VEHICLE DRIVER'S DOMAIN FOR DRIVING ATTENTION ALLOCATION ANALYSES

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ABSTRACT

The increasing number of roadway accidents has led researchers to focus on accident-prone scenarios to get a clearer picture of the accident occurrences through accident chain. However, such scenarios explain the conditions and mechanism of a collision rather than its true cause. To fill the gap between occurrence and causality, analyzing individual drivers' attention allocation processes is vital for clarifying the nature of accidents. Noting that driving is a continuous process of information collection, drivers need to allocate attention to different objects to perceive useful information. Attention misallocation can be seen as the missing link between an accident-prone scenario and the occurrence of an accident. Modeling drivers' attention allocation in different conditions is a major step in identifying the external information drivers perceive and react to. The purpose of this research is to analyze the process of driving attention allocation through the divided attention model. Moreover, the concept of the vehicle driver's domain is proposed. By identifying the risk level of threats to safety in each type of vehicle driver's domain, the central allocation policy of attention resources can be identified.

INTRODUCTION

To enhance the understanding of accidents, researchers have worked on mining aggregated accident data to extract accident patterns. Numerous contributing factors, including the demographic characteristics of the driver (Chang and Yeh, 2007; Clarke *et al.*, 1998), vehicle (Albertsson, 2005; Chang and Yeh, 2006), road geometry (Chin and Quddus, 2003; Mitra *et al.*, 2002; Wang and Abdel-Aty, 2006), and environmental conditions (Eisenberg, 2004; Keay and Simmonds, 2006), have been found critical to roadway safety. Despite the significant effect of single factors, recent research has further claimed that accidents should be analyzed from a chain perspective in which remote factors also may contribute to their occurrence (Verschuur and Hurts, 2008; Wong and Chung, 2007a; 2007b; Wong *et al.*, 2010).

Exploring accident chains provides valuable clues that indicate accident-prone scenarios in which drivers usually have a higher risk of being involved in a dangerous situation. Such accident-prone scenarios explain mostly the conditions in which drivers face higher risks of being involved in an accident, and possibly the mechanism through which such accidents occur. However, an unanswered question remains, namely, why accidents occur under specific conditions. In fact, different drivers react differently in identical situations. While most drivers can still drive safely in a high accident risk scenario, but some fail to maintain safety, resulting in dangerous situations. The question thus arises: How do different reactions to identical conditions result in various outcomes. Answers to the question rely on the understanding of drivers – the decision-maker of a running vehicle.

Research conducted in different countries has suggested that human factors are the most important contributor to accident occurrence (Chen *et al.*, 2005; Horberry *et al.*, 2006a; Dahlen *et al.*, 2005; FMCSA, 2009; Liu and Lee, 2005; Makishita and Matsunaga, 2008; Reed-Jones *et al.*, 2008; Ulleberg and Rundmo, 2003). In Taiwan, for example, 85 percent of fatal accidents in 2008 resulted from human-related factors (such as traffic violations and aggressive behavior). Among those factors, “failed to note road conditions,” which can be considered as attention misallocation and failure of risk awareness, accounted for 22 percent of human-related fatal roadway accidents (MOTC, 2009). Research conducted in the United States also found that distraction and inattention of a driver are the most important human-related causes in accidents (FMCSA, 2009).

In fact, the frequent occurrence of failing to note road conditions represents distraction and misallocation of attention. Attention misallocation can be seen as the missing link between accident-prone scenarios and accident occurrence within the concept of an accident chain. Driving in an accident-prone scenario may not necessarily result in an accident, provided that the driver’s attention is well allocated. Attention misallocation in such scenarios will sharply increase the likelihood of an accident.

Noting that driving is a continuous process of information collection, comprehension, decision-making, and execution, collecting complete information is the key factor in safe driving. Driving-related information includes speed, the existence and attributes of other vehicles, roadway geometry, route information, signs, and traffic signals. Acquisition of incomplete or useless information will lead to insufficient comprehension of the current driving environment, misjudgment, and possibly accidents. To drive safely, drivers are forced to pay attention to multiple information sources in order to make correct driving decisions. Therefore, attention allocation issues arise.

Attention is consciousness and perception with focalization and concentration toward stimuli (Zomeren and Brouwer, 1994). The attention model proposed by Kahnement (1973) claimed that one’s mental resources are limited. Therefore, attention must be divided and given to different activities. The concept of divided attention is based on the idea of mental effort, which describes how demanding an activity might be. From a driver’s point of view, (s)he has a central processor of attention allocation policy to allocate mental resources and attention under the limit of attention capacity. Problems of divided attention may degrade the ability to detect potential threats while driving (Creaser *et al.*, 2007; de Waard *et al.*, 2009; Laberge *et al.*, 2006; Marmeleira *et al.*, 2009).

Driving distractions can be defined as attention misallocation and the shifting of attention from driving tasks to other stimuli activated by objects or events (FMCSA, 2009). Shifting attention away from road conditions and driving tasks may increase the time required to perceive and react to external stimuli, and thus increase accident risks (Neyens and Boyle, 2007). In-vehicle distraction caused by undertaking secondary tasks, especially cell phone communication, has attracted much attention from researchers. Numerous studies have proposed that using in-vehicle instruments, such as cell phones, navigation systems, or in-vehicle information systems, increases the amount of task activity and decreases drivers' ability to react to emergencies (Caird *et al.*, 2008; Horberry *et al.*, 2006a; Liu and Lee, 2005; Nunes and Recarte, 2002; Patten *et al.*, 2004). Furthermore, external clutter such as advertising billboards, roadside buildings, or traffic flow were also found to be critical to driving performance (Horberry *et al.*, 2006a). In addition to the degradation of risk perception, driving distractions can also be seen as misallocation of mental resources. Maintaining attentive focus on road conditions and vehicle operation is the primary task of driving. Undertaking secondary tasks can cause distraction and increase the mental workload.

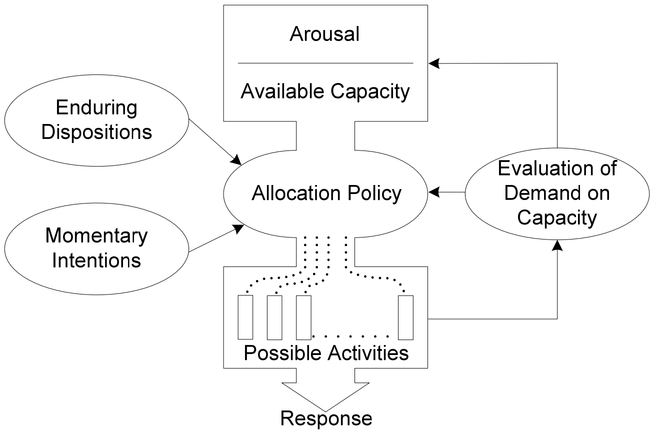
Furthermore, driving information provided to drivers may also cause distraction and increase mental tasks while driving. Providing driving information is intended to help driver better plan the allocation of mental resources and prevent dangers arising from uncertainty. From a user perspective, drivers note that providing more information can support decision-making and thus reduce task demands (Brookhuis and de Waard, 1999; Creaser *et al.*, 2007). Gathering real-time information, such as that regarding weather, traffic flow conditions, or accident-prone sites, reduces drivers' uncertainty and allows them to pre-allocate their mental resources to deal with future traffic conditions (Fuller, 2005; Vashitz *et al.*, 2008; Verway, 2000). However, its improper use of information can yield negative effects. Complex laws proposed by Elvik (2006) state that accident risks increase with the amount of information drivers must attend to during a given period of time. Providing only the proper information to the right driver at the appropriate time and place can exert positive effects and reduce accident risk (Vashitz *et al.*, 2008; Wong and Chung, 2007a). The side effects of information should also be considered. Drivers influenced by multiple sources of information are likely to be distracted and miss critical information (Liang *et al.*, 2007; Vashitz *et al.*, 2008).

