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駕駛注意力分配模式

A Novel Approach for Modeling Driver Attention Allocation

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摘要

注意力分配為行車安全的重要關鍵，駕駛人必須將其有限資源妥適分配至車輛前方、車內與車外等區域，以維持適當之情境察覺，並得與前車保持安全距離。然而過去對於注意力分配之研究多侷限於對各焦點的總體分析，無法探究其個體行為特性，此外，對於視線移轉過程之呈現方式往往過於著重於「前方」焦點，致使研究成果當中的多數路徑皆為移往或來自前方，此一現象導致研究無法完整呈現駕駛人視線移轉的完整過程，因此，如何呈現注意力分配以及分析其特性為事故分析與防範的重要基礎，唯有提出適切的量化方法，才能正確呈現駕駛人移轉注意力之過程。

以注意力分配為題，本研究欲回答下列問題：1) 駕駛人注意力分配應如何呈現？ 2) 駕駛人是否會採取特定的注意力分配型態？ 3) 若有，有哪些型態？ 4) 有哪些變數會影響駕駛人注意力分配？為回答上述問題，本研究首先提出「注意力分配循環」之概念，以前方焦點視為一基準點，將視線移開前方至他處最後再回到前方的循環過程視為注意力分配之基本元件，呈現駕駛視線分配的完整過程。本研究於分析階段採用美國 100-car 自然駕駛資料庫當中的事件資料庫進行分析，透過序列關聯法則，找出駕駛人將視線在前方與非前方之間移轉的路徑，並透過羅吉特模式之應用，計算駕駛人在不同狀況下，選擇不同類型視線移轉與選擇各焦點的機率分配。

研究結果發現，研究發現超過 90%以上的注意力分配循環僅包含一個非前方焦點，亦即當駕駛人將視線移開時，多數僅會注視一個非前方焦點 (以車內分心、左後視鏡與車內後視鏡為主)，以避免因移開視線時間過長而無法觀察前方路況之狀況發生；本研究亦發現駕駛人會將視線在前方與同一焦點間來回移轉，此特性尤以車內後視鏡與車內分心最為明顯，顯示駕駛人於該二焦點收集資訊時，會不斷將視線移回前方，以確保將視線移開前方的過程中仍可維持對前方的情境察覺能力。此外，駕駛人會避免將視線直接自一非前方焦點轉移至另一非前方焦點，而是先將視線移回前方再移往下一焦點，以確保車前安全。駕駛人選擇焦點時，傾向將視線分配至較近、對安全影響較大、較明亮且資訊出現頻率較高的焦點上。

最後，本研究將注意力分配循環之概念應用於安全評估，並以駕駛反應時間為基礎，設定駕駛人得以將視線移開前方的最長時間。研究發現，當駕駛人連續注視的焦點數越多時，其無法觀察前方路況的總時間越長，因此，對前方刺激的餘裕反應時間越短；其中，分心、駕駛操作意向等因素皆會影響其實際的反應時間長度。若以注意力分配角度出發檢視，目前現行之 2.5 秒反應時間設計標準已無法滿足現況，若以 90 百分位為基準，道路設計應將反應時間設定為 3 秒。

囿於資料限制，本研究所引用之資料雖無法代表駕駛人的典型注意力分配型態，然而所提模式與其結果仍可提供後續分析探討之參考，並可作為事故防範與安全分析之用，此一領域仍待後續進一步探討。

關鍵字：注意力分配、循環、視線移轉、分心、自然駕駛

A NOVEL APPROACH FOR Modeling DRIVER ATTENTION ALLOCATION

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ABSTRACT

Attention allocation is the key of driving safety, which relies on the adequate distribution of the driver's attention to the forward area and to other non-forward focal points. However, most representation of attention allocation are the aggregated result of vision transition. It is not able to observe drivers' microscopic behavior against dynamic changing environment. Moreover, thus far, current methods seem to be over-emphasized on the dominant forward area, causing the observed paths were mostly ones shifting from or heading to the frontal side. The whole process of transiting vision among focal points cannot be observed. Consequently, a mechanism for attention allocation is a critical issue in crash prevention.

There are four questions that this study aims to answer: 1) How is driver attention allocation represented? 2) Do patterns of driver attention allocation exist? 3) If yes, what are these patterns? and 4) What are the factors affecting driver attention allocation? To answer these questions, this study proposes the concept of renewal cycle, which is the entire process of drivers glancing at forward side, transiting vision away, and finally transiting vision back to the front. Using the renewal cycle as the basic component of attention allocation analysis, this study is able to represent drivers' vision transition in a more realistic way. In the section of empirical analysis, this study adopted the event database of 100-car naturalistic driving studies. Sequential rule mining and multinomial logit model were used for generating the patterns and probability of drivers transiting vision among focal points.

This study found that over 90% of drivers' attention allocations were 2-glance renewal cycles, suggesting that drivers usually glance only one off-road focal point, among which the in-vehicle distraction, left mirror and rearview mirror are the three most frequent appeared ones. Among these 2-glance renewal cycles, some were found repeatedly appeared several times, particularly the ones related to in-vehicle distraction and rearview mirror. It suggests a compensation of lost awareness against leading area by separating their long glance off-road into several shorter ones. In addition, drivers prefer not to transit vision from one non-forward focal point directly to another. Instead, they glance at forward side between two non-forward glance for checking the timely status ahead. As for the choices of focal points, four constructs of attributes (Salience, effort, expectancy and value) in SEEV model were included in this model. The result shows that drivers would allocate more attention to the focal point with higher information expectancy and value. On the other hand, less salient and higher effort would inhibit the vision transition.

Finally, this study adopted the Perception Reaction Time (PRT) as the reference for setting the maximum time for drivers to transit vision away from the frontal side. It clearly indicated that drivers glancing consecutively at more non-forward focal points in a sequence were more likely to have insufficient time for responding to harmful changes in front of them. In addition to distractions, maneuver intentions, number of glances in a renewal cycle, and their interactions all significantly affected drivers' attention allocation. As for the current 2.5-s PRT rule, it may not be robust enough to satisfy every situation. Based on the results derived from the 100-car event database, a 3.0-s PRT may be better for designing safer roads.

Although the sample drivers adopted in this study were not representative, the preliminary research results were promising and fruitful for potential applications, particularly educating novice drivers. These findings might have striking implications for accident prevention. This area of study deserves further attention.

Keywords: *Attention Allocation; Renewal Cycle; Vision Transition; Distraction; Naturalistic Driving*

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黃士軒

筆於交研所最後一夜
2013.7.31

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CHAPTER 1 INTRODUCTION

1.1 Background and Motivation

Crash predictability has long been a controversial issue. Bortkiewicz, usually considered the pioneer of modern crash research, stated that crash occurrences are random and thus inexplicable in his 1898 study (Elvik 2006). However, the development of modern analysis techniques has inspired various attempts to explore the causality of accidents. In recent days, it is suggested that scenario of crash-proneness do exist (Visser *et al.* 2007). Exploring the causes of motor vehicle crashes has become a pressing issue. Finding the causality of crashes is thus possibly one of the most effective ways to improve road safety and to prevent crashes from happening.

To enhance understanding of crashes, researchers have worked on mining aggregated crash data to extract crash patterns. Numerous contributing factors have been found critical to roadway safety. For example, rear-end accidents increased with the number of signal phases and width of traffic island (Chin and Quddus 2003). Demographic characteristics such as age and gender also have been extensively studied (Clarke *et al.* 1998, Clarke *et al.* 1999, Chang and Yeh 2007). Despite the significant effect of single factors, recent research has claimed that crashes should be analyzed from a chain perspective (Elvik 2003, Wong and Chung 2007b, Verschuur and Hurts 2008, Wong and Chung 2008a, Wong and Chung 2008b). In addition to the scenario of crash occurrence, some remote factors of crash occurrence must be considered. For example, personality traits can be treated as prior-to-driving factors that affect risky driving behavior (Wong *et al.* 2010b, Wong *et al.* 2010c).

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. However, a crash-proneness driver driving in a crash-proneness scenario does not necessarily lead to the occurrence of crashes. Such accident-prone scenarios explain mostly the conditions in which drivers face higher risks of being involved in a crash, and possibly the mechanism through which such crashes occur. For example, Wong and Chung (2007b) found that young and inexperienced student drivers had an increased likelihood of being involved in off-road accidents on roads with speed limits between 51 and 79 kph under normal road conditions. The reality is that for each accident under certain conditions, there are numerous young and inexperienced student drivers who drive under identical conditions without experiencing accidents. In fact, the majority of crashes are considered preventable, provided that the surrounding area is properly observed by the driver and adequate maneuvers are successfully executed (Wong *et al.* 2010b).

