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When terminology hinders research: the colloquialisms of transitions of control in automated driving

Davide Maggi[1] · Richard Romano[1] · Oliver Carsten[1] · Joost C. F. De Winter[2]

Abstract

During the last 20 years, technological advancement and economic interests have motivated research on automated driving and its impact on drivers' behaviour, especially after transitions of control. Indeed, once the Automated Driving System (ADS) reaches its operational limits, it is forced to request human intervention. However, the fast accumulation and massive quantity of produced studies and the gaps left behind by standards have led to an imprecise and colloquial use of terms which, as technology and research interest evolve, creates confusion. The goal of this survey is to compare how different taxonomies describe transitions of control, address the current use of widely adopted terms in the field of transitions of control and explain how their use should be standardized to enhance future research. The first outcome of this analysis is a schematic representation of the correspondence among the elements of the reviewed taxonomies. Then, the definitions of "takeover" and "handover" are clarified as two parallel processes occurring in every transition of control. A second set of qualifiers, which are necessary to unequivocally define a transition of control and identify the agent requesting the transition and the agent receiving the request (ADS or the driver), is provided. The "initiator" is defined as the agent requesting the transition to take place, and the "receiver" is defined as the agent receiving that request.

Keywords Taxonomies · Transitions of control · Automation · Automated vehicles · Human factors

1 Introduction

The past 20 years have seen the introduction and the commercialization of vehicles with growing degrees of automated capabilities. The introduction of increasingly enhanced automated systems has pushed research to produce taxonomies to categorize the levels of automation (LoA), also referred to as levels or degrees of automation (DoA) (Sheridan and Verplank 1978; Flemisch et al. 2008; Carsten

✉ Davide Maggi
  tsdm@leeds.ac.uk

  Richard Romano
  R.Romano@leeds.ac.uk

  Oliver Carsten
  O.M.J.Carsten@its.leeds.ac.uk

  Joost C. F. De Winter
  j.c.f.dewinter@tudelft.nl

[1] Institute for Transport Studies, Leeds, UK

[2] Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, The Netherlands

and Nilsson 2001). In parallel efforts, the German Federal Highway Research Institute (BASt), the National Highway Traffic Safety Administration (NHTSA) and the Society of Automotive Engineers (SAE) developed classifications of driving automation (Gasser and Westhoff 2012; National Highway Traffic Safety Administration 2013; SAE 2014) to simplify the discussion and increase the comparability of like systems. The SAE classification is the most widely adopted scheme, and research studies use it frequently to concisely describe the focus of the specific study and the limits of applicability of the obtained results. In the last 6 years, SAE has revised the original classification three times (SAE 2016b, 2018, 2021) in line with the evolution of the technology and its most pressing implications.

By far, the most addressed implication of increasing DoA is the issue of transition of control authority. Transitions of control authority are made necessary by either an immature technology, which cannot handle the Dynamic Driving Task (DDT) outside its Operational Design Domain (ODD) (SAE 2014), or by system malfunction. Hence, in both planned and unplanned situations, drivers must be ready to resume control to ensure the safety that the Automated Driving

System (ADS) is unable to provide. Just as a classification was deemed necessary for DoA, classifications were developed for transitions as well. These classifications considered a transition either as a period in which the ADS changes from one DoA to another (Flemisch et al. 2008; Merat et al. 2014; Varotto et al. 2015) or as the moment when an activation/deactivation of a function of a specific DoA takes place (Pauwelussen and Feenstra 2010; Gold et al. 2013; Miller et al. 2014; Nilsson et al. 2015). The derived classifications were generalized to be able to describe transitions in both directions (from driver to the ADS and vice versa) and considering who requested the transition (either the driver or the ADS) (Martens et al. 2008; Hoeger et al. 2011; Lu et al. 2016; McCall et al. 2016). For example, Lu et al. (2016) proposed a taxonomy of transitions of control based on three dimensions:

1. Who initiates the transition?
2. Who is in control after the transition?
3. Is the transition optional or mandatory?

The proposed taxonomies failed to regulate the colloquial use of the take-over term and, similar to the reported standards, they have not been widely adopted in the research literature, which has been mainly focused on a very specific type of transition: the process in which ADS requests drivers' intervention where the drivers must resume control within a limited time. This transition was introduced first in Dambböck et al. (2012) but reached the research community with Gold et al. (2013), and is termed "take-over" or, in Lu et al. (2016), Automation Initiation—Driver in Control (AIDC) mandatory transition.

Gold et al. (2013) addressed the "take-over" as the process in which drivers take over control. Thus, "take-over time" was defined as the time between a "Take-Over-Request (TOR)" and the automatic deactivation of the ADS when its limit is reached. Since publication, this paper has been cited 671 times, according to Google Scholar (accessed on 39/03/2022). The term "take-over", however, has lost consistency over time and has, in some cases, been used with a different definition.

