Control Transition Interfaces in Semiautonomous Vehicles: A Categorization Framework and Literature Analysis

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ABSTRACT

Designing safe and effective systems for control transitions between human and vehicle is a difficult task, due to increased reaction times and potentially inattentive drivers. In order to respond to these difficulties, this paper presents an overview of interaction solutions for control transitions between manual and autonomous driving modes. The paper examines technology patents, as well as academic publications. The paper's first contribution is an examination of the current state of the art of control transition interfaces in automated vehicles. The paper's second contribution is the reusable categorization framework developed for this overview. The results are used to identify holes and potentials regarding control transition design, including strong focus on the system over the human, lacking fallback performance, and the potentials of effective driving mode communication. These aspects point the way towards the challenges to be solved – together with how they might be solved – for safe and effective control transitions.

CCS Concepts

•Human-centered computing → HCI theory, concepts and models; Interactive systems and tools;

Author Keywords

Automated vehicles; control transitions; handover; takeover; categorization; overview.

INTRODUCTION

The advancement of semi- and fully autonomous vehicles is well on its way. Most leading car manufacturers have made promises of introducing automation to the market in some shape or form, some even as early as 2021 [6], so the overall question regarding automation in vehicles seems to have transformed from an “if” to a “when” a long time ago already.

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AutomotiveUI '17 September 24–27, 2017, Oldenburg, Germany

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ACM ISBN 978-1-4503-5150-8/17/09.

DOI: <https://doi.org/10.1145/3122986.3123014>

Vehicle automation is not a binary affair and there are several levels of increasing automation, from level 0 (no automation) up to level 5 (full automation with no driving related tasks to be performed by a human), according to the widely accepted SAE Standard for Driving Automation Systems [52]. SAE level 3 occupies an interesting position within the spectrum of autonomy levels, as it is the level at which the vehicle can complete all aspects of an autonomous driving task, including monitoring the environment, but still requires intervention capabilities for a human driver within a reasonable time frame. It seems that the requirements associated with a technology that requires such a demand of flexibility, have proven to be too much for some, as making such transitions safe is hardly an easy task. As a consequence, both Ford and Google have expressed to aim for full automation (i.e., skip level 3 entirely) and omit the potentially troublesome human factor from the automotive equation [68].

It is unlikely, however, whether automation level 3 can be wished away like that, as this would entail excluding a good part of the transition phase from fully manual to fully autonomous traffic as well. The wish is well-motivated of course, as it is the human factor and its proneness to errors that causes most on-road accidents. On the other hand, it has been shown that a higher level of interactivity of an automated system increases acceptance to use such a system [51], so safe automated driving technology will likely not be very effective without a corresponding willingness to use it. In addition, system failures occur even in well-behaved and safe environments, and it is not clear why vehicle automation should be excluded as the one failsafe technology that defies the rule. Current legislation is also still at a point where a driver is required to be able to take over and intervene at any time. Vehicle automation is likely going to involve human intervention in some way for at least a few more years. Much of it will be delegated but some of it will have to be cooperative in some way [12].

From a scientific point of view, the difficulty of designing effective control transitions is a challenge first and foremost and one that should be worth solving. It should not matter exactly how many years the transition from manual to fully autonomous driving takes. What matters is that it will not happen overnight and that both engineering and research can

contribute to both an accelerated and safer transition time with a combined effort. Since the automotive domain, especially regarding automation technology, is rapidly changing constantly, this alignment can be difficult. Thus, it is important to provide ways to categorize and summarize the state of the art of in-vehicle automation interface technology. This allows to keep pace with the rapid developments, identify trends and challenges for future development efforts.

In 2016, Pflöging et al. [47] conducted a survey in which they gathered user-requirements for non-driving related activities in automated vehicles, including preferred in- and output devices. Gold et al. [21] conducted a study to investigate the effects of transition duration on reaction time. Debernard et al. [13] created a high-level cognitive work analysis of human-machine interface design for automated vehicles. Bengler et al. [5] provided a review of driver assistance systems, together with future perspectives and opportunities. Their suggestions and identified opportunities mostly concerned traffic in general and infrastructure and less individual human-machine interactions.

In this paper, we want to supplement the existing body of literature by focusing on this interaction aspect during transitions in particular. Thus, we look at and categorize transition designs from the engineering domain, as well as from academic simulator or study setup implementations. The intended end result is not a comparison of relative implementation performance, but a summary of opportunities, possible misalignments, or design spaces that have not received enough attention by one domain or both. This should help to (a) provide a common overview of the current state of the art regarding existing concepts and implementations, and (b) provide a perspective for the way forward and the challenges that still need to be solved to improve control transitions in autonomous vehicles.

