behave or act in ways that affect traffic safety."                                                                                                                                                                                                                                                                                                                                   |
| Otto et al. (2016, p. 3)                                                | TSC                                       | "... the values and beliefs shared among groups of road users and stakeholders that influence their decisions to behave or act in ways that affect traffic safety."                                                                                                                                                                                                                                                                                                                                                                    |
| Pietrek (2023, p. 590)                                                  | SC at individual level                    | "The main objective of shaping the safety culture at the individual level is to improve the knowledge, skills and motivation of individual employees of transport companies in the area of safety behaviours."                                                                                                                                                                                                                                                                                                                         |
| Sucha et al. (2016, p. 47)                                              | TSC                                       | "A traffic safety culture is rather a multifaceted concept which defines the norms, attitudes, and opinions in relation to the issue of traffic safety at the societal level (not the individual level). In other words, it is something that is shared by the given society and influences the behaviour of its members."                                                                                                                                                                                                             |
| US Department of Transportation Safety Council (2011, p. 6)             | TSC                                       | "... The shared values, actions, and behaviours that demonstrate a commitment to safety over competing goals and demands."                                                                                                                                                                                                                                                                                                                                                                                                             |
| Ward et al. (2010, p. 4f)                                               | TSC                                       | "... perceptions people have about what behaviours are normal in their peer group and their expectations for how that group reacts to violations to these behavioural norms. In terms of traffic safety, this definition applies to behaviours that either increase risk (e.g., speeding) or are protective (e.g., wearing seatbelts), as well as behaviours related to acceptance or rejection of traffic safety interventions."                                                                                                      |

(Continued)

TABLE 4 (Continued)

| Author(s)                                                      | Name of construct | Definition                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|----------------------------------------------------------------|-------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ward and Özkan (2014, cited from Mozaffari et al., 2021, p. 3) | TSC               | "Following the discussion by Ward et al. (2014), the main aspect of TSC are values, beliefs, attitudes, perceived norms, and perceived control."                                                                                                                                                                                                                                                                                                                               |
| Ward et al. (2019a, p. 8)                                      | TSC               | "... the shared belief system of a group of people, which influences road user behaviours and stakeholder actions that impact traffic safety ..."                                                                                                                                                                                                                                                                                                                              |
| Ward et al. (2019b, p. 32)                                     | TSC               | "... 'traffic safety culture' as 'the shared belief system, which influences behaviours affecting traffic safety.' This definition applies to both the behaviour of road users and the artifacts generated by stakeholder actions."                                                                                                                                                                                                                                            |
| Ward et al. (2014, p. 42)                                      | TSC               | "... the culture that emerges in a geographical area can influence driver responses to perceptions of risk associated with system hazards and driver intentions to engage in risky behaviours. For instance, drivers in rural areas may share a belief system described as 'denial of risk' that increases risk-taking behaviours such as speeding. This aspect of society that influences behavioural choices that affect traffic safety is called 'traffic safety culture.'" |

survey rounds. This applies both to the organisational safety culture survey and the traffic safety culture survey.

### 3.2.1 Organisational safety culture

In the first part of the survey, experts were asked to rate the importance of various elements of organisational safety culture in workplaces where employees drive as part of their job. They evaluated eight elements on a scale from 1 (not important) to 10 (very important). In the second round, experts re-rated the same elements and were presented with their own Round 1 ratings as well as the aggregated group results from Round 1 (mean scores). In Table 6 the culture elements are presented according to their rating in Round 2 (from highest to lowest mean), indicating level of importance ascribed in the final round.

Overall, Round 2 results show that all elements were viewed as important, but norms, values, attitudes, patterns of behaviour, and beliefs received the highest ratings and demonstrated the strongest consensus among the experts. Variation in responses was generally low ( $SD = 1.2\text{--}2.0$ ), indicating a high level of consensus across the panel.

Experts were also asked to rate the importance of key aspects of organisational safety culture. Aspects of organisational safety culture are concrete, observable features (e.g., management commitment to safety, communication, learning culture) through which underlying cultural elements are expressed and measured in practice. Rating scales and procedures across rounds were identical to the elements. Mean values and standard deviations for Rounds 1 and 2, and changes in these statistics between rounds, are presented in Table 7. The aspects are presented according to their rating in Round 2 (from highest to lowest mean), indicating level of importance ascribed in the final round.

In Round 2, we can see that experts rated seven of the eight organisational aspects highly, with mean scores well above 8.

In both rounds, experts were also invited to give qualitative feedback and share their thoughts and reflections. The qualitative findings from the organisational safety culture surveys indicate strong expert agreement that organisational safety culture for drivers is shaped by a combination of organisational conditions, managerial practices, and wider systemic influences. Key factors included work characteristics, external pressures such as regulations, clients and economic conditions, and leadership commitment expressed through visible

prioritisation of safety, adequate resources, and a learning-oriented, no-blame approach. Experts emphasised the importance of a system perspective, employee engagement, aligned safety communication, and realistic planning to reduce time pressure and stress that can undermine safety culture.

### 3.2.2 Traffic safety culture

In the first round, experts were asked to rate the importance of nine elements of traffic safety culture derived from the literature review. For each element, a brief example definition was provided to ensure a shared understanding. The elements and definitions are presented in Table 8.

The overall purpose of the two-round Delphi on traffic safety culture was to facilitate iterative convergence towards a shared, theoretically grounded definition of traffic safety culture.