Another ambiguous term is complementary to take-over: handover. Within the field of transitions of control, it was defined by Miller et al. (2014) as the process in which the driver or the ADS hands back control to the other agent. During a system-initiated transition of control from automated to manual driving, the "take-over" concept would address the drivers' role while taking over control whereas the term "handover" would denote the actions/operations the ADS performs to support drivers' take-over.

Within a year from its first use, the term "take-over" was already widespread among human factors studies investigating drivers' behaviour while taking over control

(Martens and Van Den Beukel 2013; Bahram et al. 2014; Naujoks et al. 2014; Zimmermann et al. 2014; Körber and Bengler 2014; Lorenz et al. 2014; Radlmayr et al. 2014; De Winter et al. 2014; Kerschbaum et al. 2014; Miller et al. 2014) and still retained its original meaning. However, various following studies distorted its meaning: some used it as equivalent to handover and others used it to identify transitions in general or transitions in which the driver takes back control from the ADS (Politis et al. 2015; Morgan et al. 2016; Hock et al. 2016; Schroeter and Steinberger 2016; Russell et al. 2016; Van Der Heiden et al. 2017).

Nevertheless, a major takeaway from the literature is that these two terms have been broadly adopted, as opposed to previous ones, which have been hardly used. In chronological order, examples are $H \rightarrow A$ (speak "H to A") from Martens et al. (2008) and then revisited in Hoeger et al. (2011), AIDC from Lu et al. (2016), and scheduled system-initiated handover from McCall et al. (2016). Hence, one goal of this survey was to collect information and better investigate the use of "take-over" and "handover". In particular, it was investigated whether there exists a consistent use of the "take-over" and "handover" terms depending on the specific focus of the paper and whether this use could be adopted to derive a concise definition to regulate their use in the field. Second, the use of these two terms has caused the loss of an important attribute that was always clearly defined in the above classifications: the role of the agents (i.e., the driver and the ADS) involved in a transition process. Consequently, another goal of this paper was to provide a simpler and more structured way of addressing the roles of the ADS and the driver during a transition of control authority.

2 Methods

Starting from papers published in 2013, more than 300 papers were reviewed. The search was conducted on Google Scholar. Used keywords were "take-over", "takeover", "take over", "handover", "hand over" and "hand-over". Only English written papers in the field of automated driving and transition of control were considered. For each paper, title, authors, affiliation, adopted terms and their use and referenced paper for these terms (i.e., which previous paper was cited as a reference for the adopted terms) were entered in a spreadsheet. 73 papers were selected as the root of the highlighted inconsistencies. 58% of the selected papers were published between 2013 and 2016 and the remaining 42% were published between 2017 and 2021. The recent papers that were not included were citing previous papers and adopting the same terms, thus they have inherited the same inconsistencies.

The use of the above terms will be discussed in light of the given definition and use found in taxonomies, standards, and relevant technical reports.

2.1 Taxonomies

The structured analysis of a transition process reached the attention of the research community with Gold et al. (2013). In this manuscript, the term take-over was adopted to identify the *take-over process* with which the driver takes over control from the ADS after receiving a TOR (see Fig. 1). Within the same study, *TOR-time* or *Take-over time* was defined as the advance warning time, i.e., the time between TOR and critical event. Drivers' intervention, as the sum of performed actions after a TOR, was addressed as *reaction procedure*. The reaction procedure may consist of gaze reaction, hands-on steering wheel, gaze fixations, steering/braking intervention and other actions drivers undertake while responding to the TOR. *Reaction time* was defined as the time between TOR and the first steering and/or braking intervention. Deactivation of the ADS happened as soon as drivers' intervention was detected and not after the system reached its limits. The *remaining action time* was defined as the time between drivers' intervention and system limits. In a more recent version, the incongruities concerning system deactivation were corrected (Gold et al. 2018). Therefore, drivers' first intervention triggers system deactivation and the remaining action time are the periods in which drivers are in manual control and need to intervene before the system limits, which correspond to a critical event.

Seppelt and Victor (2016) expanded Gold et al.'s (2013) take-over process by also considering the control

stabilization time, namely the period after the ADS has switched off and in which drivers could experience a degraded control.

The Human Factors Definitions for Automated Driving and Related Research Topics (SAE 2016a) do not link the term "take-over" to any specific transition. Thus, *take-over response* is defined to address a *"...specific, measurable action taken by the human user or the system to partially or fully resume the DDT"* (SAE 2016a, p. 17). Within the transition of control sequence from automated to manual driving (see Fig. 2), the *take-over time* refers to the time interval between the TORs, here addressed to as *Request to Intervene (RtI)*, and the deactivation of the ADS (request phase), which coincides with drivers' take-over response. As in Gold et al. (2013), the take-over response coincides with the drivers grabbing the steering wheel or placing their feet on the pedals. Similarly to Gold et al. (2013), gaze reaction is not considered under the definition of measurable action. The transfer phase stands between the ADS deactivation and the initiation of the take-over response (i.e., hands-on wheel and/or feet on pedals) and is also referred to as *"the period of time when the transfer switches from one entity to the other (automation to user, or, user to automation) i.e., the moment of handover."* (SAE 2016a, p. 15). The achievement of a stable DDT performance marks the end of the take-over response ("receipt and recovery" phase).