It is clear that there is a missing link between crash proneness scenarios and the crash occurrences. Knowing the causality of crashes behind accident chains is the most crucial element in crash analysis and prevention. 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. Extraction of such crash pattern and possible crash-proneness driving population can only reveal partial nature of crash occurrence. The question thus remains: 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 various countries has suggested that the human factor is the most important contributor to crash occurrence. Among those human factors, misallocating attention is one of the most critical cause of crashes or near-crash circumstances (Brown *et al.* 2000, McKnight and McKnight 2003, Underwood *et al.* 2003a, Underwood *et al.* 2003b, Chen *et al.* 2005, Dahlen *et al.* 2005, Underwood 2007, Di Stasi *et al.* 2009, Olson *et al.* 2009, Chan *et al.* 2010). In Taiwan, drivers failing to note roadway conditions accounted for 17% of the fatal crashes in 2011 (MOTC 2012). Presumably, a failure to allocate attention appropriately can be seen as the missing link between crash-prone scenario and crash occurrence within an accident chain. Problems of dividing limited attention resource would cause longer reaction time and higher crash possibility (Cheng *et al.* 2011). Thus, understanding the patterns of attention allocation is crucial to analyzing the relationship between crashes and ways to maintain situational awareness through visual transition.

Safe driving requires drivers to pay continued attention to various areas and to constantly update awareness of the driving environment. Information perception, which is the first stage of Ensley's situational awareness, is the key step of comprehending, anticipating, and reacting against tasks or events (Endsley 1995). Acquisition of incomplete or useless information will lead to insufficient comprehension of the current driving environment, misjudgment, rush reaction, and possibly to a crash. To drive safely, drivers must pay attention to multiple sources of information to make informed driving decisions. However, one's mental resources are limited (Kahnemen 1973). Each driver has a central processor that determines the policy of attention allocation, which divides their mental resources within the limits of their mental capacity. Problems of divided attention may degrade one's ability to detect potential threats while driving (de Waard *et al.* 2008, de Waard *et al.* 2009, Marmeleira *et al.* 2009). Complex driving tasks with more information that drivers must attend to would cause drivers making more errors (Elvik 2006).

Distraction is one of major causes of attention misallocation. Shifting attention away from driving to undertake secondary tasks, such as answering cell phones, may increase the time required to perceive and react to external stimuli, and, thus, increase the risk of crashes (Neyens and Boyle 2007a, 2008). Providing drivers with information via in-vehicle information systems, such as GPS, is intended to help drivers more effectively plan the allocation of mental resources and prevent dangers from uncertainty. However, improper use of such devices can yield a negative effect and cause drivers to miss critical information (Liang *et al.* 2007, Wong and Chung 2007b, Vashitz *et al.* 2008). Horrey and Wickens (2007), a driving simulation experiment, stated that long glances over 1.6 seconds inside vehicles accounted for 86 percent of crashes. Klauer *et al.* (2006) also stated that shifting vision away from the forward area longer than 2 s increases the crash/near-crash risk by at least twofold.

It is obvious that a malfunction of attention allocation is the critical link that connects crash-prone scenario with crash occurrence. Misallocating attention may result in one’s awareness being distracted by useless information; thereby missing important information. In just a fraction of a second, one’s visual inattention can lead to unsuccessful information perception. Maneuvering without sufficient information of road conditions could generate unsafe situations easily and increases the likelihood of driver error. To explore the causality of crashes and to prevent them from happening, a functional mechanism for attention allocation is a vital issue that should be tackled. Knowledge of the patterns in which drivers allocate attention among multiple focal points provides insight into the information-seeking behavior of drivers and its relationship to safety.

Unlike those measurable attributes (such as roadway, environment or maneuver conditions) used in crash causation analyses, exploring attention allocation mechanism may face difficulties of observing a driver’s inherent behavior. Fortunately, the recent technique improvement enables the large scale data collection, including eye movement, bio-medical signal and associated maneuvering behavior. For example, the naturalistic driving studies were widely conducted for recording drivers’ every motion of attention allocation and maneuvering. Such a method provides ample opportunities for researchers to further explore drivers’ characteristics from mental and cognitive perspectives. Grabbing those chances would help explore the accident chain in deeper depth and bridge the missing link between crash occurrence and crash-proneness scenarios.

1.2 Research Problems

Demonstrating a driver’s behavior of attention allocation is a challenging issue in various aspects. Mental model is a complex system which contains numberless rules for driver to allocate attention, perceive information, and take actions against dynamic driving tasks. A sophisticated model of attention allocation must be able to reflect the distinct pattern that drivers shift attention between potential sources of driving information.

The first and the most fundamental problem that this study must solve is the representation of attention allocation. Driver attention is not a manifest variable that can be measured directly. Thus, developing an appropriate representation of attention allocation is challenging. An adequate attention allocation representation should enable representing the continuous process of drivers transiting attention from one area to another, and allow researchers to examine the characteristics of different focal points in naturalistic driving tasks. Following the development of an attention allocation representation, the core process of attention allocation is the allocation mechanism, which determines one’s decisions in selecting a specific target for observation. One question must be asked: do driver have an explicit pattern to allocate attention? If yes, what are these patterns? Finally, focal points do not attract drivers’ attention randomly. Some cues from environmental conditions, traffic flow and roadway devices may direct drivers attention in distinct ways. Finding the factors and examining the way they affect attention allocation is a serious issue for identifying the potential risk-proneness sites.

All in all, this research is trying to explore attention allocation by examining the following problems.

(1) How is driver attention allocation represented?

(2) Do patterns of driver attention allocation exist?

(3) If yes, what are these patterns?

(4) What are the factors affecting driver attention allocation?

1.3 Research Objectives

The objectives of this research are two-fold.

(1) Propose a novel approach for attention allocation analysis:

In this study, the representation aimed to quantify the unobservable attention for analyzing its characteristics, and to analyze its relation to driving behavior. Different representation method may reveal varying aspect of attention and play essential role in interpreting situational awareness strategies. This study aims to explore the paths of drivers transiting vision from one focal point to another. Based on the path approach that has been utilized, this study proposes a new representation of *Renewal Cycle* to reflect drivers' naturalistic driving behavior.

(2) Identify the patterns of attention allocation that drivers commonly held under varying conditions:

The primary goal of this study is identify whether there is a pattern that drivers usually hold to transit vision. If the pattern do exist, this study should be able to explore and represent the drivers' central mechanism of governing their attention allocation. To reach the goal, the study reviewed previous research for identifying the factors contributing to attention demand of a focal point. Then, based on the contributing factors and the representation proposed, the process of attention allocation was analyzed for deriving its characteristics and the scan path of vision transition while driving. Moreover, it has been stated that the driving safety relies on observing every individual motion that drivers make against driving tasks (Laureshyn *et al.* 2010). Thus, a microscopic model of attention allocation was estimated for deriving the probability of choosing specific focal point. In this model, the choices of different type of vision transition and the path of transiting vision among focal points were analyzed and presented.

(3) Incorporate the contributing factors that may affect the attention demand of a focal point and vary the drivers' vision transition process:

Driving in a dynamically changing environment. Numerous factors would vary drivers' attention allocation in different ways. One of the objective of this study is to select the contributing factors based on literature review and to include the factors into models for evaluating their effect on attention allocation.

1.4 Research Scope

(1) Only visual attention was included.

Attention is a multi-channel resource that drivers can used to perceive information using different senses, such as sense of sight, hearing or touch. Seeing that the visual stimuli accounted for the majority part of driving information (Ho 2008, Shinar 2008), this study considered only the visual attention and treated the visual glance to focal point as attending to gather information.

(2) “Looked but failed to see” was not included.

Consciousness and attention are two similar but distinct concepts. Sometimes, drivers may allocate their attention and direct vision to a selected target. Yet, in the level of consciousness, attributes of the targeted object are neither identified nor perceived. However, due to limitation of 100-car dataset, the phenomenon of “Looked-but-Failed-to-See” was not discussed. This study did not differentiate if drivers consciously perceive the information they intended to gather.

1.5 Research Flow Chart

Aiming to answer the problem and reach the goal of this research, this research was organized as Figure 1-1. Noting that attention allocation is critical in perceiving information and making decisions, clarifying the connection between attention allocation and accident chain can help explore the essence of crashes. In Chapter 2, the literatures regarding the crash analysis and attention allocation were reviewed. Particularly, the factors affecting attention demand were discussed. On the basis of these works, the framework of a microscopic driver attention allocation model was proposed. Prior to the validation process, a numerical study is performed to identify the feasibility and appropriateness of proposed model. Advantages and limitations of this model were discussed. Then, in Chapter 4, the concept of *Renewal Cycle* was proposed. Using the 100-car naturalistic driving data, the attention allocation process was analyzed and modeled. Safety performance was evaluated based on this concept. In Chapter 5, this study evaluated the safety performance from the renewal cycle perspective. Finally, the model applications in driving safety and the conclusions were made in Chapter 6.