As stated, attention misallocation can be seen as the missing link between accident-prone scenarios and accident occurrence within the concept of accident chains. To model drivers' attention allocation and distraction, the concept of the vehicle driver's domain is proposed in this research. Modeling attention allocation and subsequent behavior through the vehicle driver's domain is a major step in identifying the external information drivers perceive and react to. As a consequence, the effect of information on perception, driver behavior, and mental workload can be further clarified. Moreover, the connection between accident risks attributed to distraction and drivers' mental processes could be established.

An attention allocation model and its application to driving are introduced in section 2. In section 3, the concept of the vehicle driver's domain is proposed. Section 4 then proposes a model framework of driving attention allocation. Finally, discussion and concluding remarks are presented.

ELEMENTS IN ATTENTION ALLOCATION

The divided attention model (Kahnement, 1973) stats that several activities can be focused on and carried out at the same time, provided that their total effort is below the limit of available capacity. Four attributes of attention are mentioned. First, attention capacity is limited and varies from time to time. Available mental resource vary with the arousal level based on the physiology characteristics.. Second, the amount of attention or mental resources allocated is based on the demand level of current activities. The more demanding an activity is, the more attention would be allocated to it. Third, attention is divisible. Fourth, attention is selective and controllable. A central policy exists for allocating attention to selected objects or activities. The framework of the divided attention model is illustrated in Figure 1.



Source: Kahnement (1973)

Figure 1 *– Model of divided attention*

Four major elements are used to determine attention allocation policy in the model of divided attention: arousal, enduring dispositions, momentary intentions, and evaluation of demand on capacity. Arousal refers to factors such as physical condition, fatigue, or nervous tension that may activate the maximum attention capacity. An adequate level of arousal must be maintained. Under-arousal causes low attention capacity, whereas over-arousal impairs the ability to discriminate relevant objects from irrelevant objects. Enduring dispositions and momentary intentions reflect the characteristics of the external environment and behavioral intentions. Enduring dispositions represent state changes in the environment, such as deceleration of the vehicle ahead, and reflect involuntary attention. Momentary intentions, in contrast, represent the intended attention allocation at that instant, such as searching for information using an in-vehicle information system. Finally, the feed back of attention allocation would continue to evaluate and adjust the arousal level and revise the allocation policy to fit the current situation.

To obtain complete information for driving, drivers need to allocate attention on multiple objects not only on the road but also off-the road. For example, if a driver focuses only on traffic conditions in an adjacent lane and is not aware that the vehicle ahead is decelerating while changing lanes, an unexpected headway decrease may shorten the available time for the driver to react properly and increase the risk of collision with the vehicle ahead. This accident chain may describe a rear-end collision while changing lanes. However, the key points of accident risk in such a situation are the failure of divided attention and the driver's attention misallocation. Thus, the concept of divided attention is useful for analyzing driving safety.

Previous research has indicated that the capacity for divided attention is critical for situational awareness, especially for senior drivers (Creaser *et al.*, 2007; de Waard *et al.*, 2009;

Laberge *et al.*, 2006; Marmeleira *et al.*, 2009). Experiments on the influence of driving distraction on safety have also been conducted (Caird *et al.*, 2008; Horberry *et al.*, 2006a; Liu and Lee, 2005; Nunes and Recarte, 2002; Patten *et al.*, 2004). However, little numerical evidence has been provided for the mechanism that determines how drivers shift attention among different areas, objects on the road, and information sources. To better comprehend how drivers allocate attention to multiple threats and information sources, the model of divided attention is adopted to dissect the process of driving and information perception. Meanwhile, the vehicle driver's domain is proposed as a tool for representing the complicated interaction of objects in a real driving environment.

VEHICLE DRIVER'S DOMAIN

The vehicle driver's domain is proposed to simplify the complex interaction of multiple threats to safety by setting three virtual boundaries, which form three domains, around subject vehicles. It helps to identify the location and characteristics of threats to safety. Threats inside different domains under different driving conditions reflect different meanings to drivers and draw different levels of attention. In this section, the role of the vehicle domain in mental processes and attention allocation in driving is introduced. Then, the characteristics and measurement of each domain are explained.

Definition of Vehicle Driver's Domain

The vehicle driver's domain is the area within a specific distance around the subject vehicle. It is a driver's conceptual area in which external objects may appear to interact with the subject vehicle and degrade driving safety. Such threats to safety include other vehicles, fixed objects, curbs, and pedestrians. The concept of the vehicle driver's domain is important for situational awareness, risk perception, and decision making regarding threats to safety while driving. This distinct area contains the information that drivers are able to perceive, collect, and process. To prevent collisions, drivers must allocate attention inside the vehicle driver's domain and seek complete information. As shown as Figure 2, drivers generally set three boundaries, forming three kinds of vehicle driver's domains: the distant area in which drivers can perceive external stimuli, the area in which the driver is preparing to make a maneuver, and the relatively close area where driver must secure to prevent traffic conflict within limited time. These domains are named the perception domain, reaction domain, and critical domain, respectively. The content of these three domains can attract the driver's attention and effect traffic safety differently.

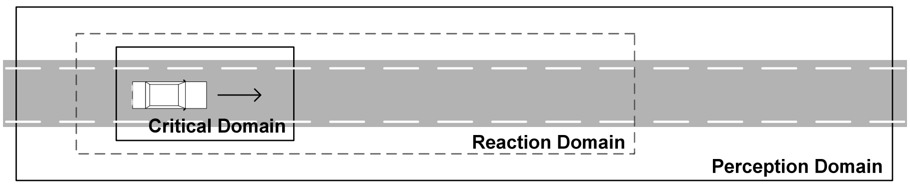


Figure 2 *- Concept of vehicle driver's domain*

A vehicle can be seen as a system containing subsystems with different functions to ensure safe driving. Each subsystem will vary the conditions of the three vehicle driver's domains. The person behind the wheel is one of the most important components within the vehicle system. Objects located in different domains should activate different reactions and behavior from the driver owing to their varying risk levels. Figure 3 shows the mental process of driving and the role of the vehicle driver's domain in this process.