Wintersberger et al. (2017) provided a different taxonomy. *Handover* was used instead of take-over, hence *handover reaction time* corresponded to *take-over time* and *handover signal* referred to the TOR. *Sufficient handover* was coined to address what was defined in SAE (2016a) as *take-over response initiated* and thus denotes what in Gold
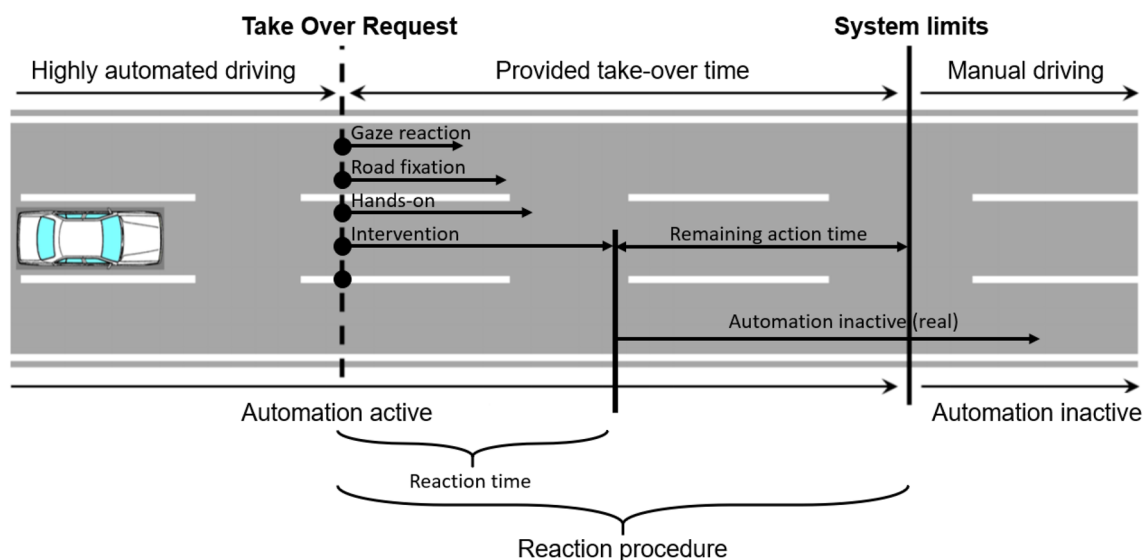
Fig. 1 Schematic illustration of the sequence of a take-over process, adapted from Gold et al. (2013) and corrected based on Gold et al. (2018) to better define "Automation inactive (real)"

Transfer of Control Sequence
AD to Manual control
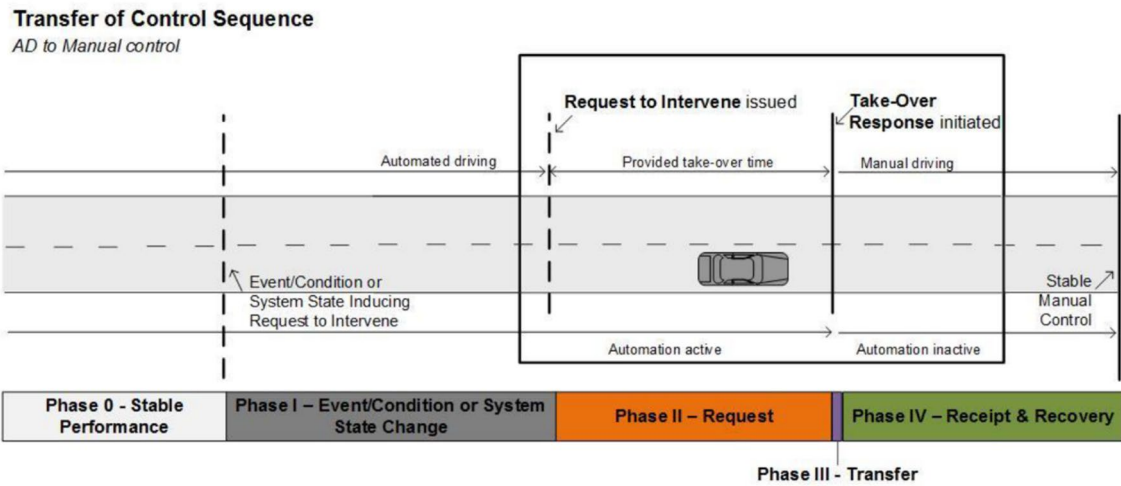
Fig. 2 Schematic illustration of the sequence of a take-over process, taken from SAE (2016a). SAE adapted this figure from Seppelt and Victor (2016)

et al. (2013) was the first measurable steering and/or braking intervention. *Complete handover* identified the end of the receipt and recovery phase. *Handback* was coined to address the drivers handing back control to the ADS as a substitute of what was more precisely defined as *"Transfer of DDT function sequence from manual control to automated driving"* (SAE 2016a, p. 13).