LEVELS OF VEHICLE AUTOMATION

The most commonly used categorizations of automation levels in vehicles are those by the German Federal Highway Research Institute (*Bundesanstalt für Straßenwesen* – BAST) [4], the National Highway Traffic Safety Administration (NHTSA) [1], and SAE International (Society of Automotive Engineers) [52]. All of these describe automation as incremental with an increasing number of tasks being performed by the system the higher the automation level is. As of September 2016, the NHTSA has adopted the SAE levels of automation in their official Federal Automated Vehicles Policy [2]. Due to their widespread use and clear distinction between the different levels, we will also use the SAE levels of automation in this paper.

The SAE standard defines six levels of automation in vehicles, from level 0 (no automation) to level 5 (full automation). Levels 2 to 4 encompass what is usually referred to as “semi-autonomous driving”, i.e. driving that is neither fully manual nor fully autonomous. On level 2, several driving functions are handled by the vehicle, while monitoring of the driving environment and fallback performance are left to the driver. At level 3, this changes to the driving environment being monitored by the system, which, at least in theory, is the starting point to enabling the driver to engage in non-driving tasks primarily while driving. Level 4 delegates the entirety of a

certain driving task, including fallback performance, to the autonomous system. Level 4 can be difficult to distinguish from level 5 in some cases but is mostly used to refer to last mile solutions or other autonomous vehicles operating in closed environments. Level 5 is most easily understood as full automation in virtually every possible driving situation with no driver input required beyond the most basic navigational information (i.e., the desired target destination).

TYPES OF CONTROL TRANSITIONS – DEFINITIONS

Transition of control in a vehicle can occur in two **directions**: either from driver to the autonomous system or from the autonomous system to driver. Such control transfers are also referred to as *handovers* and *takeovers*. A handover occurs when control is transferred from the human to the system, whereas a takeover occurs when control is transferred from the system to the human. In Gold et al. [21], requests by the system for the driver to take over control are called “Take over requests” or “TORs”. To accommodate this established terminology, in this paper “takeover” will only reference control transitions from system to driver and vice-versa for the term “handover”.

Another distinction that can be made, dependent on the interface and system capabilities, regards the **initiation** of a transition. A transition can be initiated by either the driver or the system, resulting in either *driver-initiated* or *system-initiated* transitions [35]. This distinction is important as it has a direct impact on the design of hand- and takeovers. When the driver initiates the transition, he/she is presumably already in the right mindset to do so, whereas when the system induces the transition the driver might need some time to be prepared.

Furthermore, we distinguish three additional types of transitions in this paper regarding driver **involvement**. These describe the role of the driver in the control transitions. We introduced this additional distinction to further differentiate systems that allow the driver to confirm or deny transitions from those which do not, which is not covered by the distinction between driver- and system-initiation alone.

- *Active* transitions occur when the driver can initiate a transition directly, be it via pressing a button, turning the steering wheel or actuating the pedals while in autonomous mode, or via other direct means of input. Active transitions can be both handovers and takeovers, and are always driver-initiated.
- *Semiactive* transitions occur when the driver, while not initiating a transition directly, can confirm or deny a control transition via direct input. Semiactive transitions are always system-initiated takeovers.
- *Passive* transitions occur when there is no input foreseen to either initiate or confirm a control transition. The transition might or might not be explicitly signaled to the driver. Passive transitions are system-initiated, but can have an active component to them via their initial activation. (e.g., Electronic stability control (ESC) is applied by the system when a loss of traction is detected but the car's ESC functionality

can usually be activated or deactivated by the driver via direct input). Just like the other two types, passive transitions can be both handovers and takeovers.

Categorization Framework

We developed our framework for categorization based on the preceding definitions and prior work on automation classification (e.g., [35], [47], [5]), as well as common aspects of interface design (input and output modes, locations, etc.). In total, we defined the following categories:

- **Direction** refers to whether the transition is from system to driver, driver to system, or both. Possible values are **Takeover (T)**, **Handover (H)**, or both.
- **Initiation** refers to who can initiate a transition. Possible values are **User (U)**, **System (S)**, or both.
- **Involvement** refers to the respective definition described previously. Possible values are **Active (A)**, **Semiactive (SA)**, **Passive (P)**, and any combination of these.
- **Completeness** refers to whether some or all driving functions are transferred. Possible values are **Full (F)**, **Partial (P)**, or **Incremental (I)**. 'I' is a variant of 'P', in which driving functions are incrementally transitioned until a full transition is achieved. Transferring one, several, or all driving functions can differently impact cognitive demands, in-/output information density, and transition times.
- **Fallback** refers to system strategies in case a transition is unsuccessful. Possible values are slowing down and stopping on the vehicle's **Own lane (O)**, slowing down and stopping **outside** the vehicle's own lane (**U**), and **System (S)**. 'S' is used when the presence of a fallback mechanism is mentioned without any further specification of the mechanism's strategies or actions. Combinations of these are possible, when the publication in question describes several fallback capacities. It should be noted that the SAE standard [52] explicitly defines fallback performance on the driving task level, i.e., who is responsible for completing a driving task in case of either human or system failure. According to this definition, the fallback responsibility lies with the (human) driver at levels 2 and 3, and with the system at level 4. 'Fallback' in this framework is defined at a transition level, i.e., are there any mechanisms or behaviours in place in case the transition from one driving mode to the other fails and if so, what are they?
- **Input** refers to the input modalities available to initiate transitions or respond to transition requests. Possible values are **Physical (P)**, **Touch (T)**, **Speech (S)**, **Gestures (G)** and any combination of these. 'P' encompasses all physical interactions outside of touch displays, including turning the steering wheel, actuating pedals, pushing buttons, or flicking levers. 'T' is listed as a separate category due to separate interactions with touch displays from the more traditional modes of physical interaction. This category covers most common input methods in interaction design.
- **Output** refers to the transition-related output modalities available. Possible values are **Visual (V)**, **Haptic (H)**, **Acoustic (A)**, **Speech (S)**, or any combination of these. While 'S' is technically a subcategory of 'A', 'A' is intended to only refer to non-speech auditory signals (e.g., beeps) in order to appropriately distinguish between the differences in length, informational content, etc. of speech vs. non-speech auditory communication. This category covers most common output methods in interaction design.
- **Visual Output Position** refers to the position of visual interfaces in the vehicle, which are involved in control transitions. Visual output modalities are available in all vehicles by necessity (instrument cluster gauges, etc.) and limited to certain areas (mostly for legal reasons). Thus, possible values are **Dashboard (D)**, **Console (C)**, **Heads-Up Display (H)**, **Windshield (W)**, or any combination of these. 'W' refers to either full windshield displays or output anywhere in the area of the windshield but outside of where a HUD or dashboard would be (in order to also cover nonstandard implementations).
- **Haptic Output Position** refers to where transition relevant haptic output is located in the vehicle. Possible values are **Steering wheel (S)**, **seat (T)**, **Pedals (P)**, **Wristband (W)**, or any combination of these.
- **Temporal Output Mode** refers to whether transition-related output occurs once or several times per one single transitions. Possible values are **Once (O)**, **Several (S)**, or **Incremental (I)**. 'I' is a special case of 'S', where a certain output is increasing or decreasing incrementally to signal a transition.
- **Mode Awareness** is the presence and modality of output to inform the driver of the system state (whether it is in manual or autonomous mode). This is separate from 'Output' (visual or otherwise) since it is not directly connected to a transition (although it can be, e.g., in case of emergency takeovers due to system failure, when said failure is communicated via a mode awareness interface). Possible values are **Symbol (S)**, **Color (C)**, **Text (T)**, **Audio (A)**, **Other (O)**, and any combination of these. 'C' comprises both color coding and light-based interaction, since both are closely related in the vehicle context (in-vehicle displays are often illuminated and light displays often allow color variations for different communication contents).

These categories are intended to cover (a) the agency and involvement of the driver in the transition process, (b) the possibilities of the driver to provide transition-relevant input to the system, (c) the capabilities of the system to provide transition-relevant output to the driver, and (d) whether individual or several driving functions are transferred, all of which we consider essential for distinguishing attributes of transition implementations

To illustrate these categories, we use the Tesla Model S as an example. The Tesla Autopilot features partial automation (lane keeping, distance to other vehicles) on both straight and curved roads. The Autopilot can be activated and deactivated via a *physical* switch to the left of the steering wheel. It allows *user-initiated* intervention in the form of an *active* request to switch lanes, which is a *partial transition* from *system* to *driver*

for this individual driving task. Driving *mode awareness* is communicated via a colored icon on the dashboard, emergency transition requests can additionally be communicated via *auditory* signals and *speech* messages. The vehicle is capable of both emergency braking, as well as driving to the side while slowing down, in order to avoid collisions. That way, in the case of a transition failure, deceleration and stopping both *on* and *outside* its own lane are possible.

METHOD

We focused our analysis on two areas: academic publications, and industry patents, because both contain documentation of either conceptual or implemented in-vehicle interfaces, have internal consistency by conforming to formatting standards, are publicly available, and can be referenced in a consistent manner. The academic paper analysis includes both short and full papers. Short papers have, by their nature, less room for detailed study setup descriptions, so it might be possible that they left out details that were actually implemented but were of minor importance or out of scope for the publication purpose. Since it would have seemed more arbitrary to exclude short papers *a priori*, we decided to include short papers as well, despite this potential issue.