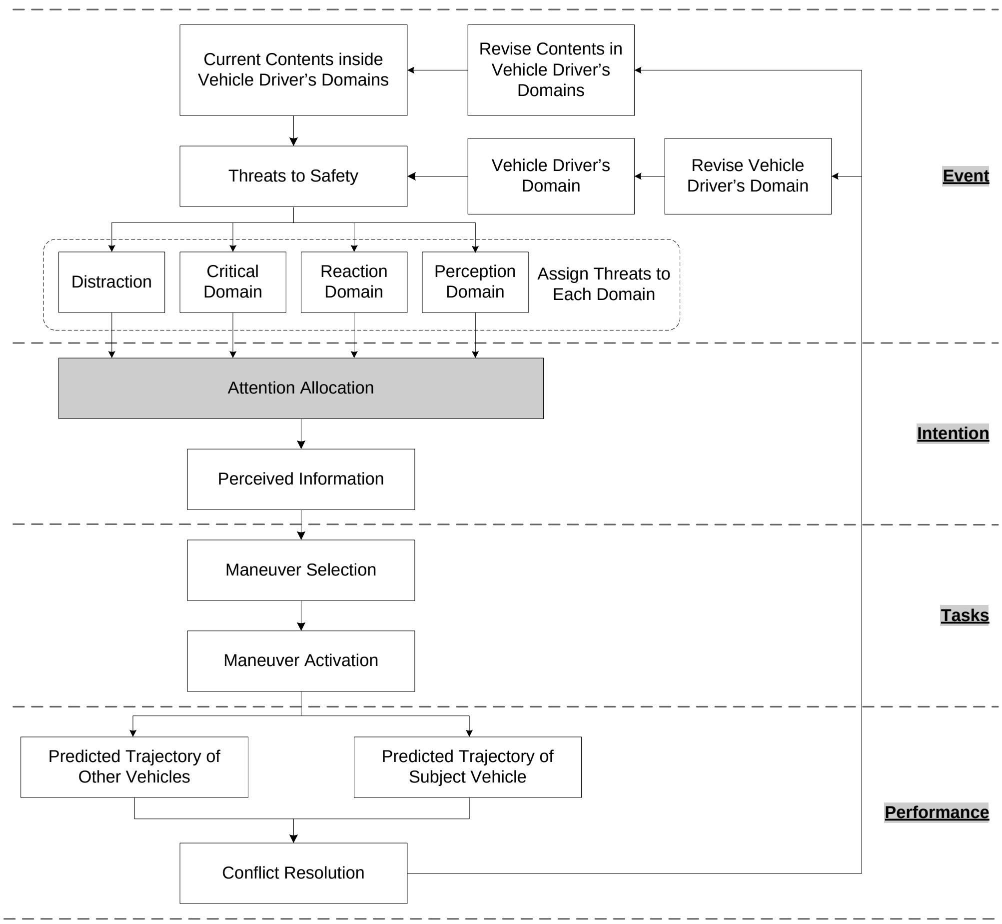


Figure 3 – *Driving mental process and vehicle driver's domain*

Driving can be divided into four mental stages: event occurrence, intention, tasks, and performance. Drivers first perceive objects, which can be seen as the current content inside the vehicle driver's domain. Each object perceived is evaluated as a threat to safety on which attention should be focused. These threats are immediately mapped onto the three conceptual vehicle driver's domains. In facing those threats, drivers, if not distracted, must allocate attention to collect information necessary for driving safely.

The second stage is attention allocation to threats to safety. As described in the model of divided attention (Kahnement, 1973), drivers can focus on multiple threats on the road and allocate different levels of attention to different objects. The more demanding the objects are, the more attention they would be allocated. In this research, drivers are assumed to allocate more attention to objects or areas with a high level of accident risk to minimize the expected negative impact on safety. However, not all objects inside the vehicle driver's domains will be observed and considered as threats to safety. Some may be ignored due to drivers' inattention. Some may be attended to and observed but seen as potential threats that pose no immediate danger of collision. On the other hand, non-driving tasks may cause distraction, shifting attention away from primary driving tasks.

Based on observation of threats to safety in different domains in a real-time driving environment and the driver's perception of their importance, maneuvers are selected and executed. After undertaking the selected maneuvers, a new driving state, including speed, location, and trajectory, is realized. Therefore, the vehicle driver's domain may need to be revised. Meanwhile, threats on the road are also changing continuously. The current contents of the vehicle driver's domain should be revised to iterate the attention allocation process.

Threats in different vehicle driver's domains require different tasks to resolve them. To model driving behavior based on attention allocation, it is important to define and explore the characteristics of each vehicle driver's domain. Then, the threats to safety that drivers really see and care about can be further clarified.

Measurement of Vehicle Driver's Domains

The concept of the vehicle driver's domain is of major importance in situational awareness, decision making, and preventing collision. The size and shape of each domain are important for defining their distinctive areas. In the following sections, the definition and measurement of each domain are explained. Also, threats to safety that may be of concerns to drivers are identified. Finally, based on threats to safety in each domain, the process of attention allocation within the domains is introduced.

Perception Domain

The perception domain reflects the respectively far area in which a driver has plenty of time to perceive stimuli from the external environment. Inside this area, moving objects are identified and evaluated as potential threats to safety. In other words, this domain contains all the information available from all the objects on the road to which the driver can attend. Once a driver perceives the existence of certain objects inside the perception domain, mental resources are consumed to evaluate the risk level of the threat to driving safety. After perceiving potential threats, drivers continue tracking the movement and predicting possible interactions between threats and the subject vehicle. However, no immediate technical tasks, such as changing speed or direction, are made when objects are located in perception domain but outside the reaction domain. Most tasks undertaken with respect to threats inside the perception domain are non-technical, reflecting the mental activities of perceiving, comprehending, and projecting information. The important factors in the perception domain are shown in Figure 4.

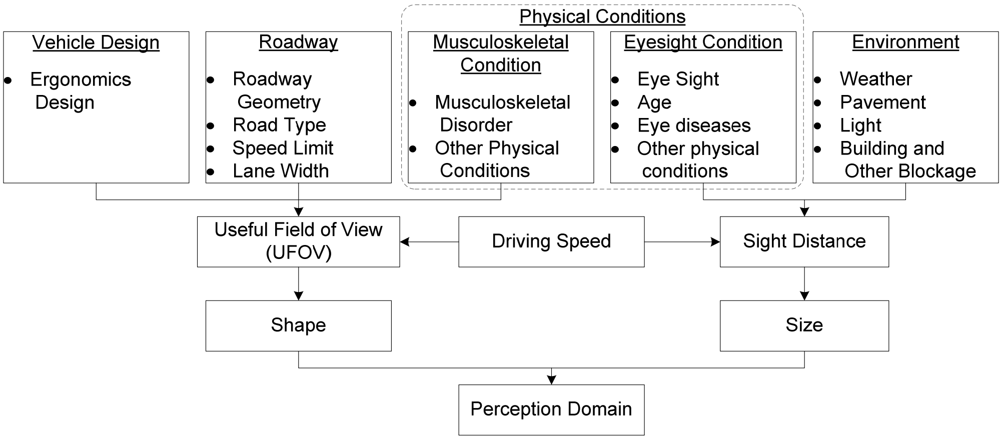


Figure 4 –*Important factors of perception domain*

The farthest distance of the perception boundary, which defines the size of the perception domain, refers to the sight distance under certain speed and environmental conditions. The maximum sight distance depends on the driver's visual capability, which is related mostly to his or her physical capabilities. For example, senior drivers have been indicated as having serious degradation of eyesight (Bayam *et al.*, 2005; Clarke *et al.*, 1999). The external driving environment also affects the available sight distance. For example, the sight distance while driving on a rainy night without streetlight is much shorter than that on a sunny day. Moreover, blockages caused by buildings and roadway geometry block driver's eyesight and shorten the sight distance.