In the most recent version of the ISO standards, "Road vehicles - Human performance and state in the context of automated driving" (BSI 2020), a more detailed discussion of what was called *take-over process* in Gold et al. (2013) is provided. As in SAE (2016a), the standard keeps a distinction between driver/system initiated transition and its direction. Considering the take-over process, here addressed as *system initiated transition from automated to manual driving* (see Fig. 3), the TOR is here named RtI, following SAE guidance (SAE 2016a, 2018). *Take-over mode* refers to the ADS behaviour after the TOR, thus to the actions the
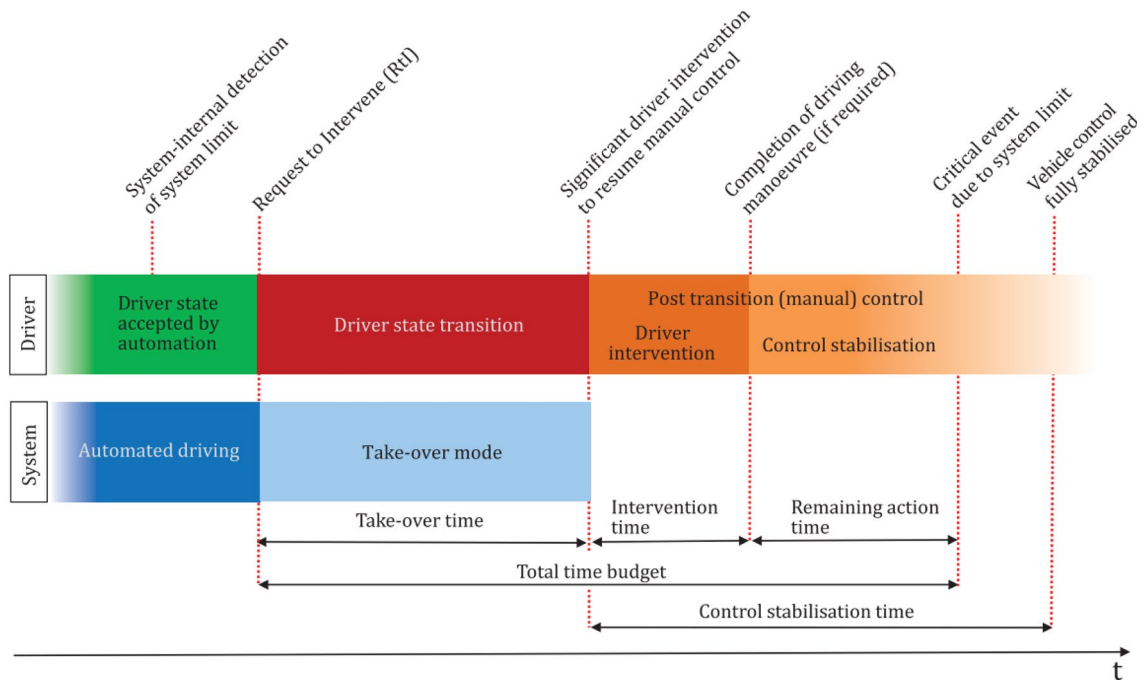
Fig. 3 Schematic illustration of the sequence of a take-over process. Image taken from BSI (2020)

ADS performs, which include, for example, minimal risks manoeuvres. *Driver state transition* is used to identify the *"process of transforming the actual driver state to a target driver state suitable to effectively take-over manual control"* (BSI 2020, p. 7) and indicates the sum of actions drivers undertake as a response to the TOR. Hence, it covers the elements of the reaction procedure described in Gold et al. (2013) before a braking/steering intervention. As in Gold et al. (2018), the TOR-time is here addressed as *total time budget* and the *take-over time* identifies what was defined as reaction time. The *intervention time* refers to the time interval required by drivers to handle the specific situation by performing an appropriate driving manoeuvre. Intervention time plus take-over time identifies the *driving recovery time*. The *remaining action time* represents the difference between the total time budget and the driving recovery time. Here, *system deactivation time* is defined as the time between the TOR and the full deactivation of automation functions (see Fig. 3).

All these documents attempt to provide a common ground for future discussion, but the use of different terminology makes it harder to follow one guidance over the other. In the following, a critical discussion of the main differences between these taxonomies will be provided alongside their respective adoption within the reviewed papers.

