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ORIGINAL ARTICLE

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Design of human–machine interactions in light of domain-dependence of human-centered automation

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Abstract This paper discusses that human-centered automation for traffic safety can vary depending on transportation mode. Quality of human operators and time-criticality are factors characterizing the domain-dependence. The questions asked in this paper are: (1) Does the statement that, "The human must be in command," have to hold at all times and on every occasion, and in every transportation mode? and (2) What the automation may do when it detected the human's inappropriate behavior or performance while monitoring the human? Is it allowed only to give some warnings? Or, is it allowed to act autonomously to resolve the detected problem? This paper also argues that human-centered automation must be multi-layered, by taking into account not only enhancement of situation awareness but also trading of authority between humans and machines.

Keywords Authority and responsibility · Human-centered automation · Levels of automation · Human interface · Transportation

1 Introduction

Today's machines can sense and analyze situations, decide what must be done, and implement control actions. The intelligent and autonomous machines have been contributing considerably to improve safety, efficiency, and comfort of transportation vehicles, such as aircraft, automobile, railroad, and marine vessels. However, humans working with smart machines sometimes suffer negative consequences of automation, such as the out-of-the-loop performance problem, loss of situation awareness, complacency or over-trust, automation surprises (see, e.g., Woods 1989; Wickens 1994; Endsley and Kiris 1995; Sarter and Woods 1995; Parasuraman and Riley 1997; Sarter et al. 1997; Inagaki and Stahre 2004; Hollnagel and Woods 2005). Appropriate guidelines or methodologies have been called for to resolve these problems. Proposal of human-centered automation is among those efforts (see, e.g., Woods 1989; Billings 1992, 1997; Sheridan 2002; Cacciabue 2004; Wickens et al. 2004).

Human-centered automation is an approach to realize work environment in which humans and machines collaborate cooperatively. However, in spite of popularity, there seems to be some ambiguity on what human-centered automation really means: Sheridan (2002) distinguishes ten different meanings of human-centered automation, and argues that contradictions can be found in those "definitions." Among various application domains, it may be aviation for which human-centered automation is defined in the most detailed manner. Aviation has a long history of automation, and has experienced both its benefits and costs (see, e.g., Billings 1997; Orlady and Orlady 1999). The concept of human-centered automation, shown in Table 1, has resulted from studies to resolve the costs of automation (Billings 1997; ICAO 1998).

This paper argues that human-centered automation can be domain-dependent and thus must be established properly for each transportation mode: e.g., "human-centered automation for automobile" can be quite different from "human-centered automation for aviation system" defined in Table 1. Quality of human operators and time-criticality characterize domain-dependence of human-centered automation. This paper focuses its attention on the following two questions: (1) Does the statement that, "The human must be in command," have to hold at all times and on every occasion, and in every transportation mode? (2) What the automation may do when it detected the human's inappropriate behavior or performance while monitoring the human? Is it allowed only to give some warnings?

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Table 1 Principles of human-centered automation

The human bears the ultimate responsibility for safety of aviation system
Therefore:
- The human must be in command
- To command effectively, the human must be involved
- To be involved, the human must be informed
- Functions must be automated only if there is a good reason for doing so
- The human must be able to monitor the automated system
- Automated systems must, therefore, be predictable
- Automated systems must be able to monitor the human operator
- Each element of the system must have knowledge of the others' intent
- Automation must be designed to be simple to learn and operate

After Billings (1997) and ICAO (1998)

Or, is it allowed to act autonomously to resolve the detected problem? It is also argued that human-centered operator support must be multi-layered by taking into account operator characteristics and circumstantial contexts, in which (1) enhancement of situation awareness and (2) trading of authority are important design aspects.

2 Factors contributing to domain dependence

Domain-dependence of human-centered automation may come from quality of human operators and time-criticality.

2.1 Quality of human operators

Quality of human operators varies depending on whether they are professional or non-professional. Professional operators, such as airline pilots, are trained thoroughly and continually so that their knowledge and skill are perfect enough to use smart and sometimes complicated machines properly. On the other hand, in cases of non-professional operators, such as private car drivers, it would not be sensible to assume that their levels of knowledge and skill are high. Their understanding of machine functionalities can be incomplete, or even incorrect.

