**Preprints of the 19th World Congress**
**The International Federation of Automatic Control**
**Cape Town, South Africa. August 24-29, 2014**

# Cognitive Causality Modelling for Human Behavior: The Method and Its Applications

**Yuji Takada*,***, Taku Naito**, Tetsuo Sawaragi*****

**Nissan Research Center, Nissan Motor Co., Ltd., Atsugi-shi, Kanagawa 243-0123, Japan, (e-mail: taka-yuji@mail.nissan.co.jp)*
***Fujitsu Quality Laboratory Ltd., Kawasaki-shi, Kanagawa 211-8588, Japan (e-mail:naito.taku@jp.fujitsu.com)*
**** Department of Mechanical Engineering and Science, Kyoto University, Kyoto, Japan, (e-mail: sawaragi@me.kyoto-u.ac.jp)*

**Abstract:** The method for modeling dynamic characteristics of human and mechanical system is proposed. Causal Loop Diagram (CLD) is applied to develop the method which is named Cognitive CLD (C-CLD) to describe dynamics aspect of mutually transforming relationship between human and mechanical system by focusing on human's cognitive process. This modeling method was tried to apply for modeling an automotive driving and also its created models are also examined whether it can be used for specific purpose, such as simulation, evaluation and system designing. These results suggested that the proposed method can be not only used for modeling dynamic characteristics of human-machine system but also understanding human's proactive behavior to achieve system resiliency.

*Keywords:* Driver support, driver model, resilience, complex system, human operator performance assessment, human-machine system, distributed cognition and automation.

## 1. INTRODUCTION

Describing image of human user is important process when mechanical system is designed. The process is generally called user-modelling, and most of user models are categorized into 2, i.e. internal state model and input-output model (Michion 1985). Internal state model aims to achieve clear explanation of his/her decision and behavior during using mechanical system. Input-output model aims to simulate human behavior during using mechanical system by implementing the model on computer. Both types of human modelling help to understand the interaction between human and mechanical system and contribute to achieve appropriate mechanical system design.

When designing mechanical systems which involve time shifts, both types of human-model are also referred to capture dynamic aspect of human behavior. Here, internal state model is used to acquire the description on changes of human's mental state according to environmental transitions. Input-output model provides calculation of human behavior with respect to the environmental change, on the other hand.

However, it should be focused on that these models assume human as a reactive factor for the environmental stimulation. It is unavoidable fact that human sometimes makes mistake. As a result that the reactive aspect has been too much focused on, the internal stress of operator who made mistake is too much brought up regarding internal state model. In terms of input-output model, if the reactive aspect is strictly replicated, the model produces outputs with variability and/or probabilistic errors. As the result of having been both types of model referred when mechanical system is designed, the mechanical system are designed to prevent human's errors by employing automation technologies for example. But this policy has brought other difficulties. (Bainbridge 1983)

On the contrary, theories in resilient engineering (Hollnagel 2006) persuade positive involvement of human in operation of mechanical system rather than excluding human factors from the system design, because the recent analysis revealed that human is proactively contributing to improve robustness and persistent operation of mechanical system. This background gives enough motivation to start the study on methods for involving human as an essential component of system. The point to realize this relationship is how to make human involve in the system as a proactive agent rather than reactive one. To do so, the method for modelling human's proactive characteristics is also investigated.

In this paper, a modelling method which can deal human's proactive aspect is proposed.

## 2. PROPOSITION

### *2.1 Cognitive Causality Loop Model*

The purpose of this research is to develop the modelling method which can model successive driving as usual. The hypothesis of successive drive here is that drivers always finely pick off the sign of accident before the sign becomes reality. This hypothesized feature of driver can be explained by Neisser's perceptual cycle model (Neisser 1973). This model illustrates that human cognitive proceeds fundamentally recurrently, i.e. the cycle of information seeking, making behavior and recognizing changes, and this cyclic characteristics promotes corrective behavior and learning. To model this process within driving behavior, Causal Loop Diagram (CLD) is applied.

CLD implicitly involves behavior of dynamic system in qualitative manner. Sterman(2000) exampled a few system architectures and each of them outputs typical characteristics of time-series dynamics. Owing to these characteristics behind, CLD can describe complex system behavior by combining these componential systems. CLD model is consists of nodes, links which connects between nodes based on those causality, sign which indicates the causality is positive or negative and delay. In this paper, CLD is modified as follows to describe human's cognitive behavior, and the modified CLD is named Cognitive CLD (C-CLD).