3 A structured critique of the existing taxonomies

3.1 The introduction of a structured analysis of a take-over process

In Gold et al. (2013), the ADS deactivates before reaching the system limits, in particular as soon as a drivers' intervention is detected. Therefore, the *remaining action time* defines the difference between the provided take-over time (i.e., *time budget*) and the *reaction time*. However, the *reaction procedure* is enclosed between the TOR and the end of the provided take-over time. The SAE report (SAE 2016a) partially addresses this ambiguity, namely the fact that the term "reaction" has two different meanings in *reaction time* and in *reaction procedure*. In the first, it indicates the first driver intervention (i.e., steering and/or braking) whereas, in the second, it defines the action drivers undergone from the TOR onwards. In Gold et al. (2013), Seppelt and Victor (2016) and SAE (2016a), the overall driver response starts when a driver places the hands on the steering wheel or feet on the pedals (*take-over response initiated*) and, as Seppelt and Victor (2016), does not end until a stable manual control is achieved. Although system limits are not presented in Figure 2, the published taxonomy (SAE 2016b) placed system limits as in Gold et al. (2018), thus after the *take-over*

response initiated. Between the *request* and the *receipt and recovery* phases stands a phase not considered in Gold et al. (2013): the *transfer* phase or the moment of handover. Within SAE (2016a), the transfer begins with the start of the release of automated control (e.g., TOR) until the *take-over response*. This contradicts a definition of transfer provided earlier in the same document, which states that the transfer of DDT function sequence represents *"the period of time from when a transfer is initiated, either by the human user or the system, to when stable performance is (re-)established"* (SAE 2016a, p. 13). Standing between the *automation active* and *automation inactive* states, the transfer SAE (2016a) considered consists of an immediate automation deactivation, as in Gold et al. (2013). The transfer sequence is consistently used in SAE (2016a) when describing the transfer phase during transitions from manual to automated driving, in which the transfer ends once the ADS has achieved stable DDT performance. This again leaves ambiguities, as SAE (2016a) does not mention ADS limits (i.e., end of ODD). Is the transfer supposed to happen before the system limits or must the manual stable DDT be achieved before system limits during transitions from automated to manual driving? How can a *transfer* release longitudinal and lateral control to the drivers if it ends as soon as drivers place their hands on the steering wheel or feet on pedals?

The common ground between Gold et al. (2013), Seppelt and Victor (2016) and SAE (2016a) is the use of the term "take-over" to address the driver-centred aspect of the transition. SAE (2016a), with the description of the transfer phase, introduced also the term "handover", referred to the ADS or the driver releasing part of the DDT to the other agent. Nevertheless, it is imperative to acknowledge the importance that Gold et al. (2013) and Seppelt and Victor (2016) had in shaping the structured analysis of a transition of control.

3.2 Handover and handback in Wintersberger et al. (2017) taxonomy

Wintersberger et al. (2017) undoubtedly addressed some of the ambiguities found in the SAE report. The end of the transfer phase, as it was used to describe the automation to manual transition in SAE (2016a), was termed *sufficient handover*, referring to the fact that the driver is ready (hands-on-wheel) and fit to intervene. The *full handover* ends as the *receipt and recovery* does, thus as soon as a stable manual control is reached. The sum of sufficient and full handover constitutes a handover. This revised taxonomy adopted "handover" to describe what in Gold et al. (2013) was termed as *reaction procedure* and in SAE (2016a) as *take-over response*. The *control transition function* happening in the *transfer* phase overlap with the previous definitions of handover. In fact, previous works had already defined handover from automated to manual

driving as a process starting as soon as a TOR (or RtI) is issued (Miller et al. 2014; Walch et al. 2015; McCall et al. 2016).

Wintersberger et al. (2017) underlined the inconsistency of the transfer phase as defined in SAE (2016a) and the need for a deeper investigation of control transition functions. However, this paper could have followed previous definitions and integrated them into the SAE (2016a) taxonomy. Thus, during transitions from automated to manual driving, a handover defines the ADS actions (i.e. the *control transition function*) to hand back control to the drivers (ADS perspective). During transitions from manual to automated driving, a handover defines the drivers actions to hand back control to the ADS (drivers' perspective). Wintersberger et al. (2017), although using different terms, provided a clear correspondence between the provided taxonomy and SAE (2016a) taxonomy.

3.3 The ISO standard: does it bring any clarity?

Being the last published taxonomy, the ISO standard was supposed to connect the previous taxonomies more clearly, also accounting for their common use within the papers on the topic. However, this is not the case yet. The standard introduced a better picture of what a transition of control entails. It considered the transition as a period in which the ADS and the driver undergo different but complementary parallel processes.

There exist several re-defined terms, from the very beginning of the transition process (see Fig. 5). RtI is used as in SAE (2016a) to address the TOR. The "driver state transition" could be considered as part of the *reaction procedure*. However, in the ISO standard, it seems that the system deactivation takes place as soon a noticeable driver intervention is detected, hence is not representing all the actions drivers undertake to respond to a TOR, but only those up until their first intervention. Hence, a "sufficient handover" or initiation of the *take-over response*, can be assumed within the *driver state transition*, before a significant driver intervention. This is because a significant driver intervention is defined as a clear request to deactivate the ADS, either using a button press or steering/braking above a threshold as opposed to the hands-on-wheel and/or feet-on-pedals events. After the RtI, in parallel with the driver state transition, the ADS switches to a *take-over mode* (BSI 2020). The choice of words seems strange and creates confusion when compared to *Take-over time* for example. The latter is explicitly defined as a human-centred term and identifies drivers' intervention time (or reaction time) but the second refers exclusively to the ADS state. This stage could represent part of the *control transition function* and surely falls within the *request* and *transfer* phases of the SAE taxonomy.