Example 1: The adaptive cruise control (ACC) systems are designed to reduce the driver's workload by freeing him or her from frequent acceleration and deceleration. Sometimes they may be differentiated into two classes: *high-speed range ACC* and *low-speed range ACC*. When there is a preceding vehicle to follow, both ACC systems control the speed of the own vehicle so that the time gap to the target vehicle may be maintained. Suppose the sensor lost sight of the target vehicle, the high-speed range ACC continues to stay in its active state. In cases of the low-speed ACC, its behavior differs depending on control logic design. Two designs are possible: one is to let the ACC stay in its active state, and the other is to put it into a standby state. It is hard to tell which design is better than the other. Loss of mode awareness or automation surprises can occur in either type, but in a different way. Inagaki and Kunioka (2002) conducted an experiment with a PC-based driving simulator where no information was displayed regarding the state of the ACC. Subjects were requested to carry out procedures of perception, decision-making, and action implementation based on their mental models. Even after training or experience with the ACC systems on the simulator, loss of mode awareness and automation surprises were observed, which reflect over-trust in and distrust of automation, and inertness of mental models.

2.2 Time criticality

Time criticality differs appreciably depending on the transportation mode. Consider the following examples in which an automated warning system is available for the operator.

Example 2: Traffic alert and collision avoidance system (TCAS) is a family of airborne devices designed to help pilots to avoid a mid-air collision. Its functionalities are described as follows (US Department of Transportation & FAA 2000): TCAS sends interrogations at 1,030 MHz to which transponders on nearby aircraft respond at 1,090 MHz. By decoding the replies, the position and altitude of the nearby aircraft are identified. Based on the range, altitude, and bearing of nearby aircraft, TCAS performs *range and altitude tests* to determine whether the aircraft is a *threat* or not. When the nearby aircraft is declared a threat, TCAS selects an avoidance maneuver (to climb or descend) that will provide adequate vertical miss distance from the threat. If the threat is also a TCAS-equipped aircraft, the avoidance maneuvers will be coordinated between the two TCAS systems so that one aircraft climbs and the other descends. TCAS then issues a *resolution advisory* (RA) to let the pilot know the appropriate avoidance maneuver. The estimated time to the closest point of approach is 15–35 s. The pilots are supposed to respond to the RA within 5 s.

Example 3: The enhanced ground proximity warning system (EGPWS) is designed to help pilots to avoid a ground collision (Bresley and Egilsrud 1997). EGPWS collects air data, radio altitude, barometric altitude, and airplane position through some other systems, such as flight management system, GPS, and the airplane air data system. Receiving these data, EGPWS determines potential terrain conflict by use of its self-contained worldwide airport and terrain databases. EGPWS displays the terrain in dotted patterns with colors indicating the height of the terrain relative to the current airplane altitude. EGPWS continuously computes terrain clearance envelopes ahead of the airplane. If these envelopes conflict with data in the terrain database, EGPWS sets off alerts. A caution-level alert is issued approximately

40–60 s before a potential terrain conflict, and a warning-level alert is set off approximately 20–30 s before a conflict.

Example 4: Nowadays, some types of automobiles are equipped with a forward vehicle collision warning system. The system detects the forward vehicle and measures its speed and the distance to it by a distance radar (mostly, a laser radar or a millimeter-wave radar) sensor mounted on the own vehicle. When there is a possibility of collision against the preceding vehicle, the system sets off a collision warning. The estimated time to collision is at most a few seconds.

As can be seen in Examples 2 and 3, if the collision warning were against another aircraft or terrain, enough amount of time would be available for the pilot to grasp the situation, validate the given warning, and initiate a collision avoidance maneuver. In case of the automobile, however, time criticality is extremely high, and little time may be left for the driver, as can be seen in Example 4.

3 Operator support must be multi-layered

How can we design functionalities for assisting human operators appropriately? Discussions may be made on two aspects: (1) enhancement of situation awareness and (2) trading of authority.

3.1 Enhancement of situation awareness

Driving requires a continuous process of perception, decision-making, and operation. Understanding of the current situation determines what action needs to be done (Hollnagel and Bye 2000). Once *situation-diagnostic decision* is made, *action selection decision* is usually straightforward (Klein 1993). Various intelligent functionalities have thus been proposed to assist driver's situation-diagnostic decision. Human interface design is central for enhancing driver's situation awareness, assisting diagnosis on the situation, avoiding automation surprises, and establishing appropriate trust in automation. The human interface must enable the human to: (1) understand the rationale why the automation thinks so, (2) recognize intention of the automation, (3) share the situation recognition with the automation, and (4) perceive limitations of automation's functional abilities.