*2.2 Node and link*

The target of modelling is proactive human behavior which interacts with environment and automobile. As explained briefly, the kind of proactive behavior is cognitively recurrent. To model this cyclic feature, 4 kinds of node (i.e. State, Observation, Environmental Restriction and Consequence of Behavior) are prepared and these nodes are connected by allow diagrams as in Fig.1. Here, it is notable that this basic structure can be kept when any human behaviors are modelled.

This modelling is processed as follows. For example, when driver press an accelerator pedal, accelerator of vehicle will be opened according to the degree of driver's press. In this case, the degree of accelerator opening is the "consequence". As a "consequence of behavior", mechanical system and its surrounding environment change or maintain their state, i.e. the vehicle accelerates or keeps its speed. The updated "state" is observed by driver. The "observation" is mostly evaluated by referring "environmental restriction", i.e. the speed is high or slow is up to the given environmental restriction.

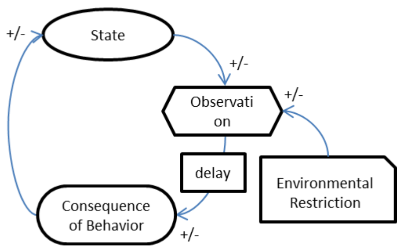


Fig.1. Basic structure of proposed model

*2.3 Sign*

There are two types of causalities between two nodes, positive causality and negative causality. Positive causality is like follows, the wider the accelerator opens, the higher the speed becomes. On the other side, negative causality is like follows, the stronger the brake is pressed, the slower the speed becomes. '+' is attached to the link to indicate positive causality. And also, '-' is attached to the link to indicate negative causality.

*2.4 Delay*

Delay is a sort of time and it can be put on the link so that timing of node transition can be controlled. In generally, any link accepts the delay. For example, any mechanical system shows delay between human operation and system reaction. This delay could be allocated on the link between "Consequence of Behavior" and "State". The duration between the timing of state changes and the timing human noticed the change is another example of delay. This delay could be allocated on the link between "State and Observation". But, in this paper, only the delay between "Observation" and "Consequence of Behavior" is focused on (Fig.1). This is because only this delay can reflect human's proactive characteristics. It is natural way of operation that human decides his/her operational timing by observing gap between current state and the ideal state. If the gap is within the tolerance (Woods 2006) which current situation allows, human don't have to make his/her operation. This means, if the tolerance is large, driver can take long delay and don't have to operate immediately so that human can share his/her operational resources to other operation. On the contrary, if the tolerance is small, driver should make decision immediately and operate frequently because small delay is allowed. Moreover, if delay can be regarded as infinity, human can ignore the loop.

## 3. EXPERIMENT

Driving behavior is selected to achieve human behavior model by applying proposed method. To collect the data for the modelling, an experiment is conducted.

*3.1 Experimental Conditions*

Traffic environments are simulated by using PC based driving simulator. Front, left and right driving environment are displayed in front of participants through three 26" large monitors (Fig.2). The road is 500m length, and guardrail is placed along the both side. 3 kinds of road widths are prepared, i.e. 2.79m, 4.185m and 5.58m. 3 kinds of condition of pedestrian are also prepared, i.e. 0 person/100m, 1 person/100m and 2 persons/100m. All the combinations result in 9 experimental conditions. Fig.3 shows the condition with 4.185m road width and 2 pedestrians/100m.

*3.2 Experimental Procedure*

10 males participated in this experiment. Before the actual experimental run, each participant conducted practice runs until they used to simulator driving. The practice took from 8 minutes to 20 minutes. After the practice, all 9 conditions of experiments were conducted. The order of these conditions was varied by each subject to cancel the order effect.

Participants were requested to image to drive as usual on the road with 30km/h speed limit. And, they were also requested to drive not to contact with pedestrians or guardrail.