We concentrated on only these two publication types and excluded existing vehicles and prototypes of car manufacturers from this categorization. A conscious decision was made for this exclusion. First, autonomous driving technology is changing day-by-day and it can be difficult to keep track of the exact capabilities and interaction modes of all vehicles—both production vehicles and prototypes—of even a single manufacturer. Second, there has been a very recent but notable shift towards skipping level 3 automation and focusing entirely on levels 4 and 5 instead [68], which makes the current industry state-of-the-art paradoxically a less suitable source for level 3 transition interfaces. Most importantly, information on existing vehicles with automation capabilities beyond level 4 is fragmented across official reports, press statements, press materials, news articles, and so on. This makes it very difficult to extract the level of detail necessary to condense them into an analysis framework in a reliable way.

Patents are certainly also not the perfect source where accuracy is concerned, as they do not require a fully working implementation beyond a reasonable display of eventual feasibility. Patent authors also often try to cover every eventuality to secure a market advantage for their Assignees, which can end with them being rather broad and covering several different implementation concepts. However, they do have more permanency than a conceptual prototype, which may or may not change significantly over a time span of mere months. In addition, pattern formatting and content requirements are more consistent than company statements, press materials, news articles, or demos, which is why we ultimately decided for patents to be the most suitable window into the automotive engineering domain for this analysis. The Tesla S example from the previous section illustrates that the framework *can* be successfully used to categorize existing in-vehicle interfaces, provided sufficiently detailed information about them is available, for potential future extensions.

Selection Process

For the academic publications, we conducted searches on the ACM Digital Library, ScienceDirect (Elsevier), and IEEE Xplore. We employed AND- and OR- searches of the author keywords with three keyword groups. Group one consisted of “car” and “vehicle”. Group two consisted of “self-driving”, “autonomous”, and “automated”. Group three consisted of “handover”, “hand-over”, “hand over”, “takeover”, “take-over”, “take over”, and “transition”. The terms in each keyword group are synonyms and, therefore, always connected via ‘OR’. Connections between keyword groups were always done via ‘AND’. To provide an example, the syntax for a search of groups two and three on ACM would be *keywords.author.keyword:("handover" OR "hand-over" OR "hand over" OR "takeover" OR "take-over" OR "take over" OR "transition") AND keywords.author.keyword:("self-driving" OR "autonomous" OR "automated")*. We only included publications starting with 2014, as this coincides with the first publication of both the NHTSA (late 2013) and SAE (early 2014) levels of driving automation. Due to the often lengthy iteration and publishing of patents, we extended the time frame for patent search back to 2010.

We conducted a first search of all three keyword groups and included all resulting papers in the analysis. We then conducted a second search with only groups one and two and did a manual check of each resulting paper and also included any papers that seemed relevant in the analysis. Search on ScienceDirect was further restricted to the Computer Science and Engineering topics. On ScienceDirect, we found 0 publications after the first search, even when extended to all topics. The second search yielded 469 results, which was reduced down to a total of 10 publications after the manual abstract check. From ACM, the first search returned 8 results, the second search 105, which resulted in 15 publications total after the manual abstract search. IEEE Xplore yielded 116 results after the first, and 411 results after the second search. This was reduced down to a number of 10 after the manual abstract search. The final number of academic papers from all publishers combined was 35.

The procedure for patents was similar but with a different set of keywords, due to differences search engine interfaces and capabilities. Both Depatisnet and Google Scholar were searched with the keywords “autonomous driving”, “level 2”, “level 3”, “car”, “vehicle”, “driver”, “hand over”, “transition”, and “take over”. Searches on both platforms returned several thousands of hits, even when limited to the period between 2010 and 2017. Thus, all results were ordered by relevancy and the first 100 from each source (for a total of 200 patents) were included in the analysis. After the abstract check, 28 patents remained. This number was reduced further after a thorough read of each pattern and excluding those that did not describe an actual transition mechanism or interface, which resulted in the final number of 22 patents for the categorization.

Analysis and Coding

All resulting papers were then analyzed in full with the categorization framework described in the previous section. This was done by two researchers separately, who, after the initial