The shape of the perception domain represents the directions in which a driver can see and allocate attention. It can be defined by the extent of the vision field, which is influenced by the driver's physical condition and the vehicle's ergonomics. Peripheral vision is one characteristic of the useful field of view (UFOV) that affects the visual field span. Although peripheral vision can extend 90 degrees to the right and left sides, only the center of the visual field is clear enough to capture stationary objects on the road (Roess *et al.*, 2004). Moreover, a driver's peripheral vision reaches a limitation as the speed of the vehicle increases. Also, a driver's musculoskeletal condition restricts the visual field's span. Drivers with muscle disorders and other physical disabilities may find it difficult in turning the head to increase peripheral vision. Vehicle ergonomics design is another critical factor that restricts the visual field. Rear-view mirrors allow drivers to detect and observe traffic conditions behind the vehicle, where drivers cannot observe and pay attention directly. However, blind spots may still exist and may pose risks to driving safety.

Critical Domain

The critical domain represents a safety boundary; drivers must secure this area and prevent objects from entering it. Objects inside the critical domain are seen as the occurrence of accidents. Although drivers can still allocate attention to threats inside the critical domain, yet, accidents are not preventable. If the threats to safety are close to the critical boundary or inside the critical domain, immediate technical tasks must be performed. The important factors in the critical domain are shown in Figure 5.

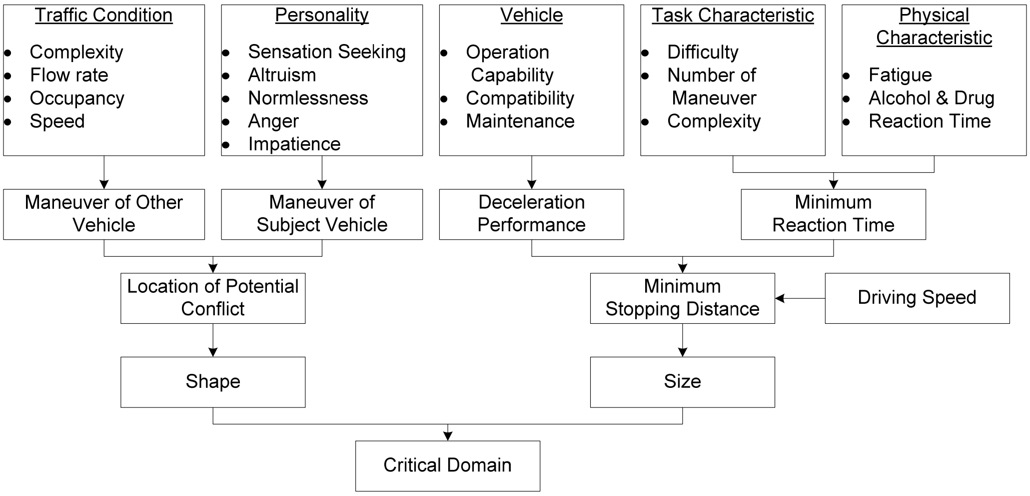


Figure 5 –*Important factors of critical domain*

Reaction capability is the key factor determining the size of the critical domain. Factors contributing to reaction capability include the driver's reaction time and the vehicle's deceleration performance. Those two factors determine the minimum stopping distance in response to external stimuli. When the distance between the subject vehicle and a threatening object is shorter than the stopping distance, an accident cannot be prevented. In regarding to the size of a critical domain, the driver's reaction time is rather important. Fatigue and alcohol or drug usage may degrade one's reaction capability by increasing the reaction time. Regardless of a driver's physical characteristics, task difficulty may influence the reaction time as well. Characteristics of technical tasks, such as complexity or difficulty in performing them, are reflected in the reaction capability and the critical domain. Drivers may take more time to notice an emergency situation, make decisions, and take action if they must perform more maneuvers.

The shape of the critical domain is determined by event characteristics and the maneuvers chosen based on the driver's intentions. It indicates the direction and location at which threats may appear and lessen driving safety. In other words, the shape of the critical domain indicates the area drivers should focus on to prevent collisions. It depends on the predicted potential conflicts of vehicle trajectories. Each event occurrence and task creates different potential conflicts in different locations on the road, making differently shaped critical domains. Figure 6, for example, shows three different maneuvers: driving in the current lane, changing lanes, and turning right. Each creates a unique potential conflict and critical domain. When driving without changing lanes, as in Figure 6 (A), the critical domain contains only the area in front of the vehicle to prevent collisions with the vehicle ahead, and limited space in adjacent lanes to prevent other vehicles from entering the current trajectory. However, when drivers decide to change lanes, as in Figure 6 (B), the critical domain extends to the adjacent lane to prevent collision with vehicles ahead and behind. Thus, attention should still be allocated to the current driving lane to maintain a safety gap with the vehicle ahead while awaiting a time to change lanes. In the case of a right turn when approaching an intersection, the critical domain may extend in the direction perpendicular to the direction of travel. Drivers have to secure the area and prevent pedestrians and other moving objects from entering the critical domain.

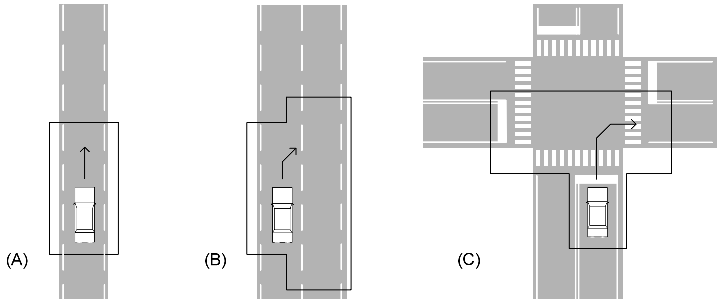


Figure 6 – *Critical domain under different maneuvers*

Reaction Domain

The reaction domain is the area in which potential threats are determined to be threats to safety that drivers must pay close attention to and in which drivers must react to any stimuli appearing. Typically, the reaction domain is located between the perception and critical domains. When a potential safety threats crosses the boundary of the reaction domain (the reaction boundary), drivers determine that those objects are threats to safety and allocate more attention to them. Drivers may make certain maneuvers to prevent collision. Both technical and non-technical tasks are necessary when handling threats inside the reaction domain. The important factors in the reaction domain are shown in Figure 7.