Fig.2. Experimental setup

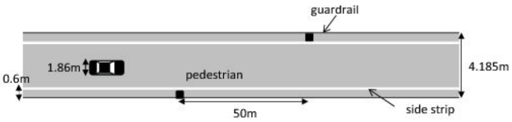


Fig.3. An example of driving condition for experiment

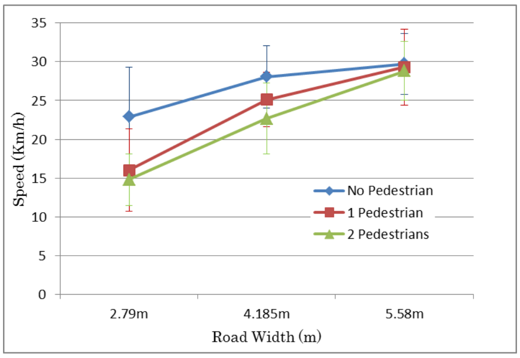


Fig.4. Comparison of speed with respect to conditions

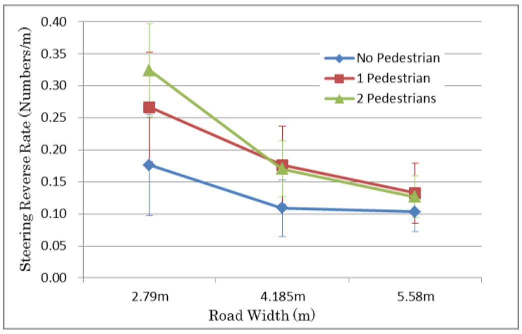


Fig.5. Comparison of SRR with respect to conditions

*3.3 Results*

Fig.4 shows that the comparison of averaged vehicle speeds with regard to each experimental condition. 2 typical characteristics are observed from this figure. The first is that when the road width gets wider, the vehicle speed gets faster. The second is that when the pedestrians are appeared on the road, the speed gets slower. However, the effect of the number of pedestrian is not clear. Fig.5 shows that the comparison of Steering wheel Reversal Rate (SRR) with regard to each experimental condition (McLean, Hoffman 1975). Here, SRR is calculated from time-series data of steering angle by picking up extreme value and counting the number of picked extreme per predetermined distance, which was 100m long in this research. From this figure, 2 typical characteristics are observed. The first is that when the road width gets wider, SRR gets smaller. The second is that when the pedestrian is appeared on the road, SRR gets bigger.

More precisely observed, when the road width is 5.58m, the speed converge with 30km/h, which is the speed participants are requested as speed limit, independent from the number of pedestrians. On the contrary, driver could not achieve to 30km/h in the conditions of other road width. The condition of narrower road width and existence of pedestrian prevent driver from driving at higher speed.

## 4. MODELING

Driving behaviors are modelled by applying the proposed method (C-CLD) to the previous experimental results. From simple model to complicated, 3 models are organized below.

*4.1 Speed Keeping*

Automotive vehicle increases its speed *(state)* according to the opening ration of accelerator *(consequence of behavior)*. The opening ratio is decided by driver the difference between the current speed and desired speed *(observation)*. This desired speed is usually decided by environmental limitation, such as regulation, existence of other vehicle, etc. In this experiment, participants are requested to image their driving is limited at 30km/h *(environmental restriction)* and the result indicates that participants are regulated at the speed 30km/h, especially in the conditions with 5.58m width (Fig.4). These causalities can be modelled as Fig.6.

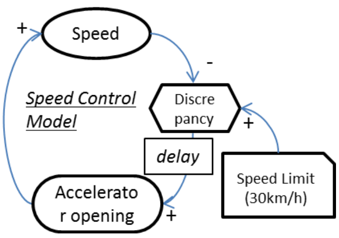


Fig.6. Speed Keeping Model

In this model, “delay” is attached on the link between “discrepancy” and “accelerator opening”. This is because driver may not strictly keep the speed at a target. In generally, the speed and accelerator opening is fluctuated.

*4.2 Travelling within a Lane*

Vehicle itself has a trend to go off the road if driver does not give any steering control. For this reason, travelling within a lane is one of essential tasks of driving. Based on the causality, the model of travelling within a lane is described in Fig.7 by adding specific loops (in red) to the previous speed keeping model. This model consists of dual loop, the inner loop is the model for steering behavior and the outer loop is the model for braking behavior.