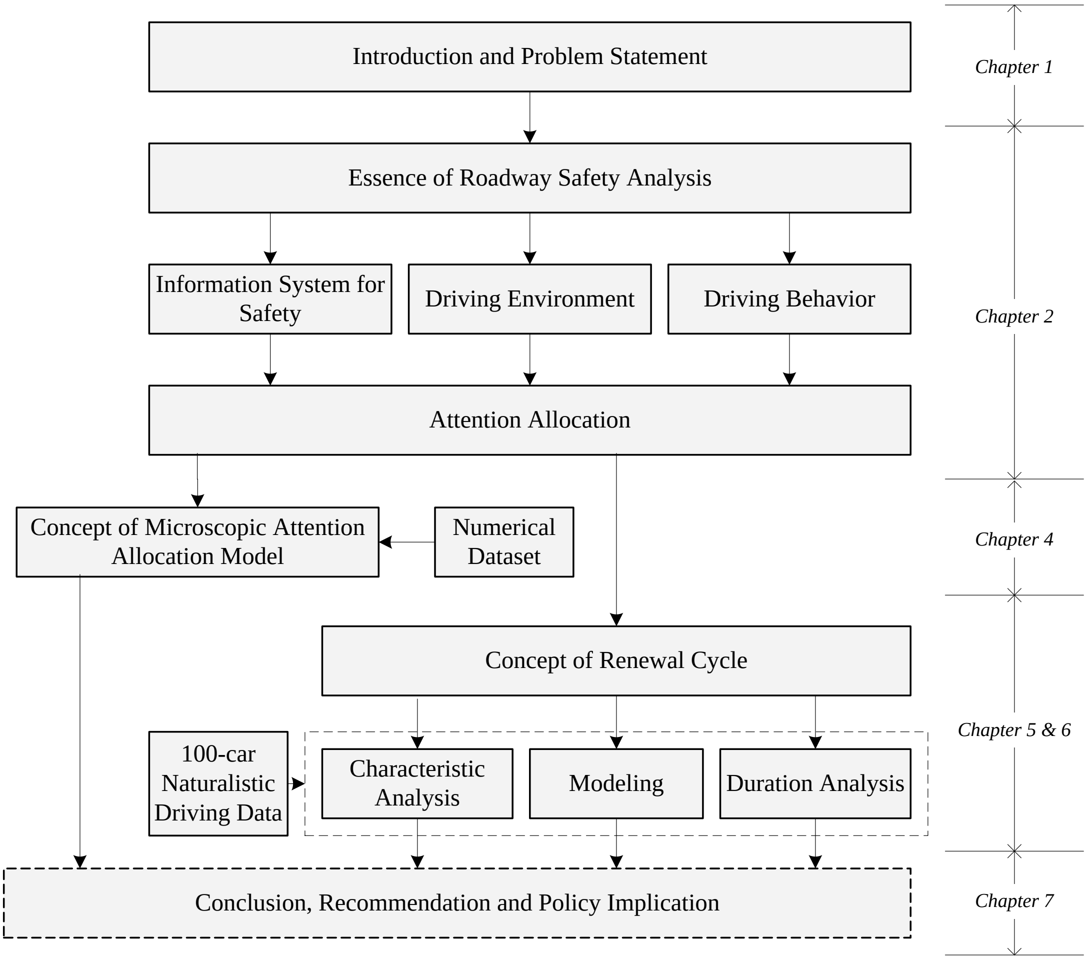


Figure 1-1 Research flow chart

CHAPTER 2 ESSENCE OF DRIVING SAFETY ANALYSES

The ultimate goal of an attention allocation analysis is to improve driving safety. Its connection within the crash occurrence can help identify the way that drivers interact with driving tasks, and probably the reason causing crashes. To elucidate the role of attention allocation in driving safety and crash prevention, the essence of crash analysis must be clarified. In this chapter, a comprehensive framework of safety analyses is constructed as Figure 2-1.

In general, a crash prone scenario represents a combination of risky factors within the driving stage of an accident chain. While driving in such crash-proneness scenarios, crashes were more likely, but not necessarily, to occur. There is a clear gap between the risky scenarios obtained from accident chain analysis and the crash occurrence. From the perspective of attention allocation, these risky scenarios may represent a condition that the drivers cannot perceive and process information adequately. The incomplete information perception would lead to higher chances of unexpected events, which induce reduced reaction time for drivers to response. In other word, the attention allocation analysis can illustrate in-depth characteristics of crashes from a chain perspective and help explore the last stage of an accident chain, namely the pre-crash stage.

The mechanism of drivers directing attention and processing information is the core of an accident chain. Certain factors in the pre-driving stage, such as drivers' physical or psychological conditions, may affect the process of attention allocation. It does not only determine the habitual behavior pattern that drivers usually held, but also affect each driver's capability of processing information. Seeing the limited attention resource, perceiving safety irrelevant information would decrease the attention resource being invested on the critical area for critical information. Additionally, drivers may evaluate the attention demand differently owing to the difference of their individual traits. Misjudging the attention demand of focal points may cause drivers allocating attention inappropriately.

To better understand the characteristics of attention allocation and its role in accident chain, section 2.1 and 2.2 reviewed the factors related to crash occurrence, including the crash-prone environment and drivers. Then, from an attention allocation perspective, contribution of these risk factors to attention demand was discussed in section 2.3. Considering the widely adoption of information system in recent days, section 2.4 illustrate its possible effect on attention allocation.

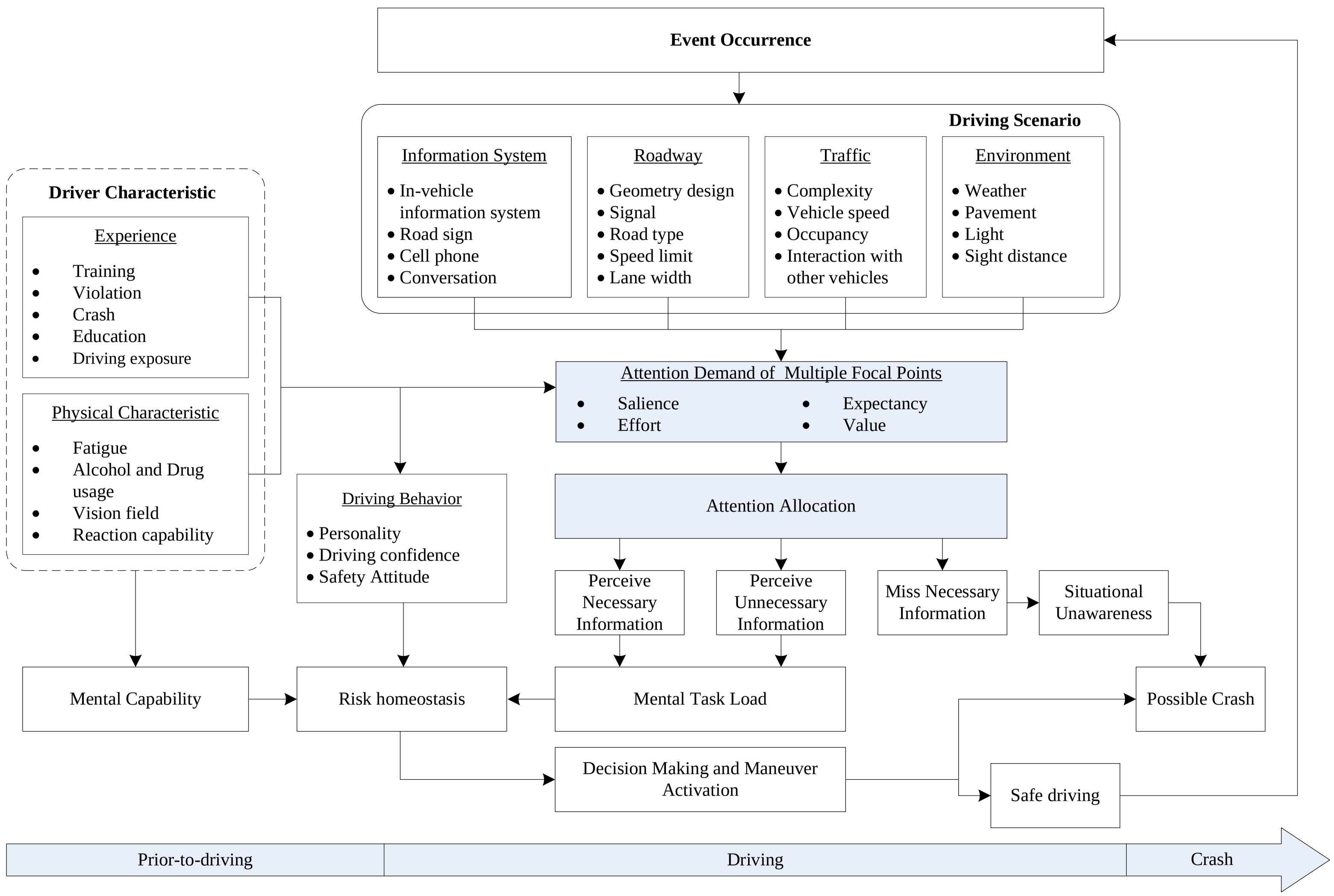


Figure 2-1 Comprehensive framework of crash analysis

2.1 Crash Pattern Analysis

Extracting patterns of crashes would help researchers understand the causality of a crash, and also find the way to prevent it. Comprehensive knowledge of contributing factors can provide clues to discover and reveal the nature of crash occurrence. In previous research, three types of crash pattern analysis were conducted: black spot analysis, crash type analysis, and crash severity analysis.