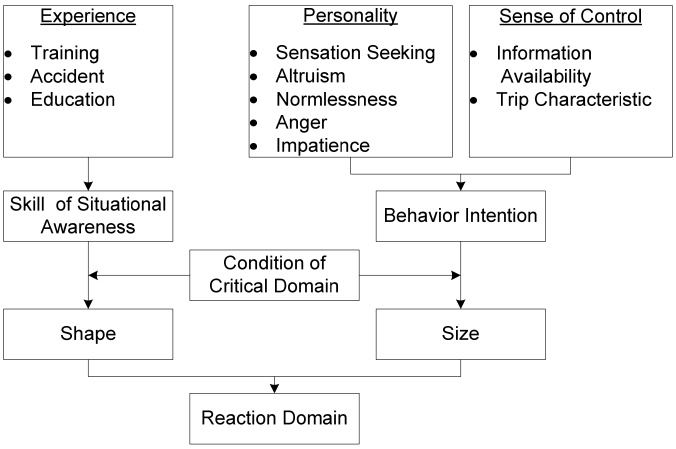


Figure 7 – *Important Factors of Reaction Domain*

The reaction domain is mostly affected by the individual driver's characteristics. The size of the reaction domain depends on where the driver locates the reaction boundary for activating reactions to safety threats. The selection of the reaction boundary depends on the driver's skill and situational awareness. Laws of learning and rare events proposed by Elvik (2006) stated that the accident rate decreases with increasing exposure and driving experience, since positive experience accumulation and training can help drivers predict and control uncertainties. In other words, experienced drivers likely are able to make a better decision when facing safety threats. Additionally, previous research has found that experience, personality, attitude, and other psychological factors play a role in one's driving behavior (Chang and Yeh, 2007; Taubman-Ben-Ari *et al.*, 2004; Ulleberg and Rundmo, 2003; Wong *et* *al.*, 2009a; 2010). With different behavioral intentions, drivers may make different decisions and react differently in the reaction domain. This suggests that individual drivers' characteristics should be considered.

The driver's sense of control also contributes to the selection of reaction boundary. For instance, having road information, such as traffic conditions, weather information, and routing assistance, at hand can help drivers understand the situations they may encounter and increase their confidence. The more self-confident and in control drivers feel, the easier it is for them to allocate attention and maintain their driving performance at a reasonable level. On the contrary, driving under conditions where a gap exists between expectations and the real traffic environment stresses and discourages a driver. Research has stated that stress can influence a driver's capability and cause attention misallocation cause attention misallocation (Hill and Boyle, 2007).

The shape of the reaction domain is closely related to the conditions of the critical domain; it is similar to the critical domain but different in size. Like the size of the reaction domain, its shape relies on the driver's skill and situational awareness. It reflects a driver's behavioral intention and determines a driver's attention allocation policy regarding objects and quality of decision making.

DRIVING ATTENTION ALLOCATION

This section discusses the threats inside each domain and the interaction between threats and the subject vehicle. The driving attention allocation process can be divided into two parts. First, threats to safety in each domain are identified. The risk level of the threats can be seen as a combined index of enduring dispositions and momentary intention while driving. The risk level also reflects the demand of each object for attention allocation. Second, the attention allocation policy, which is represented as the probability of a specific domain being focused on by drivers, is determined based on the risk level of threats to safety in different domains.

Threats to Safety

Threats in this study can be defined as possible dangers that may harm driving safety. To identify the attention allocation process while driving, it is important to determine the kind of threat that may influence safety and to what extent. The risk level of threats to safety is adopted to represent the criticalness of threats is in different maneuvers and driving environments.

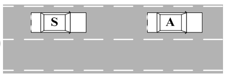
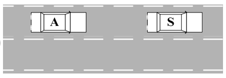
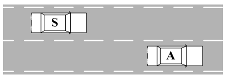
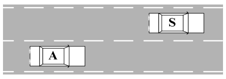
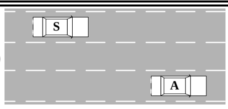
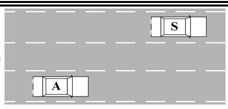
Risk is evaluated on the basis of three factors. The first is the distance between a subject vehicle and a threat. In this research, the location of a specific threat can be represented by the domain to which it belongs. The second factor is the traffic flow in which drivers are driving. When facing different traffic flow conditions, drivers may allocate attention to different domains. Three levels of traffic are considered: free flow, synchronized flow, and congested flow. The third factor is the interaction between the subject vehicle and the threat. It relies on the relative locations of the vehicle and the threat and the maneuvers adopted by the vehicle's driver. Provided that the maneuvers decrease the headway, they can be considered as raising the risk of conflict, requiring more attention from drivers. Characterizing threats using these three factors can help identify the interactions of the subject vehicle and other objects on the road. Furthermore, it can help describe the actual driving environment and capture critical attributes that can influence driving safety.

The risk level of threats to safety caused by interactions between a subject vehicle and other vehicles under different traffic flow conditions are summarized in Tables 1 to 3. Assuming that only interactions within driving lanes are discussed, four maneuvers (maintaining speed, accelerating, decelerating, and changing lanes) may be undertaken by the subject vehicle (Vehicle S) and the threat (Vehicle A). Seven scenarios representing the relative locations of two objects and reflecting different driving maneuvers and types of potential conflicts are illustrated.

The first and second scenarios indicate the potential threat of rear-end conflicts with vehicles in the same lane. In the first scenario, Vehicle S follows other vehicles, and in the second, the Vehicle S drives in front of other vehicles. If drivers stay on the same lane without changes, they must pay attention to threats located on the lane they are on to prevent rear-end accidents. However, drivers should pay attention to vehicles running in the adjacent lane that may pose a risk of side impact if they change lanes. The third and fourth scenarios represent the potential threat of side impact from the front and the rear in the adjacent lane. The fifth and sixth scenarios denote a threat located in a second adjacent lane. If a driver intends to change lanes, vehicles in the adjacent lane (the third and fourth scenarios) and the second adjacent lane (the fifth and sixth scenarios) are considered as safety threats. The seventh scenario refers to a fixed object on the road.

Table 1 summarizes the risk level of threats to safety when driving in the free flow condition. In this condition, by definition, drivers can adjust speed without being influenced by other vehicles. In other words, no other vehicle appears inside the reaction and critical domains, in which the driver would initiate reaction against external stimuli. The closest vehicle that could affect driving safety in free flow traffic is located in the perception domain. Thus, only threats in front of the subject vehicle would affect driving safety, including the vehicles ahead in the same lane (as in the first scenario) and vehicles in the adjacent lane that may cause risk if they change lanes (as in the third and fifth scenarios). The risk level is comparatively low, since any threats are still far away and outside the reaction domain. However, if the headway is decreasing, the threats to safety could enter the reaction domain; the risk level would increase, and the threat will draw more of the driver’s attention. Meanwhile, due to the narrow span of a driver’s vision when driving in free flow traffic condition, drivers would not only attend to the vehicle ahead but also those behind and on adjacent lane Compared to other vehicles on the roads, the risk level of fixed roadside objects is more significant for safe driving. Drivers would perceive more risk in roadside object located in the reaction and critical domains, especially roadside curbs on curving lanes, which may necessitate a technical task of wheel-turning.