3.4 What does all this leave us with?

Based on this overview, to date, there is not a clear definition or a standardized use of "take-over" and "handover", since the standards themselves have failed to use them consistently. Gold et al. (2013) made clear that the term "take-over" always refers to the operation that drivers perform to take over the DDT. SAE (2016a) achieved the greatest consistency as it avoided linking the term to any specific transition but only to the operation that the agent, who is taking over the DDT, is performing. In Wintersberger et al. (2017) and BSI (2020), the distinction was not as clear.

Both the ISO standard and SAE reports reject the use of the term "take-over" (or "takeover") to address the whole transition process. On the contrary, in literature, it has been found that the term "take-over" has been used to identify the whole transition requiring a TOR (Gonçalves et al. 2015; Schwalk et al. 2015; Bahram et al. 2015; Melcher et al. 2015; Zeeb et al. 2016; Van Den Beukel et al. 2016; Wright et al. 2016; Körber et al. 2016; Petermeijer et al. 2017; Louw and Merat 2017; Bazilinskyy and De Winter 2017; Borojeni et al. 2017b; Forster et al. 2017; Zeeb et al. 2017; Louw et al. 2017; Madigan et al. 2018; Van Dintel 2019; Zhang et al. 2019; Clark et al. 2019; Kraus et al. 2020), as inherited from Gold et al. (2013).

The "handover" term has been used more consistently, but it is still little used in comparison to its complementary "take-over". A number of papers have been using "handover" to define the ADS operation within a system-initiated transition from automated to manual driving (Walch et al. 2015; McCall et al. 2016; Clark et al. 2016; Hock et al. 2016; Johns t al. 2018; McCall et al. 2018; Naujoks et al. 2018; Mole et al. 2019). Nevertheless, even "handover" is not free from misuse and has been used as a synonym to "take-over" (Politis et al. 2015; Russell et al. 2016; Van Der Heiden et al. 2017; Schartmüller et al. 2018; Bronson et al. 2019; Chen et al. 2019; Drexler et al. 2019; Frison et al. 2019; White et al. 2019; Larsson et al. 2019), or to identify the transition from manual to automated driving (Miller et al. 2014; Borojeni et al. 2017a). Eventually, some of the reviewed papers used "handover" as, broadly speaking, the process of handing something to someone and specified the context of application to clarify their use (Miller et al. 2014; Kondo et al. 2019).

Discussion of new research interests, such as transitions from manual to automated driving, driver assistance systems during transitions of control and user-initiated transitions, might be heavily affected by the current use of the "handover" and "take-over" terms. Indeed, the lack of differentiation between these terms and the adoption of the second to address the whole transition process would make the discussion hard to follow. For example, if we consider the ISO standard, one could write that during the take-over

mode, drivers' take-over time was on average 10 s. This would make it hard to understand what the term "take-over" is referring to.

Within the reviewed papers, no one adopted the described taxonomies and all have opted for the free use of one of the two terms, namely "handover" or "take-over". The vast majority of the reviewed documents adopted the latter to effectively drive the focus of the discussion to drivers' behaviour as the ADS role was that of providing a RtI (or TOR) as in Gold et al. (2013). On the other hand, "handover" has been adopted when the focus during the same transition was shifted from the driver to the ADS, and the way it handed over the DDT to the driver as in Walch et al. (2015), which accounts for 143 citations, according to Google Scholar.

4 Conclusion

There exist correspondences among the presented taxonomies, and their graphical representation has been provided in Fig. 5. The highlighted correspondences (see Figs. 4 and 5)are proposed to be helpful to researchers and ensure comparability. The basic control sequence during a system initiated transition of control from automated to manual driving starts with a RtI (i.e., TOR). The ADS waits for the drivers to react to the RtI, allowing a predefined time budget (i.e. *take-over time* or *provided take-over time*). Once the ADS measures a significant driver intervention

(i.e., *take-over response initiated* or *sufficient handover*), the ADS switches off, and the drivers are in manual driving. Once in manual driving, drivers have a limited amount of time to handle the event (not necessarily critical but rather the edge of an ODD), which defines system limits. Once the borderline event has been handled, the transition will be considered finished when drivers manage to stabilize the vehicle trajectory (i.e., *manual stable control* or *full handover*). Taking a step back from the control sequence, and analysing how transitions of control are classified, the evidence here reported is that there are still several authors who use "take-over" and "handover" with no consistency and sometimes as synonyms. This is a result of inconsistent taxonomies that have either been misused or have not been accepted by the research community, which prefers a more colloquial terminology. However, these colloquial terms must be somehow clarified and their use standardized. According to their current and most recognized use, a possible clear distinction would see them as parallel processes. Indeed, during a transition, ADS and the driver will exchange partial or full control of the DDT; one will hand over something and the other one will take it over. Thus:

Definition 1. Take-over is the process with which one agent takes back control of part or all of the DDT;
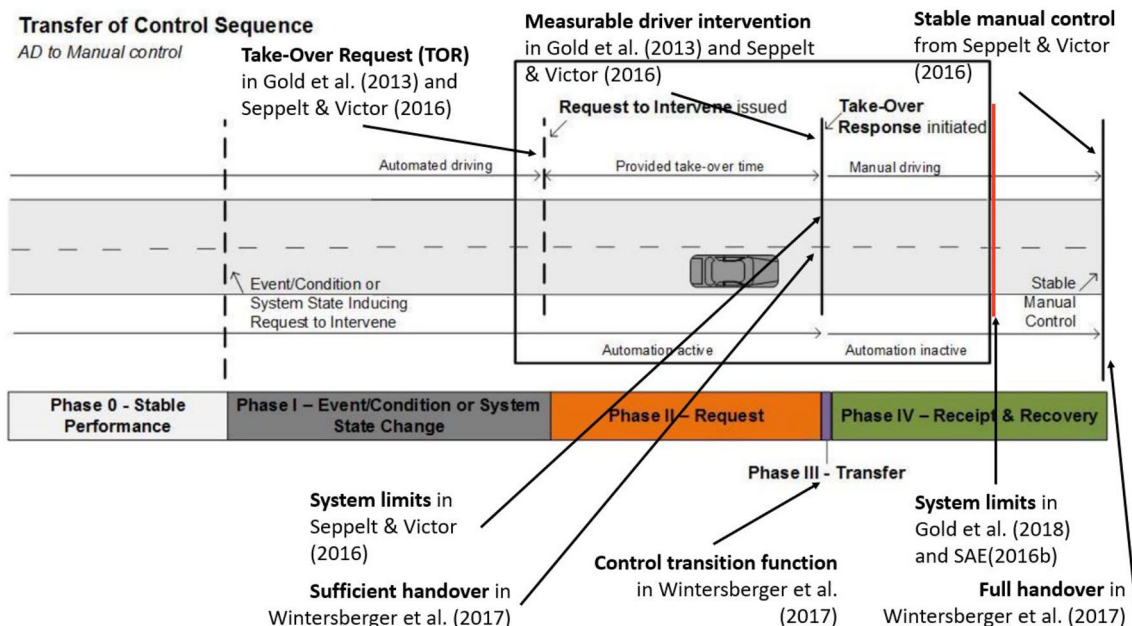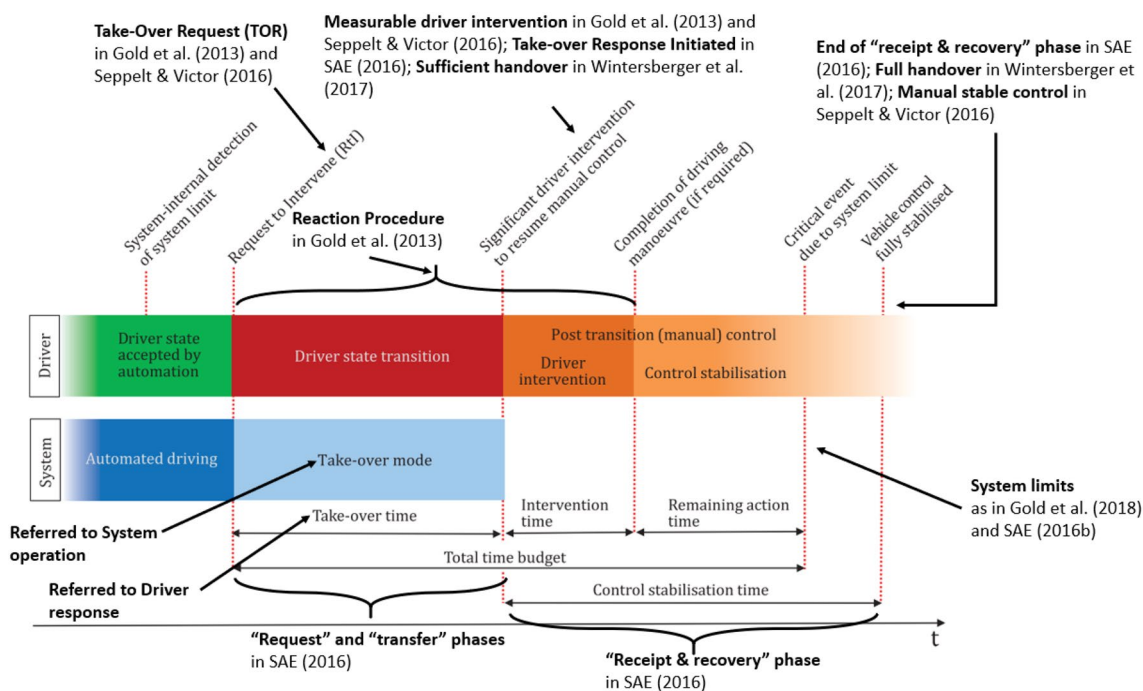