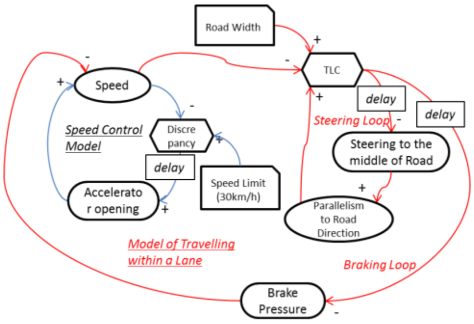


Fig.7. Model of Travelling within a lane

**Steering behavior loop:** The experimental results with no pedestrian show the trend that SRR indicates smaller when the road width becomes wider. This result comes from driver's steering behavior to keep the vehicle within the given lane. It is reported that the steering behavior is caused by driver's perception of TLC (Time to Line Crossing), which is cognitively recognized as time in sensation level of human (Godthelp, Milgram, Blaauw 1984). TLC can be placed as *"observation"* node to start with. When TLC gets smaller, driver should steer to the middle of a road frequently *(consequence of behavior)*. This is because TLC arises when the travelling direction is not parallel to the road direction *(state)*. Of course, TLC gets longer when the road-width is larger *(environmental restriction)*, which appropriately follows the experimental result with respect to SRR.

**Brake behavior loop:** From the definition, TLC gets longer when the speed becomes slower. From this point of view, the experimental result with no pedestrian which showed the trend of slower speed according to narrower road-width was reasonable. Here the "speed" node as "*state"* in the speed control loop can be negatively linked with TLC. And also, "brake pressure" node can be negatively linked after TLC as a *"consequence of behavior"*. These links describe when TLC gets smaller, driver sometimes press brake pedal to increase brake pressure. Then the vehicle reduces its speed and TLC gets longer.

**Delay:** Delay supports dynamical behaviors of sub-loops in the proposed model. There are 3 delays in this model, the delay between "Discrepancy" and "Accelerator opening", the delay between "TLC" and "Steering to the middle of the Road" and the delay between "TLC" and "Brake Pressure". The experimental result in Fig.5 shows the trend that wider road causes smaller SRR. SRR is the value of steering frequency, so the smaller SRR indicates the longer cycle of steering control loop in this model. This model behavior can be simulated by putting longer time to the delay between "TLC" and "Steering to the middle of the road ".

The comparison of the delay between "Discrepancy" and "Accelerator opening" and the delay between "TLC" and "Brake Pressure" is also suggestive. The experimental result shows slower speed below 30km/h on several experimental conditions. This indicates that "loop of Travelling with a Lane" is prioritized to "Speed Control Loop". This dynamics can be simulated by putting infinity time to the delay between "Discrepancy" and "Accelerator opening".

### *4.3 Collision Avoidance*

By focusing the causality, the model of collision avoidance is described in Fig.8 by adding specific loops (in green) to the model of "Travelling within a Lane". This model also consists of dual loop, the inner loop is the model for steering avoidance and the outer loop is the model for braking avoidance.

**Steering avoidance loop:** Driver has to avoid pedestrians, bicycles and obstacles on the road. The experimental results of conditions which pedestrians walking show the trend which the wider the road-width becomes, the smaller the SRR indicates. To explain this fact, it is appropriate to introduce TTC in the model. It is said that approximation to pedestrian is cognitively recognized as time in sensation level of human (Hayward 1972). The time is called "TTC (Time to Collision)". Here, "TTC" can be placed as *"observation"* node. When TTC gets smaller, driver should steer to the direction of lane boundary of road *(consequence of behavior)* to avoid collision. However, this consequence is against to the policy modelled as "Travelling within a Lane". It is therefore, "Steering to Lane Boundary" node is negatively linked to "Parallelism to the road direction" node. The causality after "Parallelism to the road direction" node is same as "Travelling within a Lane" explained previously.

**Brake avoidance loop:** As is the definition of TTC, TTC is obviously gets longer when the speed is slower. From this point of view, it was appropriate experimental results that conditions with pedestrian(s) indicate the trend of slower vehicle speed than these with no pedestrian conditions. Here the speed *"state"* in "speed control loop" can be negatively linked with "TTC" node. And also, "brake pressure" node in "Travelling within a Lane" model can be negatively linked after "TTC". These links describe when TTC gets smaller, driver sometimes press brake pedal to increase brake pressure. Then the vehicle reduces its speed and TTC gets longer.