A black spot is any location that more crashes are expected to occur than other similar locations (Elvik 2008). It is a site-oriented approach that aims to extract recurrent crashes. Considerable research has been carried out to establish connections between frequency of crashes and various local characteristics of roadway and traffic (Chang and Chen 2005, Oh *et al.* 2006, Abdel-Aty and Pande 2007, Caliendo *et al.* 2007). The most common variables used to predict frequency of crash are the traffic volume (such as annual average daily traffic), roadway geometry (such as sight distance, horizontal alignment, vertical alignment and curvature), and environmental condition (such as weather, pavement, and light condition). Constructing the prediction model for black spot analysis is helpful in designing road and evaluating of safety improvement program. For example, Oh *et al.* (2006) examined factors associated with railroad crossing crashes and found average daily train traffic volume and proximity of crossings to commercial areas positively affect the crash occurrences. Chang and Chen (2005) used crash frequency of freeway in Taiwan to construct a non-parametric prediction model. They found that precipitation and daily traffic volume were the key determinant of crash frequency.

Instead of extracting recurrent crashes, crash type analysis focused on the uniqueness of crashes. Different crash types imply different interactions with road environment and with other vehicles. Rear-end, for example, is one common type of vehicle-to-vehicle crash. From the perspective of roadway characteristic, more signal phases, wider traffic island, higher speed limit, and higher number of lane increased the risk of rear-end crash (Chin and Quddus 2003, Yan *et al.* 2005, Wang and Abdel-Aty 2006). Moreover, Kostyniuk and Eby (1998) suggested that maneuver undertaken by frontal vehicle determined the occurrences of rear-end crashes. Any unexpected or unobserved maneuver undertaken by front vehicle creates greater danger of conflicts. To prevent conflict with frontal vehicle or other obstacles, drivers should maintain attention on the frontal side. Misallocating attention and failing to scan road ahead, particularly in congested traffic flow where drivers must frequently stop and go, increased rear-end crashes or conflict with fixed object (Golob and Recker 2003, Neyens and Boyle 2007a).

Another type of crash analysis is the exploration of crash severity. Vehicle type is the most important factors to determine the severity of a crash (Chang and Wang 2006). Concept of compatibility is proposed to evaluate the level of protection of each type of vehicle in a vehicle-to-vehicle crash (Mizuno and Kajzer 1999). Crashes which involved vehicles with similar compatibility were less serious. Mizuno and Kajzer (1999) suggested that SUV and mini car, which are the largest and the smallest vehicle in their research, are the two least competitive types of vehicle. Albertsson and Falkmer (2005) also suggested that probability of resulting in fatality and serious injury is higher in heavy vehicles related crashes than passenger vehicle crashes. To prevent possible serious crashes, drivers may be more concerned about certain types of vehicles on road, for example, the heavy vehicles.

In this section, the extraction of crash pattern is briefly reviewed. The scenarios explained the conditions in which drivers have increased risks of being involved in crashes, and possibly the driving scenario where drivers would be more likely to misallocate their attention. However, an unanswered question remains, namely the reason that crashes occur under specific conditions. The reality is that for each crash under certain risky conditions, there are numerous drivers who drive under identical conditions without experiencing crashes. The question thus arises of why different individuals react differently to identical conditions, resulting in different outcomes.

2.2 Driver Behavior Analysis

In addition to the analysis of factors closest to crash occurrences, the remote factors took place in the prior-to-driving stage should be analyzed (Elvik 2003, Wong and Chung 2007b, Wong and Chung 2007a, Wong and Chung 2008a, Wong and Chung 2008b). Driver is the most critical element within the prior-to-driving stage of accident chain. Age and gender are two observable variables which have been widely discussed. Regarding the age effect on driving, senior drivers have been found suffering degradation in driving skills, physical and cognitive conditions (Bayam *et al.* 2005). Accidents related to senior drivers usually resulted in losing the capability of situational awareness. Meanwhile, young drivers are usually considered as risky population and have the highest accident rate among all population (Clarke *et al.* 1998, Clarke *et al.* 1999). Gender is another important factor which distinguishes the accident patterns. Research conducted by Chang and Yeh (2007) stated that male drivers usually got involved in accidents due to their risky behavior while female drivers usually suffered accidents due to insufficient experience and skill.

Driver's reaction and maneuver against external environment can be seen as the critical stage before crash occurrence. Provided that drivers are able to conduct safe maneuvers while driving in a risky scenario, the crashes are still preventable. Therefore, identifying how drivers normally drive becomes an important issue in clarifying the nature of crash occurrence. Questionnaire investigation was seen as a convenient approach for analyzing driving behavior. The driving behavior questionnaire (DBQ) was originally developed by Reason *et al.* (1990). Questionnaires containing 50 aberrant behaviors were distributed to obtain the frequency of driver undertaking specific aberrant behavior. After the factor analysis, three constructs of aberrant behaviors were extracted, which are harmless lapse, dangerous error, and violation. It was found that dangerous error decreased with the accumulation of exposure and experience. Parker *et al.* (2000) further divided the construct of violation into ordinary violation and aggressive violation. Senior driver were found conducting less aggressive violation but more lapses. It is suggested that senior population may face the degradation of mental capability which cause them unable to drive safety.

Among all human factors, psychological trait was one of the critical factors affecting risky driving behavior (Ulleberg and Rundmo 2003, Dahlen *et al.* 2005, Kim and Yamashita 2007). In order to discuss the decision making process of a driving behavior, Ulleberg and Rundmo (2003) adopted the Theory of Planned Behavior (TPB) and incorporated personality traits, attitudes towards safety and risk perception into Structure Equation Modeling (SEM) to discuss the risky driving behavior mechanism among young drivers. Based on this framework, Wong *et al.* (2010b) incorporated cost and benefit of conducting aberrant driving behavior. The results suggested that motorcyclists who have low riding confidence and traffic awareness deficiency usually over-focused on the object that pose threat and failed to observe surrounding traffic conditions. Based on the framework, Wong *et al.* (2010a) further examined the structural discrepancy that may exist in distinct groups of young motorcyclists by clustering the personality traits. Four types of young riders, risky, aggressive, conservative, and nervous, were extracted.

Clarifying the decision making process of conducting driving behavior help explain the accident chain. Combining the analyses of crash pattern driver behavior characteristics enables a deeper exploration of crashes. Yet, the real causalities were still not achieved. As mentioned in Wong *et al.* (2010b), aggressive motorcyclists tend to enjoy the utility of undertaking aberrant behavior. However, their experience and skill are able to adequately check surrounding traffic to prevent crashes from happening. In other words, a risky drivers driving in a crash-prone scenario were not necessarily resulted in crashes. Obviously, missing link between accident chain and crash occurrence still exists. The critical issue in building up the link relies on the attention allocation while driving.

2.3 Attention Allocation

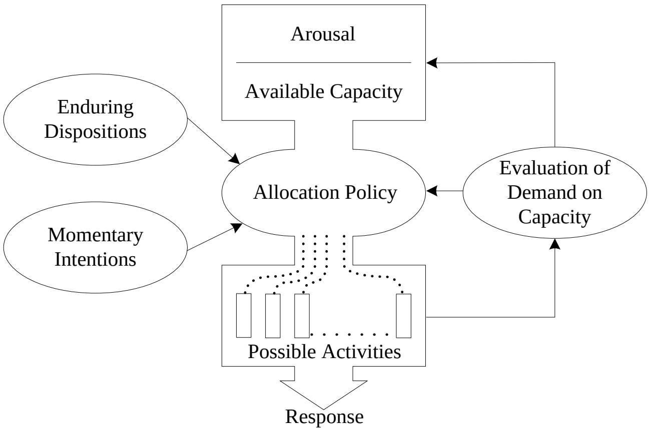
Attention allocation is the key to perceiving external information for making informed decisions to prevent crashes. Each risky driving scenario represents a set of information that drivers must gather from multiple information sources. In this section, a conceptual of driver attention allocation model is proposed based on the review of previous research.

2.3.1 Definition

The attention is a mental process of drivers' mind and cognitive. Previous research defined the attention as "*the process of concentrating or focusing limited cognitive resources to facilitate perception or mental activity*" (Streff and Spradlin 2000, Regan *et al.* 2011). Key words of this definition are "concentration" and "limited cognitive resource". That is, the attention must be a directive process, which allows cognitive resource to be invested on particular target.

Additionally, attention should be distinguished from the term of consciousness, although these two terms are highly related (Phaf *et al.* 1994, Treisman 2004, Koch and Tsuchiya 2006). There are four types of situations related to the consciousness and attention. One is attention without consciousness which represents the failure of perception; the case of "looked but failed to see". It contains the behavior of directing attention to selected focus. Yet, attributes of the targeted object are neither identified nor perceived. Another is consciousness without attention. Objects outside the focal attention can be perceived without being selected as the focus through peripheral vision. In such condition, only partial attributes and information of the objects can be perceived. The third type is the maneuvering with no consciousness and no attention. This situation is usually caused by boredom or fatigue. The last type is the attention with consciousness, which is the one considered in this research. Thus, attention is defined as consciousness with focalization and concentration toward stimuli. In other words, once the attention is allocated, the information perception will be completely effective. Thus, based on the definition and the research scope, this study uses the "vision transition" as the proximity of attention allocation. Once a driver put his/her eyes one a specific target, the attention is allocated and invested.

