Proc. IEEE SMC Conference, pp. 3932-3937, 2004

Computer Simulation for the Design of Authority in the Adaptive Cruise Control Systems under Possibility of Driver's Over-trust in Automation*

Toshiyuki Inagaki
Department of Risk Engineering
University of Tsukuba
Tsukuba, Japan
inagaki@risk.tsukuba.ac.jp

Hiroshi Furukawa
Department of Risk Engineering
University of Tsukuba
Tsukuba, Japan
furukawa@risk.tsukuba.ac.jp

Abstract - *It is often said that the human must be maintained as the final authority over the automation. However, that does not necessarily mean that human must be maintained as the final authority at all times and on every occasion. Design of authority is crucial for automobile, especially when there is possibility that the driver becomes complacent by trusting the automation excessively and when available time for safety control or information for situation understanding is limited. This paper gives a computer simulation method for analyzing the complacency effect and for investigating the efficacy of the trading of authority, by taking as an example the design of safety control schemes for driving with the adaptive cruise control systems.*

Keywords: Human-automation interaction, authority, levels of automation, complacency, adaptive cruise control system.

1 Introduction

Today's machines can sense, analyze situations, decide what must be done, and implement control actions in highly autonomous manners. It is recognized that such smart machines have contributed much to reduction of human workload, improvement of efficiency or safety. It is true, however, that the automation has brought problems, such as the out of the loop phenomena, degradation of manual skill, vigilance decrements, loss of situation awareness. Moreover, it is easy for humans to have trust in smart machines. They often become complacent by placing excessive trust in those machines, which can be harmful to system safety [9,11].

In the research community of human-machine systems, it is often said that, "the human must be maintained as the final authority over the automation." The statement is sensible and reasonable. However, it is not appropriate to assume that, "human must be maintained as the final authority over the automation *at all times and on every occasion*." It has been shown mathematically [5,7], via cognitive experiments [10], or via computer simulation [1-3], that the final authority for decision and action may be traded dynamically and flexibly between humans and automation.

Design of authority [6] is crucial for automobile. Ordinary car drivers are not professional, and it is unrealistic to assume that they are well trained. Non-professional drivers may become complacent more easily than professional operators, in the course of observing successful control by the automation. Time-criticality must also be taken into account: When a collision is anticipated, only a second or two may be available for drivers to avoid it. Considering the effect of driver's complacency plays a significant role for assuring automobile safety.

This paper gives a computer simulation method for analyzing the complacency effect and for investigating the efficacy of the trading of authority, by taking as an example the design of safety control schemes for driving with the adaptive cruise control (ACC) systems.

2 Levels of automation

Human-computer interactions can be described in terms of the *level of automation* (LOA). Table 1 gives an expanded version in which a new LOA comes between 6 and 7 in the original list by Sheridan [12]. The added level, called the level 6.5, has been firstly introduced by one of the present authors [8] to avoid automation-surprises that may be induced by automatic actions, when the actions are indispensable to assure systems safety in emergencies.

3 Model Description

This section gives a general description on our model for investigating design of driver-automation interaction for automobile safety. Parametric values for the model shall be described in section 4.

Table 1. Scales of levels of automation (expanded version)

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 after telling the human what it is going to do, or

7. executes automatically, then necessarily informs humans, or
8. informs him after execution only if he asks, or
9. informs him after execution if it, the computer, decides to.
10. The computer decides everything and acts autonomously, ignoring the human.

3.1 Driver Support Systems

It is assumed that the lane-keeping support (LKS) system and the ACC system are available for the driver on the host vehicle. The aim of the LKS system is to reduce the driver's workload to keep the host vehicle within its driving lane. Recognizing the lateral position of the host vehicle in the lane, the LKS system assists the driver's steering control to keep the car center of the lane with the use of the power steering system. The ACC system is a partial automation for longitudinal control, designed to reduce the driver's workload by freeing him or her from frequent acceleration and deceleration actions. The ACC system controls the own vehicle so that it can follow a vehicle ahead (*the target vehicle*) at a driver-specified distance by controlling the engine and/or power train and potentially the brake.

When the ACC system detects the deceleration of the target vehicle, it slows down the host vehicle at some deceleration rate. As long as the deceleration of the target vehicle stays within a certain range (say, not greater than 0.2G, where G denotes the acceleration of gravity), the ACC system can control the speed of the host vehicle perfectly and no rear-end collision into the target vehicle occurs. However, when the target vehicle makes a rapid deceleration at a high rate (e.g., 0.4G), the ordinary brake by the ACC system may not enough to avoid a collision into the target vehicle. How to prepare for such cases is one of significant design issues.