Author(s)	Direction	Initiation	Involvement	Completeness	Fallback Capability	Input	Output	Visual Output Position	Haptic Output Position	Temporal Output Mode	Mode Awareness
Mok et al.[41] (AUI '14)	T, H	S	SA	F			S				
Politis et al.[49] (AUI '15)	T, H	S	SA, P	F		P	V, H, S	H	W	O	S, C
Walch et al.[66] (AUI '15)	T	S	SA	F		P	V, A, S	W		S	
Telpaz et al.[58] (AUI '15)	T, H	S	SA, P	F	N		V, A	W		S	
Reimer[50] (AUI '16)	T	U	A	P	S	P	V	D		O	
Dikmen[15] (AUI '16)	T, H	U	A	P		P, T	V				
Van der Meulen et al.[64] (AUI '16)	T	S	SA	F		P	V, A	W		S	
Borojeni et al.[8] (AUI '16)	T, H	U, S	A, SA	F	N	P	V, A	D		O	
Forster et al.[18] (AUI '16)	T	S	SA	F	O	P	V	H		I	S, C
Walch et al.[67] (AUI '16)	T	S	SA	F	O	P, S	V, A, S	C		S	T
Jung Lee et al.[34] (CHI '14)	T, H	U	A	P		T, S	V	C		O	T
Kim et al.[32] (CHI '17)	T	S	SA	P	N	P	V	H, W		S	
Mok et al.[40] (CHI '17)	T, H	U, S	A, P	F	N					O	S, C
Van der Heiden et al.[63] (CHI '17)	T	S	P	F	N	P	A, S			I	
Johns et al.[28] (HRI '16)	T	U, S	A, SA	P	S	P	V, H, S	D	S	S	
Schwalk et al.[55] (PM '15)	T, H	S	SA	F			H		T	S	
Stockert et al.[56] (AHFE '15)	T, H	U	A	F		P	V	H		I	S, C
Melcher et al.[36] (AHFE '15)	T	S	SA, P	F	O	P	V, H, A	D, O	P	S	S
Gold et al.[22] (AHFE '15)	T, H	U, S	A, SA	F		P	V, A	D	P	S	S
Albert et al.[3] (AHFE '15)	H	U	A		S	T	V	D, C, H			S, C, T
Zeeb et al.[71] (AAP '15)	T, H	S	SA	F	N	P	V, A	C		O	C
Zeeb et al.[72] (AAP '16)	T, H	U, S	A, SA, P	F	N	P	V, A	D		O	S, C, T
Petermeijer et al.[46] (AAP '17)	T, H	U, S	A, P	F		P	H		T	S	S, C
Petermeijer et al.[45] (AE '17)	T, H	U, S	A, SA	F	N	P	H, A		T	O	
Van den Beukel et al.[62] (TRF '16)	T	U, S	A, P	F	N	P	V, H, A	D, W	T	S	C
Kerschbaum et al.[29] (IV '15)	T, H	U	A	F	N	P	V, A	D		O	O
Mok et al.[38] (IV '16)	T, H	U, S	A, SA	P		P	V, A			O	S, C
Bueno et al.[9] (ITSC '16)	T	U	A, SA	F		P	V, A			O	
Langlois and Soualmi[33] (ITSC '16)	T	U	A	F	O	P	V, A	H		I	S, C, T
Miller et al.[37] (SMC '14)	T		SA	P		P	V, S	D		S	S, C
Wulf et al.[69] (ITS '15)	T, H	U	A	P		P	V, A	H			S, C
Kim et al.[31] (ITEC '16)	T	U	A	F		P, G	V, H	C	W	O	
Wada et al.[65] (SMC '16)	T	U	A	F	N	P					
Kim et al.[30] (THMS '17)	T	U, S	A, P	F		P	V, A, S	D		S	
Tijerna et al.[59] (TIV '17)	H	S	P	P	N	P	V	H		I	

Table 1. Academic Publications - Results (N=35)

analysis, then cross-checked and corrected, when necessary, each other's coding.

The categorizations were explicitly done *as reported* in the individual publications and on a per-setup-basis for the academic publications. This is intended to avoid inaccuracies based on wrong assumptions and account for different setups or implementations at the same location. For example, while publications [41] and [28] both describe the same simulator, they differ in description content and level of detail, which results in a different result for the categorization. If, on the other hand, it was evident that several different publications described the same setup and study with minor differences (e.g., [39], [42], and [40]) then only the most recent and/or most detailed one of these was included for the analysis.

Similarly, when the transition direction was not indicated, the field was left blank instead of assuming one or both. This does not automatically mean that no transition capabilities were present but that they were not indicated clearly enough in order to make an informed decision regarding the presence of either handover or takeover capabilities (or both). Depending on the focus of a certain publication (especially for patents), some details can also simply be not present due to being out of scope and are consequently also left blank in the categorization, as seen with, e.g., [14], which describes transition procedures without specifying either in- or output in any way. A similar case are fallbacks, where publications sometimes acknowledged different fallback strategies in autonomous vehicles or simulations thereof, but did not indicate whether one was in place for the concrete study setup described in the

publication (e.g., [66]). In such cases, the field for fallback strategy was also intentionally left blank.

Both academic publications and patents did not always have interfaces as their primary focus, so the level of detail often varied between publications. When no clear statement regarding the modality of an implementation could be made, that field was left blank. Last, the categorizations in the following sections all pertain *only to actual transitions*, which means that a certain setup or implementation might feature more modalities than those described below but which are only used for other purposes (infotainment, manual navigation, etc.). This is intentional in order to keep the focus on interfaces for control transitions and not in-vehicle interfaces in general.

RESULTS

In the following section, we report the results from the analysis of both academic publications and industry patents. A discussion of the results, together with resulting identified opportunities and challenges for the automotive domain, will follow in the successive sections.