In round 1, experts evaluated nine elements identified from the literature, using a 10-point scale to indicate their perceived importance as components of traffic safety culture. The evaluation was based on the question: "For each element, please indicate how important you think it is for traffic safety culture in society (on a scale from 1 (not important) to 10 (very important) by clicking the bar or dragging the marker). How important are..." Table 9 presents the mean importance ratings for the nine elements of traffic safety culture in Round 1 and Round 2 of the Delphi study, as well as standard deviations. Overall, the results suggest substantive stability in experts' assessments across rounds.

Across both rounds, values, norms, beliefs, attitudes and patterns of behaviour received the highest mean scores, indicating they were perceived as the most important elements. Overall, the changes in standard deviations indicate that disagreement decreased from round 1 to 2 for most elements.

In the second Delphi round, experts also responded to seven qualitative open-ended questions to deepen the conceptual understanding of traffic safety culture. Traffic safety culture was widely seen as a multidimensional construct, typically comprising cognitive, normative, and behavioural elements. Experts were divided on whether a universal definition or index is feasible: While many stressed contextual variation across countries, others argued that a common core framework is possible if local expressions and weightings are allowed to differ. Traffic safety culture was considered observable through both road user behaviours and system-level features such as infrastructure,

TABLE 5 Sub-constructs of definitions of traffic safety culture (TSC) and road safety culture (RSC) extracted from reviewed papers.

| Author(s)<br>of<br>definition | Year  | Construct                      | Elements |        |                        |       |           |                       |             |                       |                      |            |           |             |         | Social unit<br>of<br>application           |
|-------------------------------|-------|--------------------------------|----------|--------|------------------------|-------|-----------|-----------------------|-------------|-----------------------|----------------------|------------|-----------|-------------|---------|--------------------------------------------|
|                               |       |                                | Beliefs  | Values | Attitudes,<br>opinions | Norms | Behaviour | Percept.<br>(of risk) | Assumptions | Knowledge<br>& skills | Perceived<br>control | Motivation | Intention | Committment | Meaning |                                            |
| Chen et al.                   | 2012  | TSC                            |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “that people share”                        |
| Edwards et al.                | 2014  | TSC                            |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “shared by members of a community”         |
| Lajunen et al.                | 2017  | TSC                            |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “road users”                               |
| McDonald & Arthur             | 2014  | TSC                            |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “shared within a meaningful defined group” |
| Mishra & Mehran               | 2022  | TSC                            |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “a group of people”                        |
| Myers et al.                  | 2014  | n.a.                           |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | n.a.                                       |
| Nævestad                      | 2021  | TSC/SC of non-prof. Road users |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “among non-professional road users”        |
| Nævestad & Bjørnskau          | 2012  | TSC                            |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “shared by members of particular groups”   |
| Nævestad et al.               | 2019a | RSC                            |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | n.a.                                       |
| Nævestad et al.               | 2019b | RSC                            |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | n.a.                                       |
| Nævestad et al.               | 2022  | RSC                            |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | n.a.                                       |

(Continued)

TABLE 5 (Continued)

| Author(s)<br>of<br>definition | Year  | Construct              | Elements |        |                        |       |           |                       |             |                       |                      |            |           |             |         | Social unit<br>of<br>application                     |
|-------------------------------|-------|------------------------|----------|--------|------------------------|-------|-----------|-----------------------|-------------|-----------------------|----------------------|------------|-----------|-------------|---------|------------------------------------------------------|
|                               |       |                        | Beliefs  | Values | Attitudes,<br>opinions | Norms | Behaviour | Percept.<br>(of risk) | Assumptions | Knowledge<br>& skills | Perceived<br>control | Motivation | Intention | Committment | Meaning |                                                      |
| National Academies            | 2018  | TSC                    |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “shared among groups of road users and stakeholders” |
| Otto et al.                   | 2016  | TSC                    |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “shared among groups of road users and stakeholders” |
| Pietrek                       | 2023  | SC (at individ. level) |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “individual employees of transport companies”        |
| Stringer                      | 2018  | Community TSC          |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | n.a.                                                 |
| Sucha et al.                  | 2016  | TSC                    |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “shared by the given society”                        |
| US DOT                        | 2011  | TSC                    |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | n.a.                                                 |
| Ward & Özkan                  | 2014  | TSC                    |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “of subgroups within society”                        |
| Ward et al.                   | 2010  | TSC                    |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “people”                                             |
| Ward et al.                   | 2014  | TSC                    |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “drivers”                                            |
| Ward et al.                   | 2019a | TSC                    |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “of a group of people”                               |
| Ward et al.                   | 2019b | TSC                    |          |        |                        |       |           |                       |             |                       |                      |            |           |             |         | “of a group”                                         |

SC, Safety Culture.

TABLE 6 Expert ratings of the importance of organisational safety culture elements in Round 1 and Round 2 of the Delphi study, based on respondents who participated in both rounds ("repeat respondents").

|                          | All R1<br>resp. | Repeat respondents |                  |                      |
|--------------------------|-----------------|--------------------|------------------|----------------------|
|                          | Round<br>1      | Round<br>1         | Round<br>2       | Difference<br>R2-R1* |
|                          | Mean (SD)       |                    |                  |                      |
| Norms                    | 8.8 (1.3)       | 9.0 (1.2)          | <b>9.0 (0.8)</b> | 0.0 (−0.4)           |
| Values                   | 8.6 (1.7)       | 8.7 (1.8)          | <b>8.7 (1.7)</b> | 0.0 (−0.1)           |
| Patterns of<br>behaviour | 8.8 (1.2)       | 8.5 (1.2)          | <b>8.6 (0.9)</b> | 0.1 (−0.2)           |
| Attitudes                | 8.5 (1.9)       | 8.6 (2.0)          | <b>8.4 (1.9)</b> | −0.2 (−0.1)          |
| Beliefs                  | 8.4 (1.8)       | 8.2 (1.9)          | <b>8.3 (1.7)</b> | 0.1 (−0.2)           |
| Competencies             | 8.2 (1.5)       | 8.2 (1.4)          | <b>8.2 (1.1)</b> | 0.0 (−0.4)           |
| Perceptions              | 8.1 (1.6)       | 8.0 (1.7)          | <b>8.0 (1.6)</b> | 0.0 (−0.1)           |

Culture elements are presented according to their rating in Round 2 (from highest to lowest mean), indicating level of importance ascribed in the final round. Round 2 means are also marked in bold.