In addition to the concentration of cognitive resource, another key term for defining attention is the resources being limited. Facing multiple sources of information, attention must be divided and allocated. The divided attention model proposed by Kahnemen (1973) stated 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. The capability of dividing attention resource to multiple targets is critical to situational awareness (Laberge *et al.* 2006, Creaser *et al.* 2007, de Waard *et al.* 2009, Marmeleira *et al.* 2009). To explain the divided attention concept, four principles of attention are mentioned. First, attention capacity is limited and varies from time to time. Available mental resources 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 dividable. 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 2-2.



Source: Kahnemen (1973)

Figure 2-2 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 feedback of attention allocation would continue to evaluate and adjust the arousal level and revise the allocation policy to fit the current situation.

2.3.2 Conceptual framework

Based on the concept of divided attention, Figure 2-3 illustrates the process of drivers dividing and allocating attention resources to different focal points for gathering information. The process comprises four stages, which are 1) accessing to the short-term memory, 2) allocating attention to focal points, 3) perceiving information, and 4) activating actions and updating memory.

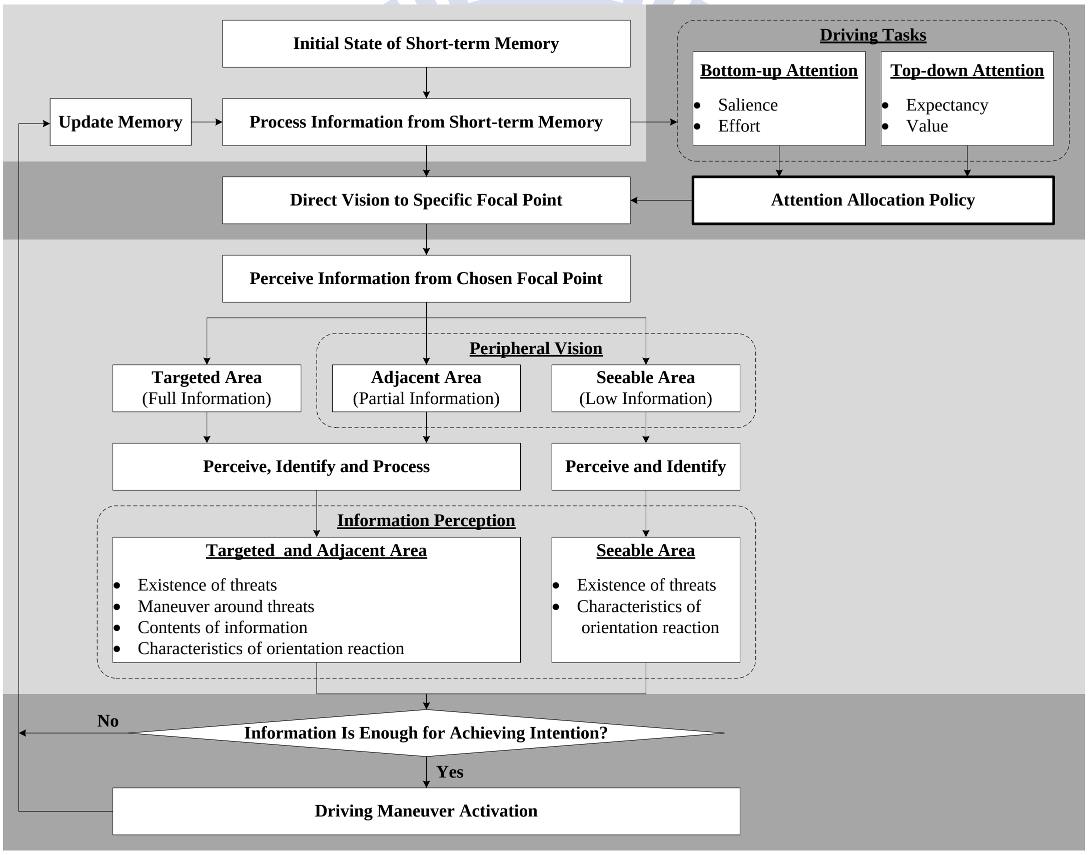


Figure 2-3 Process of driving attention allocation

In the first stage, short-term memory enables the maintenance of few information which is relevant with the ongoing tasks or activities. These information may be updated through the sustained attention and retrieved for making decisions or actions efficiently (Courtney 2010). From the perspective of driving, the short-term memory allows drivers to hold their comprehension of driving environment or other related statuses. It is also an important input for the attention allocation policy. Based on the disposition of traffic flow, roadway and driving tasks that retrieved from short-term memory, drivers are able to evaluate the attention demand of each focal point and to direct visions to their intended area.

The second and the third stage determine the focal point chosen and the information perceived. Each driver has an attention allocation policy for determining the area to be glanced. For the chosen focal point, the targeted area enables the full information identification and perception. Drivers are able to identify the threat, monitor the movement, and predict its future status. In this level, the attention can be determined as the one with consciousness. Outside the central visual cone, drivers can still perceive partial information via peripheral vision. The amount of information perception degraded with the distance to central visual cone. To the information which is on the edge of peripheral vision, which is the seeable area, are barely comprehended. Drivers can only perceive the existence of an object with little information, such as the parking vehicle.

After the information perception, the last stage of attention allocation is the maneuvering and updating short-term memory. If drivers consider the necessary information is satisfyingly perceived and the current situation of traffic and other statuses are comprehended, the actions may be activated. Otherwise, another term of attention allocation should be undertaken for continuing the information perception. Noting that drivers may activate action without necessary information being completely perceived, such an uninformed action can lead to higher chances of unexpected events and possibly crashes. That is, misallocating attention or being inattention to critical information can result in dangerous situations.

The policy of attention allocation seems to be the key element of driving safety. It has been stated that the major distinction between experienced drivers from novices is the capability of utilizing their attention and mental resource (Konstantopoulos *et al.* 2010). Experienced drivers were considered having better knowledge of driving tasks and skilled attention allocation policy (Underwood *et al.* 2002a, Underwood *et al.* 2002b, Martens and Fox 2007, Nabatilan 2007, Borowsky *et al.* 2010). By contrast, novice drivers, who had immature mental models and limited rules of attention allocation, usually failed to anticipate hidden latent hazards and tend to commit more driving errors owing to a failure in attention allocation (Martens and Fox 2007, Chan *et al.* 2010). Moreover, Underwood *et al.* (2002b) suggested that novice drivers had more difficulties in controlling their vehicles. Therefore, they tended to focus more often on technical tasks and stare at the frontal side, instead of shifting vision around vehicles (Underwood *et al.* 2002b, Underwood *et al.* 2003a, Underwood 2007, Konstantopoulos *et al.* 2010).

All the works that have been done previously suggested the essential role of attention allocation policy. An adequate policy of attention allocation is necessary for safe driving (Shinar 2008). Exploring the way of drivers maintaining situational awareness through visual attention can be fruitful and potentially applicable for analyzing drivers' behavior and preventing crashes. Therefore, to analyze the attention allocation in a more proper way, representations of attention were reviewed in section 2.3.3. Then, as stated in divided attention theory, dispositions of environmental conditions and driving tasks are critical determinants affecting the demand of attention. Section 2.3.4 reviewed the contributing factors that were adopted for attention allocation analysis.

2.3.3 Representations

Driver attention is not a manifest variable that can be measured directly. Thus, developing an appropriate representation of attention allocation is challenging. Nevertheless, various representations have been provided to analyze several aspects of attention allocation. There are three types of representation that previous research adopted to analyze the characteristics of attention allocation from various aspects.

The first type of representation aims to analyze the characteristics of a single focal point or target. Some studies utilized the portion of time that drivers spend looking at particular objects or areas as the representation of attention to show the importance of the areas (Underwood *et al.* 2002b, Underwood *et al.* 2003b, Nabatilan 2007, Di Stasi *et al.* 2009, Levin *et al.* 2009, Borowsky *et al.* 2010, Konstantopoulos *et al.* 2010, Dukic and Broberg 2012). Drivers usually spent more time on the focal point where they considered as one with higher risk of crashes.

Additionally, analyzing the duration (Falkmer and Gregersen 2001, Underwood *et al.* 2002a, Underwood *et al.* 2002b, Martens and Fox 2007, Di Stasi *et al.* 2009, Borowsky *et al.* 2010, Chan *et al.* 2010, Konstantopoulos *et al.* 2010, Dukic and Broberg 2012) and transition frequency (Salvucci and Liu 2002, Underwood *et al.* 2002b, Underwood *et al.* 2003b, Martens and Fox 2007, Kiefer and Hankey 2008, Di Stasi *et al.* 2009, Borowsky *et al.* 2010, Chan *et al.* 2010, Konstantopoulos *et al.* 2010) provided clues for identifying drivers' mental status against driving tasks. For example, when facing mentally demanding tasks, drivers would increase their sampling rate for processing information more efficiently due to psychological pressure. Consequently, they would help short duration and high transition frequency while shifting vision among focal points (Chapman *et al.* 2002, Underwood *et al.* 2002a). On the other hand, provided the scenario is worsen, drivers would hold long glance on the critical focal point with less vision transition and pay close attention to it (Underwood 2007).