**Delay:** In addition to the delays which included in "Travelling within a Lane" model, 2 delays are allocated, i.e. the delay between "TTC" and "Steering to Lane Boundary" and the delay between "TLC" and "Brake Pressure". These delays are managed according to 3 observations, i.e. "Discrepancy", "TLC" and "TTC". When steering behavior is focused on, driver takes care of both "TLC" and "TTC". According to the given TLC and TTC, driver should manage both the length of delay between "TLC" and "Steering to the middle of a road" and the delay between "TTC" and "Steering to Lane Boundary" to prevent both lane departure and collision at the same time. If TLC and TTC get shorter, steering frequency increases higher by shortening both delays. The experimental result of SRR follows this consideration.

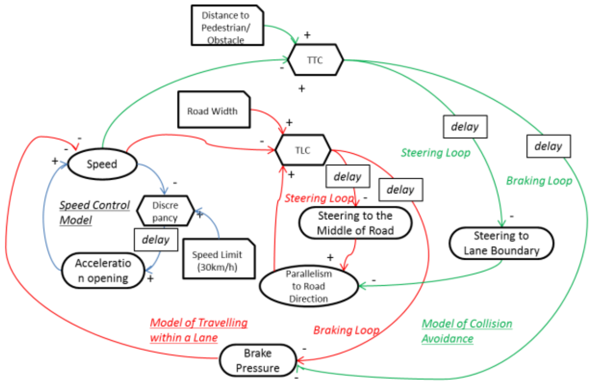


Fig.8. Model of collision avoidance

## 5. DISCUSSIONS

In this chapter, 3 usages of the proposed model are discussed.

### 5.1 *Simulation of Driving Behavior*

Dynamic behavior of system can be simulated by using the proposed model. In the simulation, important process can be presumed by finding nodes with multiple inputs and/or outputs are linked. For example, 2links with different sign respectively are plugged into "Speed" node in "Speed Control" model. If the one from "Brake Pressure" node is focused on, it is easily found that the policy decreasing speed by increasing brake pressure results in increasing the both length of TLC and TTC. This means that this braking policy significantly contributes to improve driving safety by achieving both "preventing lane departure" and "avoiding pedestrians". But once the other link from "Acceleration opening" node is focused on, it is also easily found that this safety policy is achieved by waiving "Speed Control Loop". This truth derives an expectation that if the given environment were consisted of wide-road and no pedestrians, the vehicle could be driven going along with "Speed Control" model, and if there was a solution which could prevent both lane departure and avoid collision simultaneously without decreasing speed, driver might choose the solution.

### 5.2 *Understand of Mental Workload Regulation*

Understanding of mechanism of regulating mental workload is explored in this section. SRR is one of popular indices to estimate mental workload. As described in 4.2 and 4.3, under the environment where TLC or TTC is short, the proposed model explains higher frequency of steering loop caused by given shorter delay. This means steering frequency also gets shorter, i.e. SRR becomes smaller. This trend can be also observed from the subjective rating, also popular method for estimating mental workload. Here, at the experiment in chapter 3, each participant was rated the workload by filling NASA-TLX (Hart, Staveland 1998) every after the experimental condition. The normalized AWWL scores according to the condition of road width and the number of pedestrian(s) are shown in Fig.9. In this figure, 2 trends are observed. Firstly, the wider the road width becomes, the smaller AWWL score indicates. Secondly, "no-pedestrian" condition indicates lower AWWL score than that of 1 or 2 pedestrian(s) condition. These trends are similar to the calculated SRR.

Recently, the notion of workload homeostasis is proposed. The theory explains that driver usually work homeostatically to achieve an 'optimal level' of workload by seeking tasks (Fuller 2005). If this theory is followed, driver may change their behavior under the environment of higher workload such as the environment with shorter TLC or TTC. To reduce the high workload situation, the proposed model indicates driver can select his/her behavior to reduce speed by pushing brake to achieve longer TLC or TTC. In actually, Fig.5 shows trend of lower speed in higher workload condition.