\*Difference in Round 1 and Round 2 means (standard deviations) for  $n = 21$ . Means based on all Round 1 respondents were the ones presented to respondents in Round 2.

enforcement, and societal responses to crashes. Overall, expert-proposed definitions converged on the idea of traffic safety culture as shared values, norms, beliefs, and practices that collectively shape safety-related behaviour in traffic.

### 3.3 Results of focus group discussions

The participants in the two different focus groups (onsite and online) were introduced to two definitions derived from the literature reviews and the Delphi studies:

*Traffic safety culture encompasses shared values, beliefs, attitudes, norms, and patterns of behaviours that shape how traffic safety is understood and enacted within a meaningfully defined group of road users.*

*Organisational safety culture encompasses shared values, beliefs, attitudes, norms, and patterns of behaviours that shape how traffic safety is understood and enacted within an organization.*

The participants who took part online stated that the definitions were insufficiently developed, particularly in terms of practical applicability. Several experts argued that definitions which remain superficial do not meaningfully support implementation. For traffic safety culture specifically, they emphasised the need to embed the concept more clearly within its social context, highlighting shared understandings and collective commitment to compliance. It was also noted that traffic safety culture must explicitly acknowledge the diversity of road users and contexts to which it applies.

Participants generally agreed that organisational safety culture is easier to define than traffic safety culture, given its clearer boundaries and governance structures. Nevertheless, several experts stressed that traffic safety culture should explicitly reflect leadership responsibility, including commitment at the highest levels (e.g., CEOs), and clarify the respective roles of employers, organisations, authorities, and

government. Highlighting the practical benefits of working with traffic safety culture for professionals was also seen as important.

Despite these concerns, experts recognised the value of providing a definition as a starting point for change. Several suggested that the definition could function as a benchmark for assessing progress, with implementation measured over time and the definition subsequently revisited and refined based on experience.

Practical relevance was repeatedly emphasised. Experts argued that definitions should primarily support improvements in road safety and be tailored to different audiences, including policymakers, law enforcement, and researchers. Regarding the possibility of merging the definitions of traffic safety culture and organisational safety culture, participants largely agreed that the concepts are interconnected. Increased emphasis on societal responsibility would reduce the burden on individual organisations, and vice versa.

Participants who took part onsite in Athens, generally found the definition suitable for academic purposes but less effective for public communication. While a universal definition was considered possible, experts stressed that measurement and operationalisation must be adapted to cultural and contextual differences. A key unresolved issue concerned the appropriate unit of analysis: whether traffic safety culture should be defined at the societal level, for specific occupational groups, or for other meaningfully defined groups. Identifying which groups to target for change, and why, was seen as fundamental for both definition and measurement.

Several refinements to the definition were proposed. Experts emphasised that references to "groups of road users" should imply a shared social identity, noting that while infrastructure influences immediate behaviour, social identity underpins culture across contexts. To avoid conceptual circularity, some participants suggested focusing on patterns of action rather than individual behaviours, given that behaviour is typically the outcome rather than the defining feature of culture. Distinctions between values, norms, and beliefs were also highlighted, with suggestions to clarify whether norms are formal or informal and how they structure and shape cultural practices.

The possibility of unifying traffic safety culture and organisational safety culture was discussed by reframing the definition around "actors in the transport system." While this was seen as conceptually attractive, experts noted that differences in scope pose challenges: organisational safety culture focuses on employer–employee relationships, whereas traffic safety culture entails broader societal change involving diverse actors, complicating measurement and intervention. Although all conceptual elements were regarded as important, their relative weight was expected to vary across groups and behaviours.

Discussions also highlighted challenges related to measurement and behaviour change, particularly for professional drivers. While employers were viewed as having the strongest moral and legal influence on behaviour, difficulties remain for lone workers, supply chain workers, and gig-economy drivers, who may fall outside traditional employment structures. Nevertheless, even these workers were seen as embedded in social groups, reinforcing the relevance of a culture-based approach. One participant further noted that traffic safety culture should be considered in relation to broader sustainability goals, reflecting the increasing integration of road safety within national and international sustainability agendas.