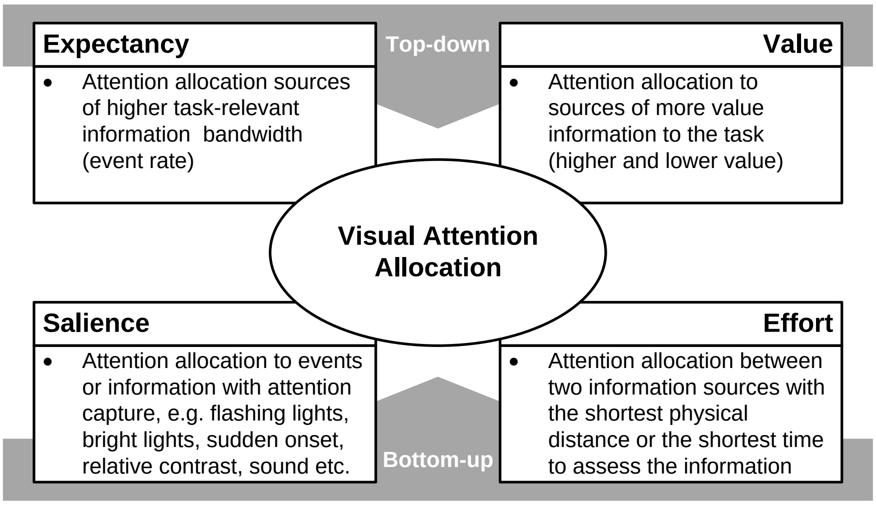
Because presenting the process of drivers transiting visual fields among various focal points is not practical by employing the single-point approach, the second type of attention allocation representation adopted scan path approach to represent process of transiting vision among focal points (Underwood *et al.* 2003b). The scan path method examines multiple and sequential focal points to which drivers divert their glance. This method explores the detailed behavior of drivers shifting attention from one focal point to another. By extracting the scan path, it provides additional information on drivers' sequential processes of attention allocation for maintaining situational awareness. The most common type of path is the one shifting vision toward the frontal side. Seeing that the drivers cannot perceive the status changes ahead while they glancing elsewhere, such a type of forward related path showed that the unawareness of leading traffic may urge drivers to transit vision back to the front (Brown *et al.* 2000).

In addition to analyzing the aggregated characteristics of attention allocation, from single point or scan path perspective, the third type of attention allocation representation is to calculate the probability of choosing specific focal point microscopically. Analyzing attention from a microscopic perspective can be seen as a mean to identify drivers' dynamic behavior, particularly the attention allocation behavior, against the real world traffic (Laureshyn *et al.* 2010). In order to explains visual attention allocation in general for analyzing the situational awareness in dynamic environments, Wickens and his colleagues proposed a SEEV model for calculating the probability of choosing specific focal point under varying environment or task conditions. The model was originally design for a pilot's attention allocation (Wickens *et al.* 2001, Wickens *et al.* 2003, Wickens and Thomas 2003, Miller *et al.* 2004). In recent years, this concept was adopted in the driving field (Horrey *et al.* 2006, Horrey and Wickens 2007, Werneke and Vollrath 2012). There are four constructs of attention demand included in the SEEV model, which are *Salience*, *Effort*, *Expectancy* and *Value*. Among the four constructs, only *Effort* provided negative effect on attention demand.

2.3.4 Contributing factors

Focal points or targets on roads do not attract drivers randomly. Instead, drivers, particularly experienced ones, usually direct their visions to focal points based the cues from environment or driving tasks (Falkmer and Gregersen 2001, Stanton and

Salmon 2009, Borowsky *et al.* 2010). Figure 2-4 shows the concept and definition of the four constructs used in the SEEV model. Among the four constructs, salience and effort are the two constructs representing bottom-up attributes of attention allocation. These attributes are exogenous and related to the characteristics of objects being targeted. Meanwhile, expectancy and value are the two constructs representing top-down attributes of attention allocation. These are endogenous attributes that characterize drivers' knowledge-based skills.



Source: Werneke and Vollrath (2012); Wickens *et al.* (2001)

Figure 2-4 The four components of the SEEV model

Expectancy was the first construct proposed in the SEEV model. It, as a top-down construct of attention demand attribute, determined the expected frequency of information appearing. Treating information perception as queuing behavior, Senders assumed that visual attention allocation was driven by the bandwidth of the information, which can be represented by the expected rate of status changes (Senders 1964, 1967, Moray 1986). Drivers would glance at the focal point where more stimuli, information or other status changes would appear (Verwey 2000, Blanco *et al.* 2006, Kiefer and Hankey 2008, Vashitz *et al.* 2008, Gershon *et al.* 2012). Moreover, traffic density and driving speed affect the level of interaction with other vehicles. When driving in heavy traffic (Werneke and Vollrath 2012) or high speed (Konstantopoulos and Crundall 2008), drivers would pay more attention to the frontal side for compensating the frequent status changes and short reaction time.

Based on the Senders' model, Carbonell incorporated *Value* as another top-down construct for representing the importance and relevance of the information (Carbonell 1966, Carbonell *et al.* 1986). In driving tasks, the value of information is determined by their maneuvering status. Generally, drivers tend to look in the direction of future vehicle trajectories, i.e., where they expect the greatest number of threats to occur

(Martens and Fox 2007, Dukic and Broberg 2012, Gershon *et al.* 2012, Koustanaï *et al.* 2012, Lehtonen *et al.* 2012). For instance, moving forward constitutes a major driving activity. Hence, the frontal area attracts the most attention in almost all driving conditions (Underwood *et al.* 2003b, Nabatilan 2007, Underwood 2007, Konstantopoulos and Crundall 2008, Shinar 2008, Levin *et al.* 2009, Dukic and Broberg 2012). Changing lanes requires heightened attention to be invested in the adjacent lane (Salvucci and Liu 2002, Underwood *et al.* 2002b, Kiefer and Hankey 2008, Konstantopoulos and Crundall 2008). Entering an intersection compels drivers to look to both sides of the intersected roads (Summala *et al.* 1996, Konstantopoulos *et al.* 2010, Werneke and Vollrath 2012, 2013). In addition to the attention required for specific intended maneuvers, drivers allocate attention to surrounding areas to maintain awareness of traffic conditions and to prevent possible conflicts caused by other vehicles (Crundall *et al.* 2006).

In addition to maximizing the benefit (*Value*) of information perceived, drivers would also try to minimize the cost while gathering information, i.e., the *Effort* invested on particular targets (Kvålseth *et al.* 1976). This bottom-up construct determines the visual angle difference or the distance between two focal points (Wickens *et al.* 2003, Wickens and Thomas 2003, Horrey *et al.* 2006). Such a construct is important for representing the process of vision transition. Drivers, in general, tended to transit vision to focal point that is close to the current one. Underwood *et al.* (2003b) suggested that experienced drivers barely transited vision from one side of vehicle directly to another. By contrast, novice drivers sometimes undertake the vision transition across vehicles. In addition to the visual angles difference, drivers usually transit vision on a horizontal band (Falkmer and Gregersen 2001, Crundall *et al.* 2006, McIntyre *et al.* 2012). Shifting attention vertically required higher effort.

Another bottom-up construct of attention demand is the *Salience*, which represents the easiness of target being differentiated and identified from the background information. Drivers were easier to identify the target with higher contrast in color or conspicuity comparing with background (Koustanaï *et al.* 2012). For example, drivers were easier to identify motorcyclists wearing dark outfit in day time or bright outfit at night (Gershon *et al.* 2012). McIntyre and his colleague suggested that different color between brake lamp and rear lamp enable quicker reaction for the drivers on the rear side (McIntyre 2008, McIntyre *et al.* 2012). Billboard with high contrast and brightness attracted drivers' attention more easily, and sometimes would cause dangers owing to distractions (Dukic *et al.* 2013). In addition to the conspicuity perspective of salience, a threat with unusual behavior and exterior can be viewed as a salient threat that is relatively easy to identify. For example, drivers will pay more attention on ambulances or aggressive vehicles, yielding to avoid potential conflicts. Moreover, heavy vehicles, such as trucks and buses, are unique in size among other vehicles and easier to be identified.

2.4 Role of Intelligent Transpiration System (ITS) in Attention Allocation

Seeking information is the key element of attention allocation. Providing information to drivers is to help drivers drive more safely and easily. Technology advancement makes it easier for drivers to obtain real-time traffic information and is supposed to make driving safer. However, different information affects drivers differently. It is important to understand the characteristics of information and its impact on driving safety. Otherwise, distracting drivers' attention to information systems would lead to less control on driving tasks and situational awareness (Thompson *et al.* 2012).