Example 5: Traditional GPWS sometimes failed to share situation awareness with pilots. GPWS could set off false alarms and no effective measures were available for the pilots to validate the alarms. In some controlled flight into terrain (CFIT) accidents, it is known that pilots disregarded correct pull-up warnings. Pilots sometimes trusted the GPWS overly, however, even though its capability to detect conflict against terrain was not perfect. Currently available EGPWS seems to be successful in sharing situation awareness with pilots by virtue of its capability to display the terrain in dotted patterns with colors indicating the height of the terrain relative to the own aircraft altitude. Also, when a pull up warning was issued, the pilots can see clearly why the warning was set off. The pilots may be able to predict a warning before it is actually set off.

Example 6: When driving a car equipped with an ACC system, we sometimes experience automation surprises. Figure 1 depicts two of such cases. In Case 1, the own vehicle accelerates by trying to follow a faster vehicle driving on the adjacent lane, while the driver expected deceleration when he or she noticed that the vehicle ahead on the same lane was slowing down. This type of failure in understanding the ACC's intention may be mainly due to insufficient information feedback regarding the target vehicle. The ACC displays a visual symbol indicating that it has detected a preceding vehicle and is following it as the target vehicle. However, even when the target was replaced by another vehicle, currently available human interface does not usually inform the driver. Also, as shown in Case 2, even though the driver noticed a cutting-in vehicle and expected the ACC would slow down the own vehicle, the ACC may accelerate the own vehicle to catch up with the preceding vehicle, failing to detect the cutting-in vehicle. This type

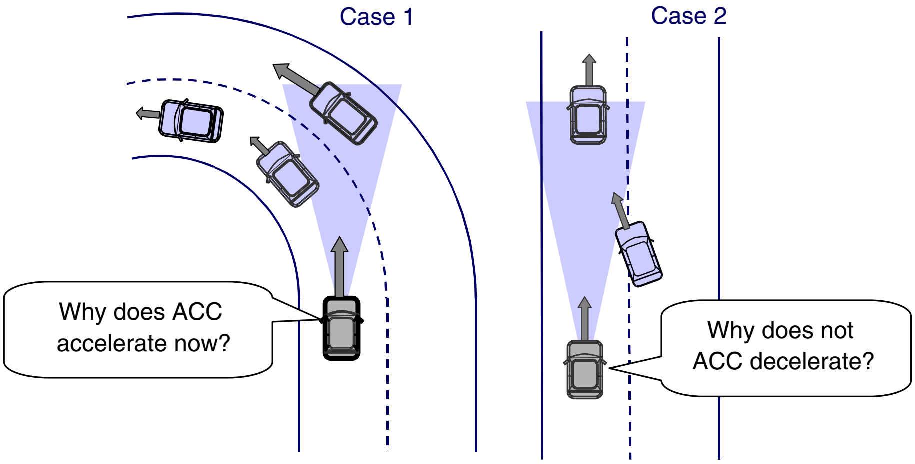

Fig. 1 Automation surprises caused by the adaptive cruise control (ACC) system

of automation surprise may be due to driver's failure in sharing situation recognition with the ACC, as well as failure in understanding limitations of functional abilities of the ACC (or its detection sensor).

3.2 Trading of authority

The enhancement of human operator's situation awareness are essential in realizing human-centered automation, in which "the human bears the ultimate responsibility for safety" and "the human must be in command" (see Table 1). However, humans may not always be able to cope with the given situation, as shown in the following example.

Example 7: ITARDA (Institute for Traffic Accident Research and Data Analysis) analyzed data of automobile accidents occurred in Japan during the period of 1993–2001. Among all accidents of four-wheel vehicles, they extracted 359 head-on or rear-end collisions for which microscopic data are available on the following items: vehicle's speed and location at which the driver perceived a possible danger, vehicle's speed right before the collision, and vehicle's speed at the collision. They found: 13.9% of drivers tried to avoid collisions with steering and braking, 42.6% with braking only, and 5.6% with steering only. Surprisingly, 37.9% of drivers did neither steer the wheel nor apply the brakes (ITARDA 2003).