In summary, the two focus group discussions revealed several unresolved tensions that need to be addressed in finalising the definition. These include balancing conceptual rigour with practical usability, reconciling universality with context-specific measurement,

TABLE 7 Means (SD) for ratings of OSC aspects in Rounds 1 and 2 of the Delphi study.

|                                      | All R1 resp. |           | Repeat respondents, $n = 21$ |                   |
|--------------------------------------|--------------|-----------|------------------------------|-------------------|
|                                      | Round 1      | Round 1   | Round 2                      | Difference R2-R1* |
|                                      | Mean (SD)    |           |                              |                   |
| Management commitment and leadership | 9.2 (0.8)    | 9.2 (0.8) | <b>9.2 (0.7)</b>             | 0.0 (−0.1)        |
| Employee involvement and behaviours  | 8.8 (1.2)    | 9.0 (1.0) | <b>9.0 (0.9)</b>             | 0.1 (−0.2)        |
| Communication                        | 8.7 (1.3)    | 8.8 (1.2) | <b>9.0 (0.9)</b>             | 0.2 (−0.4)        |
| Safety systems and procedures        | 9.0 (1.0)    | 8.9 (1.0) | <b>9.0 (0.7)</b>             | 0.2 (−0.3)        |
| Learning culture                     | 8.8 (1.4)    | 8.7 (1.5) | <b>8.8 (1.4)</b>             | 0.1 (−0.1)        |
| Risk perception                      | 8.5 (1.6)    | 8.6 (1.3) | <b>8.8 (0.8)</b>             | 0.1 (−0.5)        |
| Training and competence              | 8.5 (1.0)    | 8.4 (1.1) | <b>8.3 (1.8)</b>             | −0.1 (0.7)        |
| Flexible culture                     | 7.3 (1.8)    | 7.1 (1.8) | <b>7.2 (1.6)</b>             | 0.1 (−0.2)        |

Aspects are presented according to their rating in Round 2 (from highest to lowest mean), indicating level of importance ascribed in the final round. Round 2 means are marked in bold.

\*Difference in Round 1 and Round 2 means and standard deviation for  $n = 21$ .

TABLE 8 Elements of traffic safety culture derived from the literature review.

| Elements               | Example definition                                                                                                       |
|------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Values                 | Common ideas about what is considered important in relation to traffic safety in society.                                |
| Norms                  | Unwritten rules or standards that are socially enforced in the road traffic system.                                      |
| Attitudes              | Positive or negative evaluations of safety-relevant traffic behaviour in society.                                        |
| Beliefs                | Underlying assumptions or convictions about traffic safety in society.                                                   |
| Patterns of behaviour  | Behaviours that shape how traffic safety is understood and enacted within society.                                       |
| Perceptions of risk    | Common understandings of the likelihood and severity of danger in the road traffic system.                               |
| Motivation             | Common drive and dedication within society to prioritise traffic safety over competing goals.                            |
| Perceptions of control | Common understanding of the degree of influence individuals or groups believe they have over traffic safety outcomes.    |
| Systems of meaning     | The broader cultural narratives, symbols, and interpretations through which traffic safety is understood within society. |

TABLE 9 Results in terms of Mean (SDs) for each traffic safety culture element in the two Delphi rounds, as well as the change in means and SD.

|                        | All ( $n = 36$ )* |           | Repeat respondents ( $n = 20$ ) |                    |
|------------------------|-------------------|-----------|---------------------------------|--------------------|
|                        | Round 1           | Round 1   | Round 2                         | Difference R2-R1** |
|                        | Mean (SD)         |           |                                 |                    |
| Values                 | 8.3 (1.6)         | 8.6 (1.4) | <b>8.4 (1.4)</b>                | −0.2 (−0.1)        |
| Norms                  | 8.4 (1.5)         | 8.2 (1.8) | <b>8.3 (1.4)</b>                | 0.1 (−0.4)         |
| Beliefs                | 8.2 (1.4)         | 8.4 (1.4) | <b>8.3 (1.3)</b>                | −0.1 (−0.1)        |
| Attitudes              | 8.1 (1.5)         | 8.1 (1.7) | <b>8.1 (1.2)</b>                | 0.0 (−0.5)         |
| Patterns of behaviour  | 8.3 (1.1)         | 8.3 (1.0) | <b>8.0 (1.9)</b>                | −0.3 (0.8)         |
| Motivation             | 7.6 (1.4)         | 7.9 (1.4) | <b>7.7 (2.0)</b>                | −0.3 (0.6)         |
| Perceptions of control | 7.3 (1.9)         | 7.7 (1.5) | <b>7.7 (1.3)</b>                | 0.0 (−0.3)         |
| Perceptions of risk    | 7.8 (2.1)         | 7.8 (2.1) | <b>7.6 (2.0)</b>                | −0.3 (−0.2)        |
| Systems of meaning     | 7.3 (2.0)         | 6.9 (2.0) | <b>6.8 (1.9)</b>                | −0.1 (−0.2)        |

Results are presented separately for all Round 1 respondents ( $n = 36$ ), and for repeat respondents ( $n = 20$ ). Culture elements are presented according to their rating in Round 2 (from highest to lowest mean), indicating level of importance ascribed in the final round. Round 2 means are marked in bold.

\*The means based on all Round 1 respondents were the ones provided to respondents in the second Delphi round. \*\*Difference in Round 1 and Round 2 means and standard deviation for the  $n = 20$ .

determining the appropriate scope and level of analysis, clarifying the role of behaviour without introducing circularity, and adequately capturing the diversity of actors involved in the transport system.

## 4 Discussion

### 4.1 Should we keep one or two definitions?

#### 4.1.1 One definition, focusing on actors in the transport system

Inspired by the focus group discussions, we propose one broadened definition, focusing on the transport system and the different actors within the transport system. This definition merges the initial two separate definitions for organisational safety culture and traffic safety culture generated through the literature reviews and the Delphis. We propose the following common definition:

*Traffic safety culture encompasses shared values, beliefs, attitudes, norms, and patterns of behaviours that shape how traffic safety is understood and enacted within a meaningfully defined group of actors in the transport system. This meaningfully defined group of actors can refer to road users, organizations, authorities, or other actors within the transport system.*

One definition of traffic safety culture, that can be applied to different groups in the transport system, might seem less complex than two definitions. Additionally, this could also work as a definition which includes all relevant subgroups. This means that organisational safety culture becomes an (integral) part of, and under the umbrella of the traffic safety culture concept, while previously they were treated as two separate ones. Thus, simplicity is the main reason for suggesting one definition. It is less complex to communicate and if it should be based on a system approach it can be adapted to different actors in the system, while maintaining its applicability for operationalisation.