Academic Publications

The academic publication seen in Table 1, had an emphasis on takeovers. Although 17 publications accounted for both transition directions, only one investigated handovers specifically. This is in contrast with a number of 16 papers, which only focused on takeovers. Initiation is similarly distributed, with most papers investigating system initiated transitions and some looking at both, but with more of an even spread between only user-initiated and only system-initiated transitions.

Author(s)	Direction	Initiation	Involvement	Completeness	Fallback Capability	Input	Output	Visual Output Position	Haptic Output Position	Temporal Output Mode	Mode Awareness
Gräf et al.[24] (BMW)	T	S					H, A		T		
Pink et al.[48] (Bosch)	T, H	U, S	A, SA	P	S	P, T, S	V			O	
Boehring et al.[7] (Daimler)		U, S	A, SA	I	S	T	V, A	D, C, H			
Debouk et al.[14] (GM)		U, S	A, SA	I	S						
Gazit[20] (GM)		U	A		S	P	V, H				
Green et al.[25] (GM)	T						V	W		O	C
Goldman-Shenhar et al.[23] (GM)	H	U	A, SA, P	P	S	P, T, S	V				
Salinger[53] (GM)	T	U	A	P		P, T	V	W		S	
Tsimhoni[60] (GM)	T	U	A	P		T	V	W		O	
Cullinane et al.[43] (Google)	H	U	SA	F		P, T	V	D, C		S	T
Szybalski et al.[57] (Google)	T, H	U	A	F		P	V	D, C		I	C
Heckmann et al.[26] (Honda)	T	S	SA	F		T, S	V, S	H		O	
Hegemann[27] (Honda)	T	S	SA	F			V, H, A			O	
Norris et al.[44] (iRobot, Deere)	T, H	U, S	A, SA, P	P	O, S	P					
Ebina (A)[16] (Nissan)	H	S		P			V	D			S
Ebina (B)[17] (Nissan)	T	S	SA				V				S, C
Funakawa[19] (Nissan)	T	S	SA, P	F	S	P, T	V, S	D, W		S	
Sato et al.[54] (Toyota)	T	S	P	F			V, H, A		T	I	
Urano et al.[61] (Toyota)	T, H	U	A	I		P	V, A				
Yamada[70] (Toyota)	T	S	P	F			V, S				
Christensen[10] et al. (Volvo)	T, H	S	P			T	V, A	D, C, S		S	
Coelingh[11] et al. (Volvo)	T, H	S	SA	F	O		V, H, A	C, H, W		S	

Table 2. Industry Patents - Results (N=22)

Both active and semiactive transition modes are present frequently, and slightly more often as an exclusive interaction mode. Passive transitions can be found in 10 of the papers. It is of note that the high number of setups with both active and semiactive transition modes is due to the participants often having to enable autonomous driving mode at the beginning of a trial manually, while the rest of the trial proceeds as a series of semiactive system-initiated transitions. Semiactive transitions are, therefore, more dominant than the table might suggest. Transitions are mostly full, with nine publications reporting partial transition capabilities, and one not specifying the transition completeness further.

Fallback capabilities are not specified in about half of all publications. In 12 of the 19 cases, in which they are mentioned, fallback capabilities are explicitly not present (e.g., vehicle behavior is described as crashing into another vehicle or obstacle unless an intervention occurs). The vehicle stopping on its own lane is mentioned in four publications, system handling fallback performance in general in two publications.

Input modes are mostly physical, consisting of either turning the wheel, actuating pedals, or interacting with a dedicated autonomous mode control button or lever. Only three publications implement transition input via a touch device, which is an interesting contrast to the findings of Pfleging et al. [47], who found touch interaction to be the preferred interaction mode in their self reporting study. Two publications reported input via speech interaction. Gesture input was used in one publication.

Output modes are more varied, with visual being dominant but often accompanied by auditory and sometimes speech or haptic output modes. Haptic output as the only modality is reported as implemented in two publications, speech in one. Visual output is distributed among all available categories but most frequently located in the dashboard area. A total of four publications report visual output located in the windshield area, outside of the standard in-vehicle display locations. Haptic output was most often located in the seat, in two cases in the

pedals and two setups used wristbands for haptic feedback. Only one publication reported haptic output via the steering wheel. Temporal output modes were an even mix between one-time and several-time outputs, with five publications reporting incremental changes in frequency or intensity of their output implementations.

About half of all publications reported mode awareness capabilities, with symbols being the dominant method, often supplemented by color coding, sometimes with text in addition. One publication used a nonstandard transformable steering wheel to communicate the active driving mode (reported via 'O' in the framework).

Patents

The patents, listed in Table 2, show a strong focus on takeovers, with most describing takeovers only, some accounting for both, and only three focusing on handovers alone. Initiation is mostly evenly distributed with a slight preference of system-over user-initiation. Only four patents account for both user and system initiated transitions.

About half of all patents foresee partial transitions, with four of them even intending them to be incremental. Fallback modes are rarely mentioned and only in two cases specified regarding their actual behavior.