Table 1 – *Risk level of threats to safety in free flow*

Maneuver Undertaken by Subject Vehicle / Maneuver Undertaken by Vehicle A		Subject Vehicle Driving in Free Flow											
		Perception Domain				Reaction Domain				Critical Domain			
Related Location of Threats	Maneuver	Maintain Speed	Accelerate	Decelerate	Change Lane	Maintain Speed	Accelerate	Decelerate	Change Lane	Maintain Speed	Accelerate	Decelerate	Change Lane
(1) 	Maintain Speed	L	L	-	-	Not Applicable				Not Applicable			
	Accelerate	-	L	-	-								
	Decelerate	M	M	-	L								
	Change Lane	-	-	-	L								
(2) 	Maintain Speed	-	-	-	-								
	Accelerate	-	-	L	-								
	Decelerate	-	-	-	-								
	Change Lane	-	-	-	-								
(3) 	Maintain Speed	-	L	-	L								
	Accelerate	-	-	-	-								
	Decelerate	L	L	-	M								
	Change Lane	L	L	-	-								
(4) 	Maintain Speed	-	-	-	-								
	Accelerate	-	-	-	L								
	Decelerate	-	-	-	-								
	Change Lane	-	-	-	-								
(5) 	Maintain Speed	-	-	-	-								
	Accelerate	-	-	-	-								
	Decelerate	-	-	-	-								
	Change Lane	-	-	-	L								
(6) 	Maintain Speed	-	-	-	-								
	Accelerate	-	-	-	-								
	Decelerate	-	-	-	-								
	Change Lane	-	-	-	-								
(7) Fixed Objects	Curb with Curvature	L	L	-	-	M	M	L	M	M	H	L	L
	Curb on straight Lane	-	-	-	-	-	-	-	L	L	L	-	L
	Parked Vehicle Heading Out	-	-	-	-	L	M	-	L	L	M	L	L

Vehicle S: Subject Vehicle
Vehicle A: Threat to Safety

Risk Level
- : No Risk
L : Low
M : Medium
H : High

Table 2 summarizes the risk level of threats to safety when driving under a synchronized flow. In this condition, speed adjustment is influenced by other vehicles since there are threats exist inside the reaction and critical domains. Objects inside the reaction domain would be considered as posing a higher risk than those inside the perception domain. Furthermore, threats in all three domains would attract drivers' attention. Although drivers look at the near side of the road, objects inside the perception domain will occasionally draw their attention, even though the threats in this area pose less risk than those in the reaction and critical domains.

Table 2 – *Risk level of threats to safety in synchronized flow*

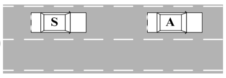
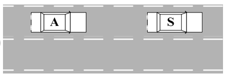
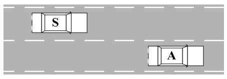
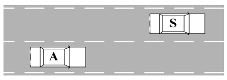
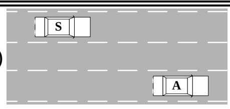
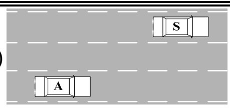
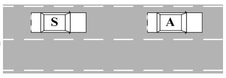
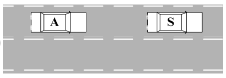
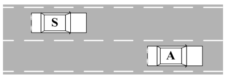
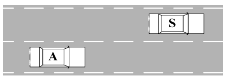
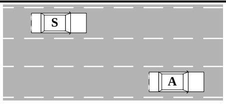
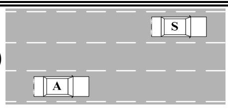
Maneuver Undertaken by Subject Vehicle / Maneuver Undertaken by Vehicle A		Subject Vehicle Driving in Synchronized Flow											
		Perception Domain				Reaction Domain				Critical Domain			
Related Location of Threats	Maneuver	Maintain Speed	Accelerate	Decelerate	Change Lane	Maintain Speed	Accelerate	Decelerate	Change Lane	Maintain Speed	Accelerate	Decelerate	Change Lane
(1) 	Maintain Speed	-	L	-	-	M	M	-	L	H	H	M	M
	Accelerate	-	-	-	-	L	M	-	-	M	H	L	-
	Decelerate	L	L	-	-	M	H	M	L	H	H	M	L
	Change Lane	-	-	-	L	-	L	-	M	M	M	L	H
(2) 	Maintain Speed	-	-	-	-	L	-	L	-	M	M	M	L
	Accelerate	-	-	L	-	M	L	M	L	H	M	H	M
	Decelerate	-	-	-	-	-	-	-	-	M	L	L	-
	Change Lane	-	-	-	-	-	-	-	-	L	-	L	M
(3) 	Maintain Speed	-	L	-	L	L	M	-	M	M	M	L	H
	Accelerate	-	-	-	-	-	L	-	L	L	M	-	M
	Decelerate	-	L	-	L	L	H	L	H	H	H	M	H
	Change Lane	L	L	-	-	M	H	L	L	H	H	M	M
(4) 	Maintain Speed	-	-	-	-	-	-	-	M	M	L	L	M
	Accelerate	-	-	-	-	L	L	L	H	M	M	M	H
	Decelerate	-	-	-	-	-	-	-	L	L	-	M	M
	Change Lane	-	-	-	-	L	L	M	M	M	L	M	L
(5) 	Maintain Speed	-	-	-	-	-	-	-	L	-	-	-	-
	Accelerate	-	-	-	-	-	-	-	-	-	-	-	-
	Decelerate	-	-	-	-	-	-	-	L	-	-	-	L
	Change Lane	-	-	-	L	L	M	-	M	-	-	-	L
(6) 	Maintain Speed	-	-	-	-	-	-	-	-	-	-	-	-
	Accelerate	-	-	-	-	-	-	-	L	-	-	-	-
	Decelerate	-	-	-	-	-	-	-	-	-	-	-	-
	Change Lane	-	-	-	-	-	-	L	M	-	-	-	L
(7) Fixed Objects	Curb with Curvature	L	L	-	L	L	M	-	L	M	H	L	M
	Curb on straight Lane	-	-	-	L	-	-	-	L	L	L	-	M
	Parked Vehicle Heading Out	-	-	-	-	L	L	L	M	L	L	M	M

Table 3 summarizes the risk level of threats to safety when driving under a congested traffic flow condition. Under such a condition, the headway between vehicles is small, so drivers must accelerate and decelerate frequently. The area to which drivers can allocate attention is limited. Most of the time, drivers can focus only on the vehicles ahead that are located near the critical boundary to prevent accidents (as in the first scenario). Although vehicles appear in the perception and reaction domains, they do not produce safety-critical information that a driver must perceive. Moreover, considering that the gap between two vehicles is very small, drivers may not worry about vehicles in adjacent lanes, since there is apparently no available space for changing lanes. A driver would typically pay attention to traffic in adjacent lanes only when Vehicle S or a vehicle in an adjacent lane is signaling a lane change (as in the third and fourth scenarios).