#### 4.1.2 Arguments in favour of two separate definitions

Although we coined one single definition, there are many reasons for keeping two separate definitions. First, our literature review indicates that organisational safety culture and traffic safety culture are two distinct fields of research. These two fields of research focus on different empirical settings, different groups, and there are to some extent based on different approaches. Our literature reviews, Delphis and focus group discussions indicate that the organisational safety culture research focusing on drivers at work is much more conceptually, scientifically and measure-wise mature than the traffic safety culture research.

The organisational safety culture research focusing on drivers at work, is based on previous studies of organisational safety culture in high-risk organisations like nuclear plants, aviation, rail and so on. For that reason, the framework for measuring organisational safety culture among drivers at work is more mature than traffic safety culture research. Additionally, the framework for understanding how organisational safety culture can be improved is much more mature than traffic safety culture research. As indicated in the literature reviews

and Delphis, management commitment to safety and safety management systems are crucial mechanisms for influencing organisational safety culture. In the field of traffic safety culture research, there are no similar clear influencing mechanisms. The main reason for this difference is the fact that organisations are more clearly limited and well defined than the units that can be ascribed to private road users, such as for instance nations regions and municipalities. Organisations have clear criteria for inclusion, which is the employment relationship. Given the managerial prerogative, managers can also influence culture and how the work is done through formal and informal means. Our data sources also point to the importance of external framework conditions (e.g., regulations, customers, economy) as important influencers of organisational safety culture. These mechanisms are different from mechanisms influencing safety culture of private road users in society, which typically relates to enforcement, education infrastructure, and other more general factors (economy, religion). These are arguments for keeping two separate definitions.

#### 4.1.3 The solution: maintaining one definition, but referring to group specific aspects

The solution to the discussions above is to maintain one definition, but refer to group specific aspects for each of the different groups in the transport system, e.g., road users at work, private road users in society, authority personnel and stakeholders etc.

Although our study indicates that the conceptual elements (values, beliefs, attitudes etc.) are similar for the traffic safety cultures of different actors within the transport system, our review indicates that different cultural aspects are important for different actors. Even within the same group of road users, for example, the impact of the different cultural aspects varies depending on the specific behaviour (e.g., Meesmann et al., 2025). When it comes to road users at work, on the other hand, these are generally part organisations in which several organisational safety culture aspects are crucial. This applies to, e.g., management commitment to safety, learning culture, just culture etc. Thus, when we apply the abovementioned traffic safety culture definition to organisations with road users at work, these cultural aspects must be added to the definition, as additional information for this group.

When it comes to private road users in society and their safety behaviour, the private road users are defined by their common cultural characteristics at, e.g., the national, regional or local level, or even within a very specific group of road users (e.g., young urban moped riders, e-scooter riders during nighttime). Relevant cultural aspects for these groups can, e.g., be shared (descriptive) norms related to acceptable levels of risk taking in traffic, shared values and attitudes related to freedom to take risk in traffic, shared attitudes related to acceptance of restrictive measures aiming to improve road safety (e.g., alcolock, 30 km/h speed limits) shared beliefs related to fatalism and religion etc. These aspects for private road users in society may touch upon political, ideological and religious issues that are part of larger sociocultural features of society.

The focus group discussions indicate that our traffic safety culture definition could also be applied to people working in authorities, or other road safety stakeholders in society, as it always applies to humans making decisions or taking actions which implicate road safety. In this case, the aspects related to organisational safety culture will be relevant, as authorities are organisations. The context for authorities is, however, different, as a main focus for these organisations is their different types of influences on private road users in society and road users at work. These influences are exerted by means of different tools, e.g.,

legislation, education, infrastructure, campaigns etc. Thus, their values, beliefs, norms, etc. related to those tools are the subject of investigation. For people working in authorities, the use of these tools depends on cultural aspects like the extent of system responsibility attitudes concerning the role of authorities, views on authorities' possibilities, capabilities and readiness to influence private road users and road users at work etc. by using their tools accordingly. Thus, when measuring traffic safety culture and applying the abovementioned traffic safety culture-definition to authorities and stakeholders, these aspects must be adapted and highlighted. This is an important issue for future research.

## 4.2 Methodological limitations and strengths

### 4.2.1 Literature review

Both literature reviews applied a targeted and restrictive search strategy. Main search terms were searched in titles, keywords, and abstracts of English-language articles and review papers. As the number of studies in the field of organisational safety culture was still too broad, only publications from 2010 to 2025 were included to ensure relevance, quality, and a manageable number of studies. No publication date limit was applied in the review on traffic safety culture. As this is a relatively recent research field, the broader approach allowed for a comprehensive overview while still keeping the number of studies manageable.

### 4.2.2 Delphi studies

A first limitation is related to the number of participants in each of the Delphi studies. On the one hand, a Delphi Round of 15–20 people comprise a very small groups for quantitative analysis. On the other hand, [Beiderbeck et al. \(2021\)](#) recommend that a Delphi-subgroup should include at least 15–20 experts. In this context, “subgroup” refers to the group of participants whose responses will be compared statistically. Issues related to response rate can also be mentioned. It should also be remembered that the populations that we target are relatively small. Also, traffic safety culture research is a relatively new field. Thus, there are both relatively low levels of both studies and experts, and for the present purposes it was more appropriate to base our work on few respondents with high levels of relevant expertise than on a higher number of less relevant respondents. Additionally, answering Delphi surveys, especially in two rounds, is time consuming and it is not unnatural to expect some attrition across rounds.