Input has a strong focus on physical interaction and, unlike the academic publications, there is a just as strong focus on touch interaction (there are even three cases where it is the only interaction mode). Three patents foresee speech input but only as a supplement, never as the only mode available.

Output is visual in almost all cases, often accompanied by either speech or non-speech auditory output. Visual output locations were often left unspecified and when specified, were mostly located in the dashboard and console. Windshield output was specified four times, HUD three times. Only one patent provided visual output via the steering wheel. Five patents contained haptic output. Two patents specified the

haptic output in the driver seat, the other three left the output location unspecified.

Five patents specified output as occurring one time per transition, four patents several times, with two of them featuring incremental increases in intensity or frequency. Driving mode awareness was present in six patents, either via symbols/icons or color coded light cues, and as color coded icons in one case. Only one patent communicated driving modes via text.

DISCUSSION

In this section, we discuss the findings from above and identify possible ways forward for both research and industry to improve transitions in automated vehicles.

The System at the Center

Both academia and industry seem to put a decisive focus on the system side. The central questions mostly concern how transitions from system to driver can be made faster, easier to read and respond to, or to contain more situation awareness cues for the driver. Similarly, the most frequent concern is how the system can make the correct decision about when (i.e., in which situations and at which point in time once a situation occurs) a transition should be initiated. This focus is understandable, as the transition from system to driver is often considered the more critical of the two [29].

However, many of the difficulties of enabling safe takeovers could potentially be handled just as well—if not better—from the other side. An aware and well-informed human can project into the future, assess driving conditions and other road users' behaviours. They can plan ahead and distinguish more from less difficult road segments, which could correspond with both takeover and handover probabilities and, in turn, increased or decreased situational awareness demand for the driver. Of course, having the driver being aware of the driving environment does not fit in well with the promises of watching television shows, reading, or even sleeping while driving, if one understands the requirement of the environment being principally monitored by the system to mean that the driver is completely (mechanically and cognitively) uninvolved until the very moment a transition becomes necessary. In addition, the potential of transition only individual driving functions could need more exploration, as there is a visible focus on full one-time transitions. This leaves out more nuanced perspectives, where a driver might actively decide to handle only one driving task, perhaps as a primary activity, possibly only to keep the situation awareness at a level that enables fast and appropriate responses to takeover requests.

Accounting for Transition Failures

It is mostly assumed that transitions will work and the main problem being, once again due to focusing on takeovers over handovers, how fast drivers respond to which cues during a takeover request. But what about when a transition simply fails? This is not the same as standard avoidance behavior, e.g., doing an emergency brake or avoiding an obstacle. When a transition fails, it usually fails after a certain time span has elapsed that would have been enough to initiate a response by either system or driver. This means that in critical cases, such

a fallback must initiate in advance; many situations simply do not provide 10 or 15 seconds to calmly initiate a transition request and then initiate a fallback maneuver if there has not been a response for several seconds. Assuming that transitions are initiated for good reasons—and are being confirmed or declined for equally good reasons—there needs to be robust fallback strategies that account for different contextual situations. After all, if standard avoidance behavior were enough, then there would not be any reason to focus on emergency takeover requests.

It should be noted that fallbacks are something that needs to be actively implemented. For academic publications, this would often mean to implement something that is out of scope at best (e.g., when reaction times to critical events are measured) or actively interfering with the actual subject of investigation at worst. Thus, the low number of fallback implementations is quite understandable and this should not mean that each and every study setup should include fallback mechanisms even when it would not even make sense given the research questions. Instead, it is worth investigating different fallback strategies and mechanisms as a separate research object, and conduct studies with accompanying setups precisely to investigate fallbacks. The equally low number of sophisticated fallback strategies in industry patents suggests that there is a real need of, and great potential for, an alignment of automotive academia and industry efforts.

A Multitude of Output Modalities

Output modalities were varied among both publication areas. While there was a clear dominance of visual output, this was hardly surprising as it is the primary output mode of existing in-vehicle interfaces and, therefore, the most obvious and consistent communication channel. However, due to both the distraction potential of visual communication and the potential difficulty of gaining the driver's attention with visual cues outside the field of view, additional output modes are worth exploring, which is reflected in both academia and industry.