How can we design a system that assists the driver when a collision may be imminent? Consider the following two types of *pre-crash safety system*.

Example 8 (Pre-crash safety system of type 1): The radar sensor monitors the preceding vehicle. When the system judges, based on distance and relative speed of the preceding vehicle, that a collision might be anticipated, it gives a warning to the driver and retracts the seatbelts.

Example 9 (Pre-crash safety system of type 2): When the system judges that a collision might be anticipated, it gives a warning to the driver and retracts the seatbelts, as in the case of type 1. When the system determines that a collision is imminent and that the driver is late in responding to the situation, it retracts the seatbelts firmly and applies an automatic emergency brake.

The pre-crash safety system of type 1 is to enhance the driver's situation awareness. If the driver applies the brakes fast enough, no collision may occur. However, if the driver failed to respond to the situation, the system gives no active help, and therefore the collision shall be inevitable.

The pre-crash safety system of type 2 has two layers of assistance: enhancement of the driver's situation awareness, and trading of authority in emergency. Trading of authority in this case is to support action implementation when the driver failed to take the action at a right time. Note that the system applies the emergency brakes, not based on the driver's directive, but based on its own decision. One of the principles in Table 1, "the human must be in command," is violated. However, that does not necessarily mean that the pre-crash safety system of type 2 should not be allowed. On the contrary, Example 7 suggests the need for system-initiated trading of authority in emergencies.

Professional operators may also fail to respond appropriately to the situation encountered, as shown in the following two examples.

Example 10: An analysis of CFIT accidents of commercial jet airplanes during the period of 1987–1996 found that 30% of the accidents occurred while the ground proximity warning system (GPWS) failed to detect terrain ahead, and 38% were due to late warning of the GPWS or improper pilot response (Bresley and Egilsrud 1997). Problems of "no warning" or "late warning" may be resolved by introducing EGPWS that can enhance pilot's understanding of the height of terrain relative to the aircraft altitude. Problem of "pilot's late response" might not be resolved fully by EGPWS, since it is the human pilot that is responsible for a collision avoidance maneuver. However, there is a system in which a collision avoidance maneuver may be initiated by automation. The automatic ground collision avoidance system (Auto-GCAS) for a combat aircraft is such an example (Scott 1999). When a collision against the terrain is anticipated, the system gives a pull-up warning. If the pilot takes a collision avoidance action aggressively, then the system will not step in any further. If the pilot did not respond to the warning, the system takes over control from the pilot and executes an automatic collision avoidance maneuver. When no threatening terrain is found any more, the system returns control back to the pilot. Thus, the Auto-GCAS determines when to intervene and when to return the authority back to the pilot.

Example 11: A 41,507-ton container vessel collided with a 19-ton fishing boat about 40 km off Hokkaido, Japan's northern island on 28 September 2005, causing the fishing boat capsized. It is reported, "The second-class navigator and the lookout failed to take necessary measures to prevent the collision even though an alarm warning of a collision with another vessel went off on the container ship" (Mainichi Daily News 2005). In order to lessen such an accident, a collision avoidance support system is under development with the aid of the Ministry of Land, Infrastructure and Transport, Government of Japan (Kayano et al. 2004). The system has functionalities not only for enhancement of situation awareness but also for trading of authority. By using automatic identification system (AIS) and a multi-image sensor system, the system detects vessels and displays them on a head-up display for the officer of the watch. When the own ship encountered a collision danger, the system displays the officer the most feasible collision evasion route. If the officer approves the route, the system controls the own ship according to the plan. If the officer failed to take any proper collision avoidance maneuver, the system takes over control, when a certain condition is met, and applies an automatic collision avoidance maneuver to keep the predefined safety margin.

4 Levels of automation

In the Section 1, the following questions have been raised: (1) Does the statement that, "The human must be in command," have to hold at all times and on every occasion, and in every transportation mode? and (2) What the automation may do when it detected the human's inappropriate behavior or performance while monitoring the human? Is it allowed only to give some warnings? Or, is it allowed to act autonomously to resolve the detected problem?

As we have already seen in the previous examples, human may fail to recognize or respond to the given situation appropriately. Even when the situation was understood correctly, the human may not be able to take necessary actions in emergencies. Some automatic decision-making and action implementation may be needed for transportation safety. Now the question becomes: How can the human and the automation share authority and responsibility for transportation safety?