3.2 Design Alternatives to Cope with Rapid Deceleration of the Target Vehicle

Suppose the ACC system recognizes that the deceleration rate of the target vehicle is much greater than 0.2G, the maximum deceleration rate to which the ACC system can cope with the ordinary automatic brake. The following design alternatives may be feasible:

Scheme 1

Upon recognition of a rapid deceleration of the target vehicle, the ACC system gives an *emergency-braking alert* that tells the driver to hit the brake pedal himself of herself hard enough to avoid a collision.

The level of automation (LOA) of this scheme is 4 (see, Table 1). If the driver disregards or fail to respond to the alert, only the ACC system can do is to continue applying its ordinary brake.

Scheme 2

Upon recognition of a rapid deceleration of the target vehicle, the ACC system gives an emergency-braking alert, and if the driver does not respond within a pre-specified time (e.g., 2 seconds), it applies an automatic emergency brake that decelerates at the rate of 0.4G.

The LOA of this scheme is 6 (see, Table 1). The driver may stop activation of the automatic emergency brake when he or she disagrees with the ACC system. On the other hand, if the driver fails to respond to the alert within 2 seconds (due to his/her inattentiveness or delay in situational recognition), the ACC system applies its emergency brake.

Scheme 3

Upon recognition of a rapid deceleration of the target vehicle, the ACC system applies its automatic emergency brake to implement the deceleration rate of 0.4G simultaneously when it issues an emergency-braking alert.

The LOA of this scheme is 6.5 (see, Table 1). An aim of this scheme is to avoid any delay in the automatic emergency brake. The emergency brake is to be applied 2 seconds earlier, compared with the case of Scheme 2. Another aim of Scheme 3 is to avoid automation surprises by telling the driver explicitly what the automation is about to do. The latter point may be understood more easily by comparing with the following scheme.

Scheme 4

Upon recognition of a rapid deceleration of the target vehicle, the ACC system firstly applies its automatic emergency brake with the deceleration rate of 0.4G. Then, the ACC system tells the driver that it applied an emergency brake some seconds ago.

The LOA of this scheme is 7 (see, Table 1). From the viewpoint of swiftness of the emergency brake, Schemes 3 and 4 are indifferent. However, in case of Scheme 4, the driver may fail to recognize what is going on, when the ACC system applies its emergency brake. Thus, Scheme 4 shall not be investigated further in this paper.

3.3 Driver's Psychological States

While observing the automation behaves correctly and appropriately, it is natural for the driver to trust in the automation. Sometimes he or she may place excessive trust in the automation. In such cases, the driver may fail to allocate his or her own attention to the driving environment, and may pay attention inappropriately to some non-driving tasks (such as, using a mobile phone, manipulation of on-board audio systems).

This paper distinguishes the following five psychological states for the driver, by modifying the original model by Hashimoto [4]:

State I: Subnormal and inactive state.
State II: Normal and relaxed state, with complete faith in the automation.
State II+: Normal and relaxed state with moderate level of trust in the automation.
State III: Normal and vigilant state (the best state for safe driving).
State IV: Hyper-normal and excited state.

Each state is characterized by a corresponding driver performance in situation recognition, response time to an emergency-braking alert. For instance, in case of State II, the driver may be choosing a favorite musical piece from a CD in his/her on-board audio system, by assuming that "The ACC system shall respond appropriately when the target vehicle makes a deceleration."

3.4 Dynamic Transition of Driver's Psychological States

It is assumed that, when the driver starts driving, his or her psychological state is positioned initially at State III (the best for safe driving), and that the state changes downward (e.g., from State III to II+) as the time goes by while observing successful longitudinal control by the ACC system. However, if the driver feels alarm by some reason, his or her psychological state may change upward (e.g., from State II+ to III).

This paper distinguishes the following two types of events in which the ACC system can perform its longitudinal control with the ordinary brake.

Type-1 Event:
The target vehicle decelerates at a certain rate and the ACC system performs its longitudinal control perfectly so that it may satisfy the driver completely.

Type-2 Event:
The target vehicle decelerates at a rate not greater than 0.2G. The ACC system can cope with the situation within the ordinary brake. However, the driver feels alarm because his/her car comes close to the target vehicle.

The contributions of the events to transitions of the driver's psychological state are defined as follows:

(1) If the driver experiences a certain number (say, 10 or 20) of the Type-1 events consecutively, his or her psychological state changes one step downward.

(2) If the driver experiences a Type-2 event, his or her psychological state changes one step upward.