Fig. 4 Transfer of DDT function sequence from automated to manual driving (system-initiated). Highlights of discrepancies among Gold et al. (2013, 2018), Seppelt and Victor (2016), SAE (2016a) and Wintersberger et al. (2017). This figure is adapted from SAE (2016a)

Fig. 5 Correspondence among Gold et al. (2013, 2018), Seppelt and Victor (2016), SAE (2016a), Wintersberger et al. (2017) and BSI (2020). Transfer of DDT function sequence from automated to manual driving (system- initiated). This figure is adapted from BSI (2020)

Definition 2. Handover   is the parallel process with which one agent relinquishes part or all of the DDT.

These definitions cannot be adopted to unequivocally define a transition as they fail to specify who is requesting a transition and who is called to provide some sort of handover. If one imagines a transition as a mediation process, there is always an agent requesting something and an agent this request is addressed to. Hence, there exists the necessity to define who is who. As Lu and De Winter (2015) already specified, the requester is the agent initiating the transition, hence a fitting term to identify this agent within a transition of control is "Initiator". Identifying who is requesting the transition defines also the agent that should be listening to that request. A fitting term would be "Receiver". The Receiver would also be responsible for providing a handover or preparing for a take-over, but this does not imply that the receiver is also supposed to accommodate the request received from the Initiator. With smarter ADS and the increasing adoption of Drivers Monitoring Systems (DMS), when the driver is the Initiator, the ADS might decide whether to fulfill the initiator's request or not. Similarly, drivers might decide not to respond to a RtI and the ADS will be forced to a minimal-risk manoeuvre. The direction of the transitions, either from automation to manual or vice versa, determines who between the Initiator and the Receiver is called to take over or to provide a handover. For

example, in a system-initiated transition from automated to manual driving, the ADS is the Initiator and the one providing the handover, the driver would be the Receiver and the one taking over. The benefit of using these 4 terms as proposed in this manuscript is twofold. On one side, they allow a clear distinction of the agents involved in the transition process and they unambiguously define the role of each agent. On the other side, they provide a simple way of discussing any transition of control by regulating terms that are already used and appreciated by the research community. This makes their use in the field very straightforward and the use of these 4 terms in a consistent manner would make the discussion clearer and would pave the road to a more structured research literature, which would otherwise require the introduction of more terms in an already dense glossary.

5 Further consideration and future challenges

Although this article revolves around the challenges that colloquialism introduced and tried to provide clear and simple definitions to address the transition processes, there is a pragmatic component that would affect the analysis of the transition process nevertheless: the way the start and end of these processes are defined and measured. This issue was already introduced by Liu and Green (2017), albeit only in forward collision warning. During transitions

of control, although longer time-budget allows for a higher situational awareness (Körber et al. 2016; Gold et al. 2016; Clark and Feng 2017; Hadi et al. 2020), Zeeb et al. (2016) argued that drivers' response times are not representative of the quality of the take-over process.

Nevertheless, following the above definitions, depending on the adopted instrumentation and metric, the start and end of both take-over and handover processes are defined. This means that, for example, during a system-initiated transition, the handover is heavily influenced by what is considered as the Receiver's (i.e., the driver's) intervention. The majority of the reviewed studies adopt a physical interaction with the interfaces, namely a steering or braking action exceeding a predefined threshold (Gold et al. 2013; Radlmayr et al. 2014; Gold et al. 2015; Körber et al. 2016; Feldhütter et al. 2018). Thus, the handover starts as soon as these thresholds are exceeded. However, the take-over process starts in the moment in which the Receiver has already redirected their attention towards the road and are already preparing to physically take over. If only the physical interaction is considered, the handover would be delayed compared to the take-over process and the quality of the transitions (e.g. performance, stabilization time, comfort, workload, etc.) might be negatively affected, especially in challenging situations (Radlmayr et al. 2014; Gold et al. 2016; Dogan et al. 2021). In fact, a handover encompasses any action that an agent performs to ease the transfer of control, which could also be, perhaps, the activation of head-up notifications to redirect drivers' focus. Similarly, the definition of control stabilization time or "receipt and recovery phase" determines how long a handover would last. From the above examples, it is clear that the start and end of any transitions, and the related take-over and handover processes, exclusively rely on the metrics one chooses to measure (e.g., steering or braking actions above a threshold, gaze fixations, contact with the interface, etc.). What threshold to choose? Of what measure? What are the situations of applicability for each measure? How does one measure "control stabilization"? These are only some of the challenges research should tackle in the future.

Declarations

Conflict of interest The authors declare no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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