ITS is an integrated system composed by techniques of computer, electronic engineering, communication, information and sensing to enhance transportation safety and efficiency (Praveen *et al.* 2005, Smith and Venkatanarayana 2005). Considering that the primary contribution of ITS is the real-time information while driving, the following discussion of information characteristics and the impact on attention allocation will focus on the category of real-time information. There are three types of ITS safety systems: route information, warning and automated control.

(1) Route information

Goal of providing route information to drivers is to improve the driver's understanding of traffic situations and their influences on driving. From a user perspective, providing more information is to support decision-making and thus reduce driving tasks (Brookhuis and de Waard 1999, Creaser *et al.* 2007). Gathering real-time information enhances driver's controllability about the journey and allows them to pre-allocate their attention resources to deal with future traffic conditions (Vashitz *et al.* 2008).

Real-time information is usually provided through In-Vehicle Information System (IVIS) or Variable Message Sign (VMS). Most VMS provide information and operation suggestion in accordance to the demand of general driving population under certain environment conditions. Al-Ghamdi (2007) conducted experiment of fog warning system which detect of visibility and adjust the speed limit through VMS. Results showed that real-time information provided by VMS can effectively change drivers' driving behavior. Intersection Decision Support (IDS) is another application of VMS which assists drivers' decision making of entering the stop controlled intersection (Laberge *et al.* 2006, Creaser *et al.* 2007, Neale *et al.* 2007). By collecting the data of traffic flow on the main lane and estimating the time to collision, IDS can provide the operation suggestion whether it is safe to enter the intersection or not.

Other than the providing information through VMS, IVIS can further customize and personalize information in accordance to individual drivers' needs, such as route navigation, traffic jam, weather, traffic flow conditions, accident prone site and other business application. Several research indicated that the use of IVIS can increase the driving safety by enhancing the controllability of driving (Boyle and Mannering 2004, van Driel *et al.* 2007, Vashitz *et al.* 2008). Accidents in long tunnels are more serious even though the frequency is comparatively low. Driving in a long tunnel induces more mental workload than driving in normal conditions. In order to enhance the communication between tunnel traffic control and drivers, tunnel IVIS is used to provide route navigation, speed limit, location of emergency events and closest emergency exit (Vashitz *et al.* 2008). Advanced Driver Assistance is another application of IVIS (van Driel *et al.* 2007). Through the collection of traffic flow data, the Advanced Driver Assistance is able to provide information of traffic jam to drivers. By telling drivers the location of upcoming traffic jam or the distance that drivers might take to pass the traffic jam, Advanced Driver Assistance can mitigate the negative impact of driver's frustration if they are already in the jam. The system also allows drivers to change routes if they are not in the jam yet.

Previous research indicated that drivers prefer the route information system which can provide more information. However, shifting attention from driving task to the information perception and comprehension may induce distraction (Liang *et al.* 2007, Vashitz *et al.* 2008). Issue of information overload should be seriously concerned.

(2) Warning

The second type of ITS safety information is the warning system which aims to remind and attract driver's attention for critical event or threat to safety. There are two major kinds of warning systems.

The first system is the Vehicle Collision Warning System (CWS). Conventional CWS use vehicle sensors mounted on the subject vehicle to search for obstacle and measure the distance between subject vehicle and threads. When vehicles or other obstacles enter the defined dangerous zone, the system would inform driver and give operation recommendation (Shaheen and Niemeier 2001, Vahidi and Eskandarian 2003, Praveen *et al.* 2005, Tan and Huang 2006, Maltz and Shinar 2007). Recently, Cooperative CWS (CCWS) was proposed. Rather than using sensors on subject vehicles to identify the risks, such system works relying on the communication between subject vehicles and other vehicles around. Each vehicle on roads is equipped with self-sensing system to obtain its own driving state, including position, speed and acceleration/deceleration. Besides, communication devices mounted on each vehicle send and receive those driving state which can be used to calculate related position, speed, angle and time to collision to surrounding vehicles (Tan and Huang 2006, Polychronopoulos *et al.* 2007). However, current development of CCWS faces several limitation and difficulties. First, not every vehicle or obstacle on roads is capable of cooperative devices. Any objects without CCWS can be seen as black hole of information and serious thread of safety (Tan and Huang 2006).

The second system focuses on the maneuver of drivers. Take speed control for example, in order to keep speed under the legal limit, drivers have to check speedometer frequently. To decrease the task of checking speed and to prevent unconscious speeding, Manual Speed Alerting (or Electronic Speed Check, ESC) is adopted to collect speed limit from roadside equipment or GPS and to alert drivers when the speed exceeds limit (Young and Regan 2007, Marmeleira *et al.* 2009). Furthermore, considering the fact that drivers can access to enormous information, shifting attention may cause distraction and fail to perceive critical information. Feedback mechanism of IVIS and distraction Alert is proposed to warn drivers when frequency and duration of glance is higher than the acceptable level (Donmez *et al.* 2007).

(3) Automated control

Purpose of automated control system is to exclude human factors from driving. Two major functions of automated control systems are assistance of driving tasks and restriction of dangerous behaviors.

Automated Highway System (AHS) aims to reach the goal of “hands-free” and “feet-free” driving (Vahidi and Eskandarian 2003). Core technique of AHS is Advance Vehicle Control System (AVCS), which is consisted of Adapted Cruise Control (ACC) and steering control. ACC is designed to control speed at design level and to slow down automatically when lead vehicle decelerate. Despite of the speed control, automated lateral control relies on the detection of lane mark

(Young and Regan 2007). Owing to the automated control of each vehicle in the platoon, no lane changing or passing are allowed. Speed variance, which is seen as a major contributing factor of accidents, can be decreased to a very low level since all vehicles are set to drive in the same speed. AHS can effectively enhance operation safety and efficiency on highways (Carbaugh *et al.* 1998, Vahidi and Eskandarian 2003, Young and Regan 2007).

The other form of automated control systems is similar to the function of warning system. Instead of warning drivers to decelerate or avoid collisions, automated control systems overrule drivers' maneuver and operate vehicle to safety conditions. Take speed alert for example, Intelligent Speed Adapter (ISA) not only provide warning of speeding, but also decrease speed automatically (Molin and Brookhuis 2007, Young and Regan 2007). Moreover, Emergency Lane Assists (ELA) is the extension of CWS and Rear Proximity Warning System which remind drivers to avoid collision with other vehicles (Eidehall *et al.* 2007). ELA is a new concept of lane guidance system which aims to prevent dangerous lane departure. By monitoring vehicles on adjacent lanes and the position of lane mark, a torque is applied to the steering if the lane-change maneuver is considered as dangerous behavior. Only when the adjacent lane is safe for lane-changing, ELA will allow vehicles to cross the lane mark.

In the ideal conditions, without intervention by human, drivers only have to consume attention resource to monitor the driving operation when using automated systems. As long as the systems are function properly, the level of attention demand can be maintained in a very low level without compromising safety. However, the successful adaptation of automated system relies on the drivers' acceptability. Previous research showed that drivers have high acceptability of ITS device except the automation system which has the function of overrule drivers' maneuver. Drivers claimed that such systems remove the power of controlling vehicles from drivers (Molin and Brookhuis 2007, van Driel *et al.* 2007, Young and Regan 2007). Instead of being controlled by systems, drivers prefer to obtain more information from route information and warning systems (Marell and Westin 1999, Donmez *et al.* 2007, Young and Regan 2007, Vashitz *et al.* 2008, Bruyas *et al.* 2009). The final decisions are mostly decided by drivers (Al-Ghamdi 2007).

Despite the difference in information content and complexity, different ways to display and present information might influence drivers differently. Visual display is usually adopted in route information systems that driver must attend to. Location of visual information is critical. It is suggested that the visual distraction have great concern to risk perception than auditory distraction and is difficult to adjust (Hatfield and Chamberlain 2008). To minimize the distraction of visual information, (Neale *et al.* 2007) indicated that the visual information should be located near driver's central and peripheral vision where they usually focus on while driving.

Other than the route information systems, auditory and haptic approach is the better way to display the warning information (Maltz and Shinar 2007, Neale *et al.* 2007). However, content of information is limited in auditory ITS systems. The auditory information should be short and clear enough of drivers to perceive and comprehend efficiently (Maltz and Shinar 2007). The reasons which visual display is not suitable for warning system can be discussed in two folds. First, drivers would rather put their visual attention on the road for situational awareness than focusing on the visual warning of conflicting traffic. Second, the warning messages are usually appear unexpectedly. Without continuously monitoring the system, drivers may not have the chance to perceive that information even though the visual warning systems provide alerts. Focusing on the monitor for visual warning may create more serious dangerous (Neale *et al.* 2007).

While information is generally beneficial, improper use of it can gain negative effects. Only providing the proper information to right driver at the proper time and place can exert positive effects and reduce accident risk. Complex laws proposed by (Elvik 2006) state that accident risks are increased with the information drivers must attend to during a given unit of time. Moreover, side effects of information should also be considered. Drivers influenced by multiple sources of information are more likely to be distracted and miss critical information. Therefore, information overload will not help drivers and may even cause serious problems by distracting them. To prevent negative effects resulting from interference of ITS systems or other sources, analyses of information optimization and allocation is crucial for future ITS development and application (Verwey 2000).