Another limitation concerns the Delphi design. While Delphi studies often involve three or more rounds, only two rounds were conducted due to time constraints. The preparatory literature reviews and subsequent focus group discussions helped compensate for this by providing additional depth and context. Moreover, high levels of agreement across both rounds suggest that an additional round was unlikely to substantially alter the results, a view also expressed by several participants.

The survey contents and varying levels of conceptual expertise among experts may also have influenced the results. Although most participants were familiar with traffic safety culture, several reported difficulties distinguishing between closely related elements such as beliefs, values, and attitudes, reflecting the conceptual complexity of the field. This also indicates the high level of competence required from participants, suggesting why recruitment of Delphi experts on traffic safety culture may be challenging.

It should also be noted that the composition of the Delphi sample may have influenced the results. For example, the traffic safety culture element “system of meaning” was rated relatively low, despite being included in several definitions identified in the literature review. One possible explanation is that this element is more abstract and qualitative than the other elements, which may make it more difficult to assess within the structured survey format. While system of meaning may still represent an important aspect of traffic safety culture, for instance in relation to how responsibility for accidents is understood, it may be less readily captured through quantitative rating scales. A system of meaning refers, e.g., to the basis of shared interpretations of traffic safety, such as viewing accidents as preventable and as a collective responsibility, rather than individual failure.

A further limitation concerns the absence of a predefined consensus threshold. While many Delphi studies operationalise consensus using specific quantitative criteria (e.g., percentage agreement or dispersion measures), the present study did not apply a fixed threshold. Instead, consensus was assessed based on the overall level of agreement and the stability of responses across rounds. The consistently high mean scores and minimal changes between Round 1 and Round 2 suggest a substantial degree of convergence among participants. However, the lack of a formal consensus criterion introduces some subjectivity in interpreting the level of agreement and should be considered when evaluating the findings.

How should we interpret the small differences between Delphi Round 1 and 2 scores? Overall, the Delphi results suggest substantive stability in experts' assessments across rounds. For most elements, the differences in mean scores were minimal, indicating that the iterative Delphi process did not substantially shift the underlying consensus. The high level of agreement among Delphi respondents seem to indicate that the culture definition elements included were well chosen. We would probably have seen lower scores for other more contested items. Thus, the high level of agreement could be interpreted as a sign of quality of the process, or in other words: that the literature review yielded the most relevant results. On the other hand, this interpretation depends on the assumption that other elements would have yielded lower scores. Our current research does not allow us to make any conclusions about this, but we saw some elements that were rated lower than others in both the organisational safety culture and the traffic safety culture Delphi (e.g., perception of risk, system of meaning). In any case, the results indicate that there is agreement between the research literature included and the Delphi experts.

### 4.2.3 Focus group discussions

The focus group discussions were more open and reflexive than the Delphi studies, concentrating not only the strengths and weaknesses of the definitions but also how they could be used. The focus group included both participants that can be labelled stakeholders and participants that were researchers. Thus, they were able to shed light on both academic and scientific and practical challenges related to the use of the traffic safety culture concept. Hence, they were important to test the usability of our definitions and how they could be improved. Most significantly, the focus group discussions inspired us to rework the two definitions into one common definition focused on different actors in the transport system.

## 4.3 Issues for future research

### 4.3.1 Universal definition of traffic safety culture?

Delphi study participants were also asked qualitative questions like: Is it possible to make a universal definition of traffic safety culture (or a universal traffic safety culture index) that applies across all countries, or are different elements and aspects of culture important in different countries/regions? The experts expressed mixed views regarding whether a universal definition, or index of traffic safety culture is practically feasible. While many emphasised that cultural, institutional, and social contexts vary substantially across countries, others argued that a broad, principle-based definition is possible if it allows for local variation in expression and emphasis. Similar tensions were reflected in discussions about a universal traffic safety culture index: some experts viewed it as overly simplistic, while others saw it as feasible if designed with cultural flexibility, careful translation, and adaptation. It should be mentioned that the main focus in the TRUST project is Europe.

### 4.3.2 Integrating the traffic safety culture definition with a (safe) system approach

Safe System has become the state-of-the-art approach for road safety management, and it is recommended to countries worldwide (Nævestad et al., 2025). Safe System policies need, however, to be coupled with a well-developed understanding of traffic safety culture to ensure effective implementation. While Safe System refers to the formal aspects of road safety management (e.g., formal laws and policies), traffic safety culture refers to the informal aspects, (i.e., what road users actually do). Traffic safety culture is important, as there often is a discrepancy between formal policies; strategies, rules and regulations; and what people actually do (Antonsen, 2009). Thus, a proper understanding of traffic safety culture, might address this implementation gap and provide new insights that may help improve road safety. Integrating the traffic safety culture definition with a (Safe) system approach is therefore an important issue for future research.