Auditory output encompasses both single sounds to accompany visual cues, over incremental changes to communicate urgency, to speech output for more informational content in auditory cues. Haptic output is also explored as a more immediate and less distracting communication channel. Both the analyzed patents, as well as the academic publications, explore the driver seat as a primary means to communicate proximity and/or lane position of other vehicles in case of a transition request via haptic feedback. Haptic output via the steering wheel is limited to a single publication, which reflects the likelihood of the driver not having their hands on the wheel at all times (as, e.g., the Tesla Autopilot requires the driver's hands on the wheel only within certain intervals and not all the time). In addition, the academic publications also explore wristbands and pedals for haptic feedback, which are both worth further exploration to supplement cues that are communicated via the driver seat

The Steering Wheel as a Powerful Metaphor

While many of the described interfaces are preliminary or partial, there are two commonalities regarding the visual out-

put. The steering wheel is by far the most often used visual metaphor to communicate transitions. Having hands on the wheel versus having them off the wheel seems to quite clearly correspond with the concept of being in control or not. A steering wheel with hands moving towards the wheel or away from it (be it via arrows, color coding, or simply showing or not showing the hands at all) has become a well-established way to clearly communicate the direction of a transition. The second commonality is a traffic light system of color coding, where the familiar spectrum of green, yellow, and red is used to communicate levels of danger or urgency of a driving situation or transition phase.

About Driving Mode Awareness

Driving Mode Awareness is rarely a factor in industry patents and while it is more frequently present in academic publications, it is most often not at the center of the investigation or even investigated at all. Being aware of the current driving mode can be very useful beyond merely avoiding confusion about who is in control. An effective mode awareness interface can distinguish between different driving tasks and further enable shared control this way. Beyond that, mode awareness can provide surveillance for the driver to “see what the vehicle sees” and, e.g., verify if sensors are dirty or otherwise impaired in their functionality. In other words: Mode awareness can help the driver make informed decisions on when to initiate transitions, which might not be attractive when aiming only at full automation, but arguably very important for partial automation in the transition phase. An effective mode awareness solution that suits these purposes should contain more information than simply informing the driver whether the autonomous driving mode is on or off but outside of a few exceptions, a binary “on vs. off” is the most frequently found implementation. This is an area that warrants more attention and that might be even crucial for the exploration of the full potential of shared driving [21], partial transitions and active driver involvement in transitions.

LIMITATIONS

The landscape of both academic publications and industry patents is larger than what this paper is able to cover. A quick Google Scholar search will reveal hundreds of thousands of publications about autonomous vehicles, which may or may not contain information about specific transition interface designs. In this paper, we tried to cover a representative spectrum that is still feasible for an in-depth review analysis by focusing on what we consider key sources in the automotive domain. But it is entirely possible that we missed important works, interesting concepts, or ongoing trends that can be found outside of what was analyzed in this paper. Since we can not claim absolute completeness in this regard, we tried to make the selection process and analysis framework as transparent as possible, so that what is reported in this paper can be verified and/or expanded, if need be.

As it turned out during the analysis, most input modalities ended up being physical, which is less informative than it could be in the current framework, as it did not account for differences in physical controls beyond touch versus “traditional”

physical interaction. A finer distinction between physical input modes is necessary to separate not only actuation of pedals and/or steering wheel from button presses, but also physical control locations (button on the wheel vs. button outside the wheel, levers to the side, etc.) or other potentially relevant factors, such as soft vs. hard button presses or shapes of physical interaction elements. While the examined works fit well into the defined fallback capabilities, we defined a very limited pool of fallback behaviours, which need to be extended as technology matures further. The temporal component of transitions is also only implicitly contained and we recommend making response times and intervals between outputs (when they occur more often than once) more explicit. Even though the initial searches returned a rather large number of hits, the resulting number of papers ended up being surprisingly small, as many publications – both industry patents and academic papers – focused on aspects such as system behavior, reaction times, situational awareness, etc., with the actual transition action being a means to an end rather than an object of investigation.

Furthermore, the results gained from this analysis do not contain any information regarding the comparative quality of the various implementations. This means that the outcomes are limited to identifying either trends or holes in research and development efforts. Cases of, e.g., numerically strong efforts with overall disappointing results or limited efforts with surprisingly effective results – both very important for a correct assessment of the state of the art – are, thus, not covered by the present analysis.

CONCLUSION AND OUTLOOK

This paper has examined academic research publications and patents from the perspective of control transition interfaces within automated driving contexts. It has presented an analysis framework which compares the following categories: direction, indication, involvement, completeness, fallback, input, visual output position, haptic output position, temporal output mode, and mode awareness. Within each of these categories, it has provided a set of values, which allows for an examination of the current state of the art within the field. As a result, it has identified areas where significant work has already been undertaken (system-initiated transitions, visual and auditory output, visual metaphors) and areas where further work is required (driver-initiated transitions, fallback performance, haptic output, driving mode awareness).

While work on structuring control transitions is available [35, 21], there is a need to examine this area in more detail, particularly regarding individual interactions and from a human-centered perspective. With this paper we provide researchers and practitioners in the automotive domain a resource to both categorize their work in the area and identify needs and opportunities for future work regarding control transitions in automated driving.

ACKNOWLEDGMENTS

The financial support by the Austrian Science Fund (FWF): I 2126-N15 and the Fonds National de La Recherche Luxembourg (FNR): CS14/IS/8301419 are gratefully acknowledged.

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