One useful tool in discussing the issue is the level of automation (LOA). Table 2 gives an expanded version in which one LOA comes between levels 6 and 7 in the original list by Sheridan (1992). The added LOA, called level 6.5, has been introduced by the author (Inagaki et al. 1998) to reduce automation surprises induced by an automatic action, as well as to make the action effective in emergencies. The pre-crash system in Example 9 is one of real-world examples with level 6.5. As long as the LOA is positioned at level 5 or lower, the human is maintained as the final authority. If the LOA is positioned at level 6 or higher, however, the human may not be in command.

In terms of LOA, the last question in the above may be rephrased as: Which LOA has to be chosen for transportation safety? Simply stated, the answer to the question is: An appropriate LOA is situation-dependent (where "situation" includes "context" and "transportation mode") and it may change from one level to another in a dynamically changing environment, which is called the *situation-adaptive autonomy* (Inagaki 1993, 1999). In case of the Auto-GCAS in Example 10, LOA changes dynamically: if the pilot takes a collision avoidance maneuver aggressively upon receiving a pull-up warning, the Auto-GCAS will not step in any further (LOA stays at level 4). If the pilot did not respond to the warning, the Auto-GCAS takes control back from the pilot and executes an automatic collision avoidance action (LOA goes up to level 6). It would also be easy to see in Example 11 that the system chooses levels 4 and 6 according to circumstances.

Table 2 Scales of levels of automation

1	The computer offers no assistance; human must do it all
2	The computer offers a complete set of action alternatives, and
3	Narrows the selection down to a few, or
4	Suggests one, and
5	Executes that suggestion if the human approves, or
6	Allows the human a restricted time to veto before automatic execution, or
6.5	Executes automatically upon telling the human what it is going to do, or
7	Executes automatically, then necessarily informs humans
8	Informs him after execution only if he asks
9	Informs him after execution if it, the computer, decides to
10	The computer decides everything and acts autonomously, ignoring the human

After Sheridan (1992), Inagaki et al. (1998), and Inagaki and Furukawa (2004)

5 Which LOA is appropriate?

Three approaches are available for choosing an appropriate LOA. Each approach is illustrated with an example.

Example 12 (Mathematical analysis): Suppose an engine fails while an aircraft is making a takeoff roll. The standard decision rule for the case is simple: (a) abort the takeoff if the aircraft speed is below V1, and (b) continue the takeoff if V1 has already been achieved, where V1 is the *takeoff decision speed* (viz., the maximum speed at which the pilot can initiate rejected takeoff maneuver to stop the aircraft safely within the remaining field length, and the minimum speed to continue a one-engine out takeoff to attain a height of 35 ft at the end of the runway). That the decision rule is simple does not necessarily mean that the decision can be made easily and correctly. An analysis of rejected takeoff overrun accidents during the period of 1959–1990 has found that 58% of the overrun accidents were due to inappropriate rejection of takeoffs in excess of V1 (FAA 1992). Inagaki (1997, 2000) has proven mathematically using a probability model with various parameters, such as reliability of engine failure warnings, reliability of human judgment (*hesitation in decision-making* has been investigated as well as *hit*, *correct rejection*, *false alarm*, and *missed detection* in the signal detection theory), expected loss because of incorrect judgment, or delay in decision. The conclusion was that Go/NoGo decision should neither be fully automated nor left always to the human pilot: (1) the human pilot must be in authority when the aircraft speed is far below V1, where LOA is set at level 4; (2) the computer must be in authority if aircraft is almost at V1 and if there is a possibility that the pilot may hesitate to judge whether the given warning was correct or not, where LOA is set at level 6 or higher; and (3) when the aircraft speed is between (1) and (2), which agent must be in command depends on the situation. Another important conclusion was that, for a human pilot to be in command at all times and in every occasion, human interface needs to be changed so that a more direct message, such as "go" or "abort," can be given to the pilot, instead of just giving an "engine failure" warning, because "engine failure" alert is ambiguous in the sense that it means Go in cases of after V1, and NoGo before V1.