Specifically, future research should explore the prevailing traffic safety culture within the different pillars of the Safe System (speed, road users, vehicles, infrastructure, and road safety management, post-crash care). Such application may help clarify how shared values, beliefs, attitudes, norms and everyday practices of the people within their function and decision-making in organisations and authorities can either support, or contest Safe System principles and outcomes. Integrating the traffic safety culture definition with a Safe System approach also means examining how elements, such as shared values, beliefs, attitudes, norms, and patterns of behaviour, shape the functioning of each component of the road transport system and vice versa. For example, even well-designed infrastructure, advanced vehicle safety technologies, and strong regulations may fail to deliver their intended safety benefits if road users' (informal) attitudes or norms encourage risk-taking or rule violations. The history of road safety research is full of examples of how people adapt to road safety measures in manners that were unexpected and sometimes counterproductive for traffic safety. A system-based integration of traffic safety culture therefore highlights how safety outcomes emerge from the interaction between formal system design and informal cultural practices, and it underscores the need for interventions that address both simultaneously rather than in isolation.

The proposed definition of traffic safety culture therefore aligns closely with the Safe System approach, which emphasises that safety is a collective outcome of interactions between road users, infrastructure, vehicles, and governing institutions. In this perspective, traffic safety culture reflects how different actors understand and enact their shared responsibility for safety, as expressed through their values, norms, and practices. By incorporating elements such as shared beliefs about responsibility, expectations regarding behaviour, and organisational and institutional practices, the definition captures the cultural dimension of how the Safe System is interpreted and implemented in practice. Thus, traffic safety culture can be seen as a complementary component of the Safe System, shaping how its principles are understood, prioritised, and translated into everyday actions across the transport system. At the same time, this perspective also highlights that prevailing cultural patterns may not always align with Safe System principles, pointing to potential gaps between formal policy frameworks and everyday practices.

### 4.3.3 Applying the traffic safety culture concept to authorities and stakeholders

A recent scoping review of the research literature on Vision Zero, Safe System and Sustainable Safety identified 129 studies reported in scientific journals (Nævestad et al., 2025). A total of 70 studies were identified as case studies of the (level of) implementation of Vision Zero, Safe System or Sustainable Safety in a country, city, municipality, region or entity at some level. These studies generally report that entities that have formally implemented the Safe System have relatively low levels of implementation, due to implementation barriers and operationalization challenges. The studies find that it is not necessarily clearly defined what Vision Zero/Safe System is in practice, and that the concept must be interpreted and translated by those who will implement it. Thus, current road safety policies do not fully realise the potential improvements that Safe System can provide, because the principles are not followed to a sufficient extent (Nævestad et al., 2025). A Norwegian study estimated that the number of road fatalities in Norway can be reduced by 50–70% by following the Safe System principles (Elvik, 2023). Thus, a major challenge, also in mature Safe System contexts, is to facilitate actual Safe System implementation, by mapping barriers/facilitators and Safe System readiness, and defining actions to realise the full potential of Safe System implementation.

Defining Safe System readiness in this context largely concerns measuring the organisational safety culture among people in implementing authorities and other road safety stakeholders (e.g., non-governmental organisations, transport companies, insurance companies, unions, employer organisations, etc.) (Nævestad et al., 2025). Several studies emphasise that the principles of the Safe System approach are at odds with cultural norms related to responsibility for accidents and prevention in the countries where the Safe System is being implemented. Otto et al. (2022) write that developing a road safety culture and adopting the Safe System approach requires organisational change. Then it becomes important to measure Safe System readiness (e.g., changeability and willingness) (cf. Nævestad et al., 2025).

### 4.3.4 Definitions for non-academic practitioners

One of the key issues discussed in the focus groups was related to how we should talk about traffic safety culture to practitioners (e.g., road safety professionals, stakeholders). It was stressed that it is important to use the language that is already used by the practitioners

and not to focus on academic definitions which might be abstract and difficult to understand. It is very important to discern between academic definitions of traffic safety culture which needs to be scientifically coherent and consistent, and practitioner definitions which need to be intuitively understandable and actionable. This is an important area for future research and policy making.

#### 4.3.5 Traffic safety culture and the sustainable development goals

Road safety has increasingly been framed as an integral component of the Sustainable Development Goals (SDGs), particularly SDG 3.6 and SDG 11.2, and as a prerequisite for achieving broader sustainability objectives related to public health, equity, climate mitigation, and liveable cities. In this context, traffic safety culture provides a useful analytical lens for understanding how shared values, norms, and practices among actors in the transport system shape both road safety outcomes and sustainability transitions.

From a cultural perspective, safety outcomes depend not only on formal policies and infrastructure, but also on whether shared meanings and expectations support Safe System principles, such as responsibility sharing, protection of vulnerable road users, and acceptance of restrictive safety measures. Traffic safety culture thus helps explain why sustainability-oriented policies, such as promoting active mobility or reducing urban speeds, may succeed in some contexts but encounter resistance or unintended risks in others.

Conversely, sustainability strategies can also reshape traffic safety culture. When climate, mobility, and urban development policies are implemented without adequate attention to safety, new risks may emerge, whereas alignment with strong safety-related norms and leadership can reinforce both safety and sustainability goals. By focusing on meaningfully defined groups of actors within the transport system, the traffic safety culture concept enables analysis of synergies and trade-offs between road safety and the SDGs and highlights the importance of coordinated governance across policy domains.

#### 4.3.6 Further validation and development of the definition

In the following, we will describe required steps in future testing, refinement, and contextualisation of our traffic safety culture definition, which will be necessary to develop a robust, operational, and widely applicable concept of traffic safety culture. These steps are needed to develop a definition that is useful both for research and policy.

Developing survey item indicators and measurement tools. First, future research should advance the operationalisation of the different elements in the traffic safety culture definition, by developing concrete indicators and measurement tools tailored to different contexts and user groups. This involves translating core elements (e.g., shared values, norms, attitudes, and patterns of behaviour) into measurable survey items. Ongoing work in the TRUST project includes a systematic review of commonly used measurement items to support this process. Survey-based approaches should also be complemented by qualitative methods to capture contextual nuances and underlying mechanisms.