(3) State I is the absorbing state; viz., once the driver enters into State I, he or she never comes out of the state even if a Type-2 event may occur.

This paper tries to investigate the automobile safety when the target vehicle makes a rapid deceleration, to which the ACC system must, either (i) issue an emergency-braking alert to urge the driver to apply the emergency brake himself or herself, or (ii) activate the automatic emergency brake that is far stronger than its ordinary brake.

The driver's response upon the emergency-braking alert differs depending on which psychological state he or she is when the alert has been issued:

(1) If the driver was in State I when the alert was set off, he or she does not respond to the alert at all.

(2) Suppose the driver was in State II. With probability 0.8, he/she stays in the state, and hits the brake pedal in T2 seconds. With probability 0.2, the driver state changes to State IV.

(3) If the driver was either in State II+ or in III, he or she applies the emergency brake himself or herself either in T2+ or in T3 seconds, respectively.

(4) In State IV, the driver panics and fails to take any meaningful actions to attain car safety.

In the above, T2, T2+, and T3 are random variables with different means (specific values are given in the next section for an illustrative example).

4 Computer Simulations

The experiment has a 2 x 3 x 3 x 2 x 2 factorial design, mapping onto (*Headway Distance*) x (*Level of Automation*) x (*Event-Mixture Ratio*) x (*Driver's Psychological State Transition Condition*) x (*Trip Length*).

Two levels, 80m and 50m, were distinguished for the *Headway Distance* between the host and the target vehicles.

Three *Levels of Automation*, LOA-4, LOA-6, and LOA-6.5, were assigned to the design alternatives for cases of a rapid deceleration of the target vehicle.

The *Event-Mixture Ratio* denotes the proportion of the number of Type-2 events to the total sum of the numbers of Type-1 and type-2 Events before the target vehicle makes a rapid deceleration. The Event-Mixture Ratio was set at 0%, 10%, or 20%.

Two cases, 10 and 20, were investigated for the *Driver's Psychological State Transition Condition*: In case of the former, if the driver experiences 10 Type-1 events consecutively, his or her psychological state changes one step downward. In the latter, 20 consecutive Type-1 events makes a downward state transition.

The *Trip Length* was measured in terms of the number of the total sum of the Type-1 and type-2 Events before the target vehicle makes a rapid deceleration. In the present study, the Trip Length was either 100 or 50.

For each combination of the conditions, 5000 Monte Carlo runs were performed with WinCrew (Micro Analysis and Design, Inc.), under the following assumptions:

(1) When the target vehicle slows down at a certain deceleration rate not greater than 0.2G, the ACC system of the host vehicle begins to decelerate 0.5 seconds after the initiation of the target vehicle's deceleration, where the ACC system applies the brake at the rate of 0.2G.

(2) The target vehicle makes a rapid deceleration, at the rate of 0.4G, while it has been running at the speed of 100km/hr.

(3) At the time of the rapid deceleration of the target vehicle, the host vehicle has also been running at the same speed, following the target vehicle. When detecting a deceleration of the target vehicle, the ACC system firstly applies its ordinary brake. One second after initiation of the ordinary braking, the ACC system recognizes that the deceleration of the target vehicle cannot be handled by the ordinary brake, and issues an emergency-braking alert.

(4) Suppose Scheme 2 with LOA-6 has been active on the ACC system. Then the ACC system applies its automatic emergency brake if the driver did not hit the brake pedals within 2 seconds. The emergency brake can decelerate the host vehicle at the rate of 0.4G. If Scheme 3 with LOA-6.5 was the case, the ACC system applies the emergency brake upon the emergency-braking alert.

(5) When the drive hits the brake hard enough, he/she can make a deceleration at the rate of 0.5G. The driver's response time to the emergency-braking alert varies depending on the psychological state at that time moment. If the driver was either in State I or IV, he/she fails to apply the brakes. The response time T2 (in State II) is uniformly distributed over the interval [2.7s, 3.3s], with the mean 3.0s. The response time T2+ (in State II+) is uniformly distributed over the interval [1.8s, 2.2s], with the mean 2.0s. The response time T3 (in State III) is uniformly distributed over the interval [1.35s, 1.65s], with the mean 1.5s.

5 Results

At the end of each trip (the length of which is either 100 or 50), the target vehicle makes a rapid deceleration at the rate of 0.4G. The number of accidents (collisions into the target vehicle) was counted during 5000 Monte Carlo runs for each combination of the conditions in five factors.

5.1 Observations for cases with the trip length 100

Table 2 shows the number of accidents and the distribution of the driver's psychological states when the trip length was 100.