Example 13 (Experimental approach): In order to examine the mathematical findings described in Example 12, a flight simulator of a two-engine aircraft has been implemented, and an experiment with a factorial design, mapping onto (Control mode) × (Phase) × (Human interface design) was conducted (Inagaki et al. 1999). For the control mode, the manual mode and the situation-adaptive autonomy (SAA) mode were distinguished. In the manual control mode, LOA was set at level 4. In the SAA-mode, the computer changes LOA dynamically within the range of levels 4 to 6, and may take over control for continuing the takeoff when it determines that it is impossible for the human to initiate rejected takeoff maneuver before V1 is achieved. It has been observed in the experiment that the new interface (that tells "go" or "abort") can reduce overrun accidents significantly compared to the conventional interface (that gives an "engine failure" warning). However, even with the new interface, overrun accidents did occur under the manual control mode. In the SAA-mode, on the contrary, no overrun accidents were observed, which proved the efficacy of system-initiated trading of control.

Example 14 (Computer simulation): This approach may be useful for investigating human-automation interaction under possibility of human's over-trust in automation. Consider a driving with the ACC system at work. While observing the ACC behaves properly again and again, the driver may begin to place excessive trust in automation sometime along the line, and may eventually fail to allocate attention to the driving environment. With an ordinary brake, the ACC can cope up to a certain rate of deceleration of the forward vehicle. Suppose the ACC recognized a preceding vehicle's excessive deceleration. Which is reasonable among the following design alternatives for assuring safety in this case? (1) ACC gives an emergency-braking alert telling the driver to apply the brakes hard enough to avoid a collision, in which LOA is set at level 4; (2) ACC gives an *emergency-braking alert*, and if the driver does not respond within a pre-specified time, it applies an automatic emergency brake, in which LOA is positioned at level 6; and (3) ACC applies its automatic emergency brake simultaneously when it issues an emergency-braking alert, in which LOA is set at level 6.5. Based on a discrete-event model of dynamic transition of driver's psychological states (distinguishing five states, from a subnormal and inactive state to a hyper normal and excited state), 3,000 Monte Carlo simulations were performed for various driving scenarios with different degrees of "peacefulness" (Inagaki and Furukawa 2004). It has been observed that, when the driving was peaceful and the ACC continued to be successful in its longitudinal control, the driver was likely to rely on the ACC, and his or her vigilance degraded. When the target vehicle made a rapid deceleration in such circumstances, the driver might not be able to cope with the situation in a timely manner, even with the aid of an emergency-braking alert. The number of rear-end collisions against the preceding vehicle was significantly larger under design (1) than either of those under (2) or (3), and no accident was observed under (3), which shows the need of high LOA for assuring car safety under time stress, especially when the driver may be inattentive.

6 Toward more precise understanding of human-centered automation

This paper has discussed how human-centered automation may vary depending on transportation modes. For more than two decades, human-centered automation concept has been investigated and practiced most extensively in aviation. In spite of the success, principles of human-centered automation for aviation systems may not always be applicable to other transportation modes in a straightforward manner. Efforts are needed to establish a "human-centered automation" for each transportation mode. Especially, more thorough investigations are necessary to answer whether the human must be in command at all times and on every occasion, or whether the automation may be allowed to initiate trading of authority from human to automation.

Whether trading of authority must be human-initiated or system-initiated has been a crucial research issue in *adaptive automation* (Rouse 1988; Parasuraman et al. 1992; Scerbo 1996; Inagaki 2003), because trading of authority is essential in function allocation in a dynamically changing environment. Although human may not be in command in case of system-initiated trading of control, such autonomous decision-making or action implementation are sometimes indispensable to assure traffic safety, especially for automobile with not fully trained drivers.

If human-centered automation is to "realize work environment in which humans and machines collaborate cooperatively," automation may be allowed to take countermeasure actions at its own discretion to help humans in difficult circumstances in which little resources are left for the humans to give directives to the machines. Billings (1992) said, in one of his pioneering work on the human-centered automation, "it (automation) should never assume command." The sentence was preceded, however, by the phrase, "Except in pre-defined situations" (Billings 1992). It has not yet been clarified fully by this time what are "pre-defined situations." It would be time for us to work on the issue extensively to make the human-centered automation concept more precise and more promising.

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associated technologies, in which authority of control is traded between a driver and automation dynamically depending on the driver's psychological/physiological state, time-criticality, and risks of the situation in the traffic environment.

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