Defining aspects of traffic safety culture. This task also involves identifying and developing aspects of traffic safety culture for private road users and authorities/ stakeholders. In the present study, we

distinguish between elements as underlying cultural constructs and aspects as their more concrete and measurable manifestations. While the organisational safety culture literature is relatively mature and includes well-established aspects that support empirical measurement and intervention, such corresponding aspects remain less developed within the traffic safety culture domain. These aspects can be identified by examining survey topics and dimensions used in existing studies, as well as by developing conceptual models that structure and relate them, similar to established approaches in organisational safety culture research. Future research should therefore focus on identifying and developing context-specific aspects of traffic safety culture for private road users, as well as for road safety authorities and other stakeholders.

Testing the predictive validity. Future studies should empirically test the predictive validity of the proposed definition of traffic safety culture. This requires collecting new data to examine the internal structure of the definition (e.g., factor structure), its reliability, and its ability to predict relevant safety outcomes such as self-reported behaviour, crash involvement, and risk perception. We are currently doing this in the TRUST project. It is also possible to use longitudinal designs to assess stability and sensitivity to change over time.

Develop a conceptual model. Third, there is a need to develop a conceptual model that specifies how the different elements in the definition of traffic safety culture relate to each other, and how they influence safety outcomes. While the present study identifies key components, future work should aim to model the relationships between cognitive, normative, and behavioural dimensions of the elements. It is also evident that the elements in the definition of traffic safety culture can be placed at different analytical levels: values are for instance more basic than attitudes, which in turn can be seen as preceding patterns of behaviour. Thus, a conceptual model may discern between different levels and mechanisms between the elements at the different levels. It is also important to develop (and test) a conceptual model of the elements' interaction with structural and contextual factors within the Safe System (e.g., Safe System policies like infrastructure elements, enforcement, education). Such a framework would enhance both theoretical clarity and practical applicability.

Application across levels of analysis Fourth, further research should examine how the definition applies across different social units and levels of analysis. Relevant units include organisations with drivers at work, as well as private road users at different levels (e.g., peer groups, local communities, and national contexts), in addition to road safety authorities and other stakeholders. This is important because traffic safety culture varies across groups and levels of analysis (Nævestad et al., 2019a). Comparative and cross-cultural studies would be especially important to examine how contextual factors (e.g., institutional settings, infrastructure, and enforcement) influence both the meaning and manifestation of traffic safety culture. Mixed-methods approaches combining surveys and qualitative methods are likely to be especially valuable in this regard.

External validity and cross-context applicability. Finally, future research should further test the external validity and cross-context applicability of the definition of traffic safety culture. Although it is grounded in international literature and expert input, the field has historically been dominated by European and US contexts, as indicated by our literature review. Applying the definition in empirical studies of underrepresented regions and diverse socio-cultural settings will be

important to assess its robustness, identify required contextual adaptations, and strengthen its global relevance. Previous research describes this as a “detective task” in the theoretically immature field of traffic safety culture research, noting that the task requires a combination of qualitative (interviews, field work) and quantitative methods.

## 5 Conclusion

In this study, we have developed a definition of traffic safety culture, based on a three-step refinement approach, combining literature reviews, Delphi studies and focus group discussions:

*Traffic safety culture encompasses shared values, beliefs, attitudes, norms, and patterns of behaviours that shape how traffic safety is understood and enacted within a meaningfully defined group of actors in the transport system. This meaningfully defined group of actors can refer to road users, organizations, authorities, or other actors within the transport system.*

The definition focuses on different actors within the transport system. Although our results indicate that the conceptual elements (values, beliefs, attitudes etc.) are relatively similar for the traffic safety cultures of different actors within the transport system, our review indicates that different cultural aspects are important for the behaviour and decisions of different groups of actors; e.g. road users at work, private road users in society, people working in road safety authorities (and stakeholder organisations).

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

## Ethics statement

The methods for data collection in the present project were approved by the Norwegian Agency for Shared Services in Education and Research (SIKT), which assists researchers with research ethics related to data gathering, data analysis, and methodological issues. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their informed consent to participate in this study.

## Author contributions

T-ON: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft. UM: Conceptualization, Methodology, Writing – original draft. HWW: Conceptualization, Formal analysis, Investigation, Writing – original draft. SK: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision,

Validation, Writing – original draft. IH: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. VM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. SF: Formal analysis, Investigation, Methodology, Writing – original draft. Formal analysis, Investigation, Methodology, Writing – original draft. MR: Formal analysis, Investigation, Methodology, Writing – original draft. MS: Formal analysis, Investigation, Methodology, Writing – original draft. DN: Formal analysis, Investigation, Methodology, Writing – original draft. GB: Formal analysis, Investigation, Methodology, Writing – original draft. AL: Formal analysis, Investigation, Methodology, Writing – original draft. HW: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. EA-B: Formal analysis, Investigation, Methodology, Writing – original draft. AE: Formal analysis, Investigation, Methodology, Writing – original draft.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with language editing and editing of paper structure and content, e.g., shortening and improving language. Specifically, the tool was used to identify grammatical errors, overly long or complex sentences and paragraphs, and sections containing repetition or excessive detail that could be condensed or cut. All outputs were critically reviewed and revised by the authors, who take full responsibility for the content of the publication.

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## Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frsc.2026.1819840/full#supplementary-material>

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