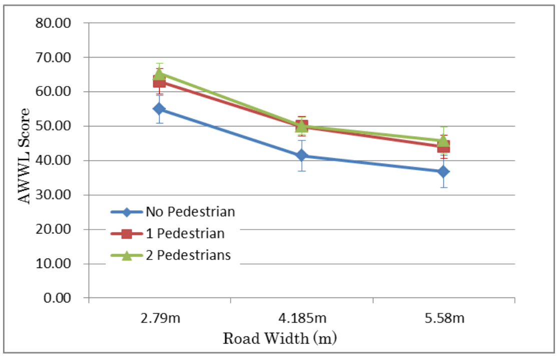


Fig.9. Comparison of AWWL score with respect to conditions.

### 5.3 *Design of Assisting Driver*

The most of current driver assisting systems sense worsening trends of relations between vehicle and its surroundings, and attempt to mitigate the trends by reducing the speed automatically. As is easily found out from models in Fig.7 and Fig.8, increasing brake pressure is actually effective policy to improve situation by extending TLC and TTC. On the other hand, as described in 5.1, this braking policy is waiving "Speed Control" loop, therefore this policy have possibility to cause cognitive dissonance (Festinger 1957) in driver. Especially, when the accidental occasion does not happen despite the autonomous speed reduction, the cognitive dissonance may be unable to disregard. This is one of the biggest issues of current driving assistant systems. To solve this issue, research on resilient engineering is making a strong suggestion that system dynamics in normal situation should be focused on more. This is because it turns out that system operator in dynamic system is how much contributing to make the system flows smoothly. Here, operators attempt to keep system operated as far as possible, rather than stop. It is naturally inferred that driver may prefer the driving assistant system which also assist driver to flow the vehicle continuously and smoothly.

If this kind of smooth driving is supported, the function of delay must be focused on. The experimental results in chapter 3 and the developed models in chapter 4 explained that driver might successfully achieve his/her driving by controlling each length of delays which are included in proposed models. This means that this prioritization of elemental driving tasks is the essential activity which prevents driving from collapsing and achieves smooth driving. Supporting driver's delay management is expected to effective policy which promotes driver's proactive involvement in driving.

2 methods for supporting delay management in driving are considered as below.

**Margin reduction:** As described in 2.4, driver set tolerance to the gap between the current state and the ideal state. If the gap is within the tolerance, driver is not required immediate operation. The gap usually includes margin to compensate driver's uncertainty in cognition. If the uncertainty is large, driver put large margin to the actual gap. This causes the size of tolerance is shrunk and driver should take his/her action immediately. Giving the sense of vehicle body in some way and providing visual information of blind area are supposed to be effective to reduce the margin and enlarge the tolerance. In particular, if the kind of merging is reduced, the tolerance on the road width is enlarged and TLC gets large. This means driver can put longer delay to the loop of the task.

**Offering Preview:** Driver can estimate the required delays by informed the situation ahead such as the width of coming road, the existence of obstacle on the road or speed limitation. When the kind of information are acquired preliminarily, it is possible that 2 competing tasks, such as preventing lane-departure and avoiding collision with obstacle, can be conducted sequentially in some case rather than simultaneously. Offering preview provides opportunity of proactive management of task handling with driver.

## 6. CONCLUSIONS

Cognitive CLD (C-CLD) which is applied Causal Loop Diagram (CLD) into human's operational task is developed and proposed. The aim of proposed modelling method is to achieve the description of contributing human activity to improve resiliency of dynamic system. To do so, the model itself is required to describe dynamics aspect of human activity, therefore the modelling method is put the characteristics of recursive configuration. Through the development, it turns out that any unit activities can be described by 1 closed loop. And also it turned out that the unit loop is consists of 4 nodes, links which connects nodes and delay which is put between "observation" node and "consequence of behavior" node.

As an example of human activity, vehicle driving is attempted to model. To process the modelling, an experiment with 10 participants is conducted and the collected data is used to model. 3 driving activities are tried to model by using C-CLD and the followings are understood.

- Dynamic driving activity was able to describe by using proposed C-CLD method.
- Multiple activities can be also described simply by combining these unit models.
- By focusing on "delay", allocation of human resources to multiple activities and task prioritization are expressible.

These features show sufficient possibility that proposed modelling method can be used for modelling the proactive aspect of human. Moreover, models developed by proposed modelling method could be actually used for 3 specific purposes, i.e. simulation of driving behavior, understanding of mental workload regulation and design of assisting system. These results suggest that the model developed by proposed modelling method is applicable for these purposes.

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