Table 3 – *Risk level of threats to safety in congested flow*

Maneuver Undertaken by Vehicle A / **Maneuver Undertaken by Subject Vehicle**		**Subject Vehicle Driving in Congested Flow**											
		Perception Domain				**Reaction Domain**				**Critical Domain**			
Related Location of Threats	**Maneuver**	Maintain Speed	Accelerate	Decelerate	Change Lane	Maintain Speed	Accelerate	Decelerate	Change Lane	Maintain Speed	Accelerate	Decelerate	Change Lane
(1) 	Maintain Speed	-	-	-	-	-	-	-	-	H	H	M	M
	Accelerate	-	-	-	-	-	-	-	-	M	M	L	L
	Decelerate	-	-	-	-	-	-	-	-	H	H	M	H
	Change Lane	-	-	-	-	-	-	-	-	M	M	L	H
(2) 	Maintain Speed	-	-	-	-	-	-	-	-	-	-	-	-
	Accelerate	-	-	-	-	-	-	-	-	-	-	-	-
	Decelerate	-	-	-	-	-	-	-	-	-	-	-	-
	Change Lane	-	-	-	-	-	-	-	-	-	-	-	-
(3) 	Maintain Speed	-	-	-	-	-	-	-	M	-	-	-	H
	Accelerate	-	-	-	-	-	-	-	L	-	-	-	M
	Decelerate	-	-	-	-	-	-	-	H	-	-	-	H
	Change Lane	-	-	-	-	-	-	-	L	H	H	M	L
(4) 	Maintain Speed	-	-	-	-	-	-	-	M	-	-	-	M
	Accelerate	-	-	-	-	-	-	-	H	-	-	-	H
	Decelerate	-	-	-	-	-	-	-	L	-	-	-	M
	Change Lane	-	-	-	-	-	-	-	-	-	-	-	-
(5) 	Maintain Speed	-	-	-	-	-	-	-	-	-	-	-	-
	Accelerate	-	-	-	-	-	-	-	-	-	-	-	-
	Decelerate	-	-	-	-	-	-	-	-	-	-	-	-
	Change Lane	-	-	-	-	-	-	-	-	-	-	-	-
(6) 	Maintain Speed	-	-	-	-	-	-	-	-	-	-	-	-
	Accelerate	-	-	-	-	-	-	-	-	-	-	-	-
	Decelerate	-	-	-	-	-	-	-	-	-	-	-	-
	Change Lane	-	-	-	-	-	-	-	-	-	-	-	-
(7) Fixed Objects	Curb with Curvature	-	-	-	-	-	-	-	-	L	L	L	L
	Curb on straight Lane	-	-	-	-	-	-	-	-	-	-	-	-
	Parked Vehicle Heading Out	-	-	-	-	-	-	-	-	-	-	L	L

The risk level of threats to safety is a subjective index since drivers make decisions based their subjective perception towards the driving environment. This index may be influenced by differences in the driver's individual characteristics. The heterogeneity of the driving population may result in different perceived risk levels with identical threats. The issue of heterogeneity, although not considered in this study, should be seriously addressed and analyzed in the future. Nevertheless, the risk level summarized in this section is an important index to help clarify the process of driving attention allocation and provides a framework for identifying the location and possible risk level of threats in different domains. This research only summarized the concept and the general condition of risk level that driver might perceive in certain traffic flow condition. Field data collection is necessary in future studies.

Attention Allocation in Vehicle Driver's Domains

The real driving environment can be seen as a dynamic system containing multiple time-dependent safety threats. Drivers should keep switching their attentive focus between different threats. However, owing to differences in behavioral intention, traffic conditions, and other heterogeneities in the external environment, the duration and sequence of focusing on a specific object while driving and the driver's subsequent behavior vary with the situation. It is important to identify whether drivers allocate enough attention to critical objects that may threaten safety. Misallocating attention may cause failure to perceive critical information and inability to react to possible dangers in time. To analyze the attention shifting process and behavior, this research proposes a driving attention allocation model for analyzing transitions in a driver's attentive focus.

The divided attention model suggests four attributes. First, the available mental resources are limited and vary with the driver's arousal level. Second, the allocation of mental resources and attention is based on the risk levels of threats. Objects with higher risk level demand more attention from the driver. Third, attentional resources are divisible. As long as the attention required is below the capacity limit, the attention can be divided and allocated to different foci, including threats to safety and other distractions. Fourth, a central attention allocation policy exists for controlling and selecting the attentive focus. Due to their training, experience, and intentions, different drivers may have different allocation strategies and allocate different levels of attention in collecting different information.

The framework of driving attention allocation is shown in Figure 8. Driving status can be represented by enduring disposition and momentary intention. The enduring disposition reflects the characteristics of all objects in the environment that would remain for a period of time. In this research, it is characterized by traffic flow conditions and other vehicles' relative locations, distances, and maneuvers. Momentary intention denotes the driver's intention to undertake a certain behavior. This research considered four possible behaviors: maintaining speed, acceleration, deceleration, and changing lanes. Events occur if the enduring disposition is interrupted, or if a driver actively changes his or her intention to undertake certain maneuvers. By determining the driving status in terms of the enduring disposition and momentary intention, threats to safety are identified and assigned to different domains based on the characteristics of the vehicle driver's domain.

The risk level in each domain, which is the summation of the risk level of each threat to safety inside the domain, is the input of the attention allocation policy. It is considered to be the combined index of enduring disposition and momentary intention. Threats to safety may vary with traffic flow conditions, the objects inside the domains, and driving maneuvers. R_{PD}, R_{RD}, and R_{CD} represent the risk level of threats to safety in the perception, reaction, and critical domains, respectively. As introduced in Table 1 to Table 3, the risk level varies with the characteristics of the vehicle driver's domain and the interaction between the subject vehicle and threats in each domain. More significant threats inside a specific domain will attract more attention to maintain safety.

The core of the driving attention allocation model is the allocation policy, which refers to the strategy of allocating mental resources. Drivers might attend to five major attentive focuses: the three vehicle driver's domains and two distraction domains. To collect complete information, drivers would tend to switch their attentive focus between different on-road, off-road, or in-vehicle areas. The contents of each of the vehicle driver's subdomains provide information for use in driving maneuvers and accident prevention. Some content may be treated as threats to safety that require more attention. On the other hand, distractions are information induced by off-road or in-vehicle stimuli. Two types of distraction are possible. The first is information about driving, including driving speed information on the dashboard, route information on navigation systems, and regulation information on off-road signs. Collecting such driving-related information would help enhance the understanding of traffic conditions and control of driving activities. The second type of distraction is non-driving-related information including cell phone conversations, music from the radio, or interesting off-road objects. Such non-driving distractions may degrade safety by shifting attention away from driving tasks. However, it also provides positive effects, such as entertainment or maintaining a minimum workload to prevent passive fatigue.