5.1.1 When the headway distance was 80m

Comparing LOA-4, LOA-6, and LOA-6.5 for the cases where the Driver's Psychological State Transition Condition was set at 10, the number of accidents under LOA-4 was siginificantly larger than either of those under LOA-6 and LOA-6.5. The property becomes more apparent as the Event-Mixture Ratio becomes smaller. The results implies the following :

When the driving is rather peaceful in the sense that Type-2 events seldom occur and the ACC system continues to be successful in its longitudinal control, the driver is likely to rely on the ACC system, and then his or her vigilance may degrade (see, Table 2, the Driver's Psychological State at the time of the rapid deceleration). If the target vehicle makes a rapid deceleration in such cases, the driver may need time to recognize what is happening and thus may not be able to cope with the circumstance in a timely manner, even if an emergency-braking alert is given. High LOA can be effective to assure car safety under time-criticality, especially when the driver may be inattentive.

5.1.2 When the headway distance was 50m

Table 2 shows that, in case of LOA-6.5, the number of accidents remains naught, irrespective of the Headway Distance and the Event-Mixture Ratio. However,

Table 2. Computational results of automobile safety at the rapid deceleration of the target vehicle (Trip length was 100).

LOA	Psychological state transition condition	Event-mixture ratio	# Runs ended in collision		Driver's psychological state at the emergency-braking alert				
			Headway distance: 80m	Headway distance: 50m	State I	State II	State II+	State III	State IV
4	10	0%	5000	5000	5000	0	0	0	0
		10%	1300	1478	1232	264	1003	2433	68
		20%	28	41	24	19	415	4538	4
	20	0%	4203	4786	3999	797	0	0	204
		10%	9	19	1	16	455	4520	8
		20%	0	0	0	0	34	4966	
6	10	0%	0	5000	5000	0	0	0	0
		10%	0	1280	1218	282	987	2451	62
		20%	0	36	27	32	415	4517	9
6.5	10	0	0	0	5000	0	0	0	0
		10%	0	0	1307	259	984	2375	75
		20%	0	0	22	27	426	4519	6

Table 3. Computational results of automobile safety at the rapid deceleration of the target vehicle (Trip length was 50).

LOA	Psychological state transition condition	Event-mixture ratio	# Runs ended in collision		Driver's psychological state at the emergency-braking alert				
			Headway distance: 80m	Headway distance: 50m	State I	State II	State II+	State III	State IV
4	10	0%	4171	4768	3981	829	0	0	190
		10%	270	418	198	214	1206	3310	72
		20%	9	15	2	7	382	4602	7
	20	0%	203	748	0	781	1979	2037	203
		10%	0	0	0	0	339	4661	0
		20%	0	0	0	0	9	4991	0
6	10	0%	0	4206	4009	794	0	0	197
		10%	0	299	234	231	1172	3298	65
		20%	0	4	0	14	414	4568	4
6.5	10	0	0	0	4023	794	0	0	183
		10%	0	0	245	245	1197	3248	65
		20%	0	0	0	15	375	4603	7

accidents occur in case of LOA-6. For instance, 1280 accidents occur in 5000 trips if the Event-Mixture Ratio was 10. Why was LOA-6 so ineffective? The reason lies in the *time-delay* (2s in the current simulation) introduced to the LOA-6 scheme for enabling the driver to initiate his/her emergency brake in that time period. Do we have to make the time-delay shorter, say to 1s? Such a discussion needs a great care, because the investigsation may be unrealistic or meaningless (e.g., imagine, whether 1s is long enough for the human to catch an alert, understand its implication, and implement some required action).

It would be easy to predict that, as the headway distance becomes shorter, the number of accidents may become larger. In fact, under LOA-4, the number of accidents increases from 1300 to 1478, as the headway distance becomes shorter from 80m to 50m. The increase under LOA-6 is drastic.The number of accidents increased from 0 to 1280, as the headway distance becomes shorter from 80m to 50m. Even though the number of accidents (1280) under LOA-6 is significantly smaller than 1478 with LOA-4 in the same settings, the increase in the number of accidents from 0 to 1280 is statistically significant. This unsatisfactory result of LOA-6 is also due to the time-delay of the safety control action.

An interesting observation may be made by comparing the number of accidents (1280) under LOA-6 with 19 under LOA-4 where the Driver’s Psychological State Transition Condition was set at 20. The larger number as the state transition condition represents that, when the driver is responsible in applying the emergency brake at all times and on every occation, the driver may stay vigilant than in cases where the automation is supposed to take safety control actions when necessary.