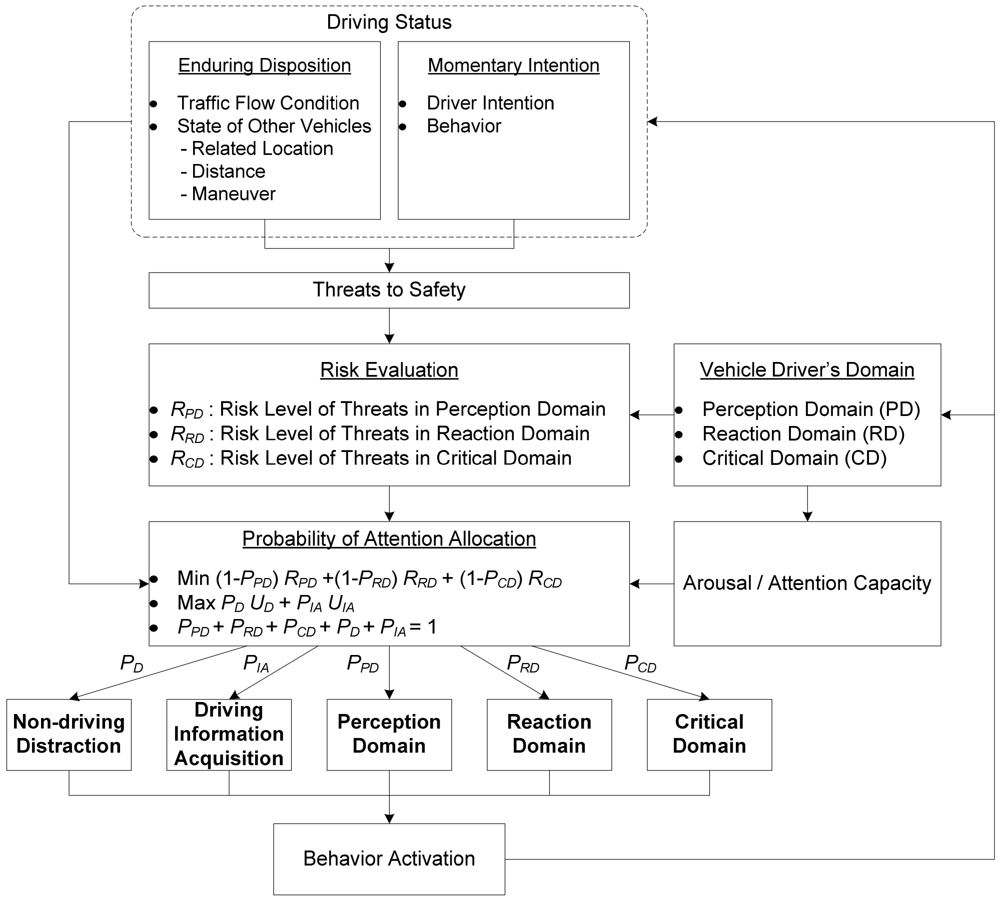


***Figure 8 –** Framework of driving attention allocation model*

The allocation policy depends on the driver's intention, the risk level of threats to safety in different traffic flow conditions, and the driver's attention capacity. The demands on attention in each area differ with traffic conditions and driving environment. For example, while driving in free flow traffic, the risk level of threats to safety is comparatively low. Speed information on the dashboard must be collected by drivers to prevent speeding. In contrast, in congested flow, speed information is no longer necessary, since all vehicles are driving slowly in a traffic jam. This case indicates that the definition of complete information is unique to the situation. It is important to identify the required information that drivers should collect in different conditions.

The probability of allocating attention to the perception, reaction, and critical domains (P_{PD}, P_{RD} and P_{CD}, respectively) can be obtained by minimizing the expected total risk of not paying attention to a specific domain. Additionally, a driver would also consider the utility derived from time spent on distractions. Despite allocating attention to the three domains on the road, distractions are also important domains that may consume attention capacity and mental resources. In this research, the probability of non-driving distractions (P_D) and the probability of driving information acquisition (P_{IA}) represent the proportion of time spent on distractions and on driving tasks, respectively. The existence of and increase in distraction probability would decrease the total probability of allocating attention to driving tasks, compromising driving safety. However, drivers would still try to maximize the utility from distractions (U_D and U_{IA}). To identify the effect of distractions such as in-vehicle information systems or cell phone usage while driving, it is important to clarify the effect of distractions in the model of driving attention allocation.

The driving attention allocation model proposed in this research is a domain-based analysis, not an approach based on individual threats. The probability obtained through the framework in Figure 8 represents the proportion of time a driver spends on each domain (including the two types of distraction) in a relatively short period of time regarding one specific event. The state of the vehicle driver's domain, which is represented in size and shape, and the contents of each sub-domain, will be revised with changes in the driving environment, event, and driver's intention. This research does not address attention allocation to each threat inside the three vehicle domains. Threat-based attention allocation can be seen as the second level of the attention allocation model. Strategies of choosing attentive focus for individual threats can still be obtained by minimizing the risk inside the domain selected in the previous stage. However, the sequence of attentive focus transitions and the interaction between threats should be addressed in a disaggregate attention allocation analysis.

CONCLUDING REMARKS

Although widespread concern about accident-prone scenarios exists, the nature of accidents is still implicit without further exploration of the mental process of driving. To clarify the role of drivers in the accident chain and to better understand the missing link between accident-prone scenarios and accident occurrence, the issue of attention should be addressed. Based on the divided attention model, this research proposed a driving attention allocation model for identifying the mechanisms of allocating mental resources among different driving activities. Moreover, considering the complexity of a real driving environment in which too many objects may provide information for drivers to collect, the concept of the vehicle driver's domain is proposed to classify the threats to safety into three domains. Applying the attention allocation model in accident chain analyses enables discussion of complete information collection. This research is the first step in elucidating the driver's mental processes. Aspects of driving attention allocation still require further discussion and study.

In this attention allocation model, the probability of attention allocation is obtained by minimizing the risk level of threats to safety. However, a driver's true attention allocation will not agree completely with the optimized results. In fact, different drivers with unique driving experience, behavioral intentions, and personality may have varying probabilities of attention allocation. For example, novice drivers may give more attention to objects on the road, while experienced drivers may have spare mental resources allocated to external information collection. The effect of heterogeneity in individual characteristics on attention allocation must be identified.

Moreover, this research focuses only on the allocation policy for identifying the amount of mental resources consumed by specific activities. This model treats the maximum attention capacity as an exogenous factor. Arousal is defined as the contributing factor that determines the available mental resources. It has been suggested that the effect of arousal on attention allocation is U-shaped (Kahnement, 1973). Over-arousal and under-arousal will not activate adequate attention capacity and will degrade driving safety. The issue of arousal and attention capacity under different physiological conditions must be addressed.

Another issue that needs more discussion is the connection between tasks and attention allocation policy. It is assumed that drivers must collect complete information to maintain safety. However, different conditions of traffic flow, driving environment, information availability, and the driver's behavioral intention may cause different levels of distraction in information collection. The importance of the interaction between threats and events is vital when undertaking attention allocation analysis on the basis of individual threats.

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