Then a small question arose. Even under LOA-6, can the number of accidents be reduced, if the Driver’s Psychological State Transition Condition is changed from 10 to 20? The answer was affirmative. Additional 5000 Monte Carlo runs were performed for the LOA-6 scheme when the Driver’s Psychological State Transition Condition was set at 20. The number of accidents was reduced drastically to 4 (recall, the number of accidents was 1280 when the State Transition Condition was set at

10). The result shows the need of measures to keep the driver vigilant without over-trust in the automation.

That does not mean, however, that the level of automation has to be kept low. As a matter of fact, the difference between the number of accidents (0) under LOA-6.5 and the number of accidents (19) under LOA-4 is statistically significant. The same comment applies to the case in which the Headway Distance was 80m.

5.2 Observations for cases with the trip length 50

Table 3 shows the number of accidents and the distribution of the driver's psychological states when the trip length was 50. The shorter trip case may be regarded as an early or an intermediate stage of a longer trip. When the Driver's Psychological State Transition Condition was set at 20 when the trip length was set at 50, it would be easy to anticipate that the driver is less likely to become trust overly in the automation. The anticipation has been confirmed by Table 3 (see, the Driver's Psychological State). Almost the same observations as in section 5.1, apply to the current cases.

6 Concluding Remarks

This paper investigated the characteristic properties of the levels of automation of a scheme for safety control of automobile under time-criticality, by taking the driver's interaction with the ACC system. It has been shown, via computer simulation, that a safety control scheme with LOA-6 may not be effective, compared to a scheme under LOA-4, if the driver may trust in the automation excessively. It has been shown also that the drawback of the LOA-6 may be mitigated through some measures to keep the driver alert. However, the LOA-6 scheme still has a problem that stems from the time-delay of the automatic action. It has been shown in the current simulation study that the LOA-6.5 scheme is more effective than LOA-6 or LOA-4, for attaining safety under extremely time-critical situations or under possibility of driver's complacency. Note that the power of the computer simulation approach given in the present paper lies in its flexibility and ease of parametric investigations by combining with perturbation analytic approaches.

Acknowledgments

The authors thank Kiyonobu Itoh, Graduate School of Systems and Information Engineering, University of Tsukuba, for his contributions in the early stage of modeling of the driver's psychological states.

This work has been partially supported by Grant-in-Aid for Scientific Research 14380186 of the JSPS.

References

[1] H. Furukawa, T. Inagaki, Y. Niwa, "Operator's situation awareness under different levels of automation; Evaluations through probabilistic human cognitive simulations," *Proc. IEEE SMC Conf.*, pp.1319-1324, 2000.

[2] H. Furukawa, Y. Niwa, T. Inagaki, "Levels of automation in emergency operating procedures for a large-complex system: probabilistic analysis on human-automation collaboration," *Proc. HCI International 2001*, Vol. 1, pp.1513-1517, 2001.

[3] H. Furukawa, M. Sato, T. Inagaki, "A probabilistic simulation method for evaluation of task allocation schemes in ship management," *Proc. IASTED Conference: Modelling, Identification and Control*, pp.533-538, 2001.

[4] K. Hashimoto, *Safe Human Engineering*, Chuo Rodo Saigai Boushi Kyokai, 1984 (in Japanese).

[5] T. Inagaki, "Situation-adaptive autonomy for time-critical takeoff decisions," *Int'l J. Modelling and Simulation*, 20(2), pp. 175-180, 2000.

[6] T. Inagaki, "Adaptive automation: design of authority for system safety," Proc. IFAC CTS, pp. 13-22, 2003.

[7] T. Inagaki, "Adaptive automation: Sharing and Trading of Control," In E. Hollnagel (Ed.) *Handbook of Cognitive Task Design* (pp. 147-169). LEA, 2003.

[8] T. Inagaki, N. Moray, M. Itoh, "Trust and time-criticality: Their effects on the situation-adaptive autonomy," *Proc. IHAS-AIR*, pp. 93-103, 1997.

[9] N. Moray, T. Inagaki, "Attention and complacency," *Theoret. Issues Erg. Sci.*, 1(4), pp. 354-365, 2001.

[10] N. Moray, T. Inagaki, M. Itoh, "Adaptive automation, trust, and self-confidence in fault management of time-critical tasks," *JEP: Applied*, 6(1), pp. 44-58, 2000.

[11] R. Parasuraman, R. Molloy, I.L. Singh, "Performance consequences of automation-induced complacency," *Int. J. Aviation Psychology*, 3(1), pp. 1-23, 1993.

[12] T.B. Sheridan, *Telerobotics, automation, and human supervisory control*, MIT Press, 1992.