2.5 Summary

Crashes are results of a series unfortunate events. The key purpose of a well situational awareness is to observe one of the possible event, correct the mistakes and to stop this chain of crashes. In other words, crash occurrences implies certain malfunction of situational awareness, which leads to inadequate understanding of driving tasks and possibly higher chances of crashes.

Crash analysis extracted the scenarios with higher crash risk. From the attention allocation perspective, such scenarios are the sites where drivers are more likely to misallocate attention. However, these sites are usually lack of the clues for identifying the necessary information, and the real information that drivers have perceived. In fact, few effort was put on the explanation of these crash-prone scenario from the drivers' attention allocation perspective. A crash can be blamed on drivers' lapses of directing vision to wrong targets, overloaded information causing drivers being unable to process in time, or inadequate environment and roadway which degrade drivers' attention allocation. Thus, analyzing crashes from the perspective of attention allocation can be a potential way for improving safety.

In recent years, the issue of safety and information became more popular owing to the advances of technologies. In section 2.4, the ITS application in driving were introduced. These advances devices inside vehicle or on-road can help drivers gather information in a more efficient ways. Devices, such as navigators or IVIS can enhance drivers' awareness of traffic and trip. Others warning systems or automation system can be used to decrease drivers' task load of controlling vehicles and observing environment. Yet, additional information will share the limited attention resource that drivers have. Even for the automation or the warning systems, they create other focal points, mostly inside the vehicles, that drivers should pay attention to. Once they spent time on collecting information that they do not need, the attention resource allowed for processing the necessary information will be reduced. Consequently, it shows the importance of possible distraction when introducing these technologies.

Summing up the essence of safety analysis, analyzing attention is an essential step toward crash prevention and safety improvement. The key issues arises in this stage is the way of representing attention. Different representations may reveal different insights of attention allocation process. Therefore, based on the literature review, this study will focus on the representation of attention allocation. Moreover, the certain contributing factors from the concept of *SEEV* model can be adopted and revised for applying in studies of driving behavior and driver attention allocation.

CHAPTER 3 MICROSCOPIC MODEL

After reviewing related references regarding attention allocation, this study aimed to propose a microscopic model for capturing the attention allocation behavior. In this study, the continuous attention allocation was treated as successive choices of focal points. That is, each focal point being glanced was considered as an alternative for drivers to choose. This section analyzed and represented the attention allocation in from a microscopic perspective for capturing the mechanisms of driver attention allocation in a world with dynamical status changes. Moreover, to demonstrate the concept of this model, a set of hypothesis data were adopted in model estimation.

3.1 Model Concept

In this section, the alternatives of attention allocation, i.e. the focal points, were defined. Then, concept of a microscopic attention allocation model using discrete choice analysis was introduced.

3.1.1 Vehicle drivers' domain

In real driving tasks, there are countless potential focuses that may attract drivers' attention, including on-road, off-road, or in-vehicle objects. Therefore, it is technically unpractical to conduct an analysis at this level of detail. From the viewpoint of operational feasibility, an appropriate approach is to classify the potential focal points into several groups based on their characteristics. Thus, objects within the area of interest should produce similar maneuvers. This study characterized the focal points based on two dimensions – the horizontal distance and the lateral location of the focal points.

Vehicle driver's domains were proposed to present the distance between the drivers and their associated focal points. It represents a driver's conceptual area, where external objects may appear to interact with the subject vehicle, including other vehicles, fixed objects, curbs, and pedestrians. To prevent collisions, drivers must allocate their attention within the vehicle driver's domain to gain information for driving maneuvers. In line with Underwood *et al.* (2003b), this study divided the interested area into three sub-domains from near to distant area.

Figure 3-1 shows the three boundaries forming the three 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 as the perception domain, reaction domain, and critical domain, respectively. The content of these three domains can attract the driver's attention and affect traffic safety differently.

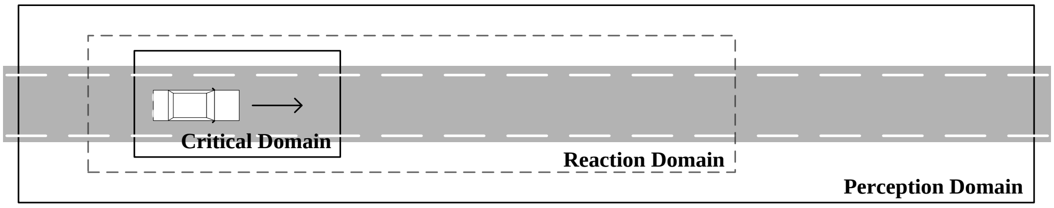


Figure 3-1 Concept of vehicle driver's domain

Vehicle driver's domain is of major importance in situational awareness, decision making, and preventing collision. Size and shape of each domain are important for defining their distinctive areas. In the following sections, the definitions and factors affecting each domain were explained.

(1) Perception domain

The perception domain reflects the respectively distant 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, a driver continues 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 were 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 inFigure 3-2.

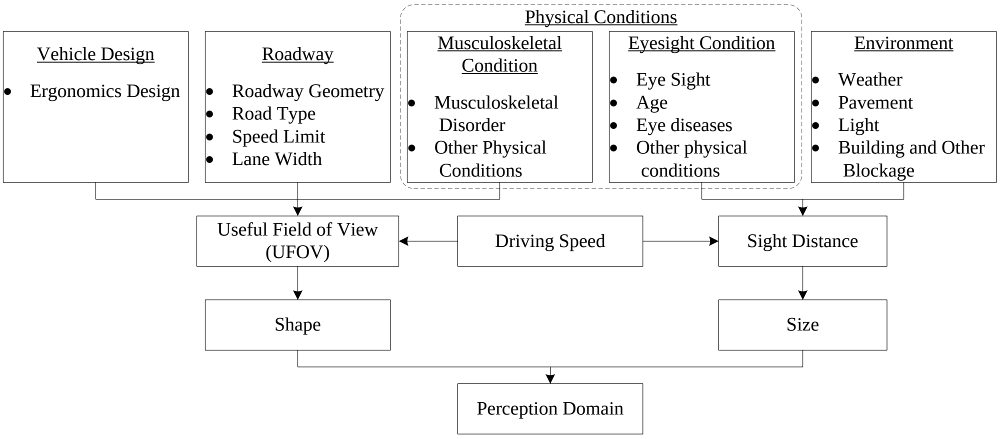


Figure 3-2 Important factors of perception domain

The farthest distance of the perception boundary, which defined the size of the perception domain, refers to the maximum sight distance under certain speed and environmental conditions. This sight distance depended on the driver's visual capability, which was related mostly to his or her physical capabilities. For example, senior drivers were indicated as having serious degradation of eyesight (Clarke *et al.* 1999, Underwood *et al.* 2003b, Bayam *et al.* 2005). 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 can 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 a driver's visible area, 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.

(2) 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 crashes. Although drivers can still allocate attention to threats inside the critical domain, yet, conflicts 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 3-3.

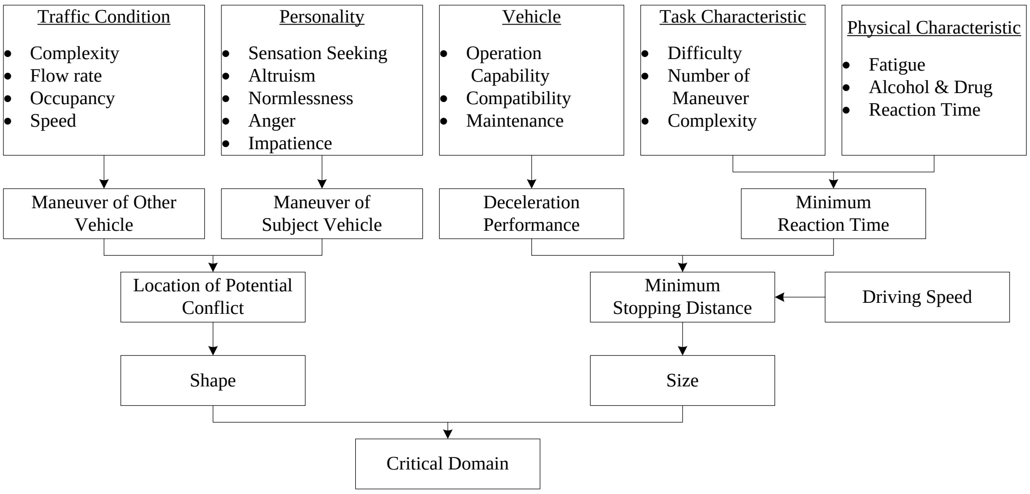


Figure 3-3 Important factors of critical domain

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 need more time to notice an emergency situation, make decisions, and take action if they must perform a complex task than a simple one.

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 drivers' area of safety interest. It depends on the predicted potential conflicts of vehicle trajectories, which is determined by drivers' maneuver intention. As the Value of SEEV model, each maneuver can produce unique future trajectories and form varying levels of importance or safety relevance; such as the adjacent lane when changing lane.

(3) 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 3-4.

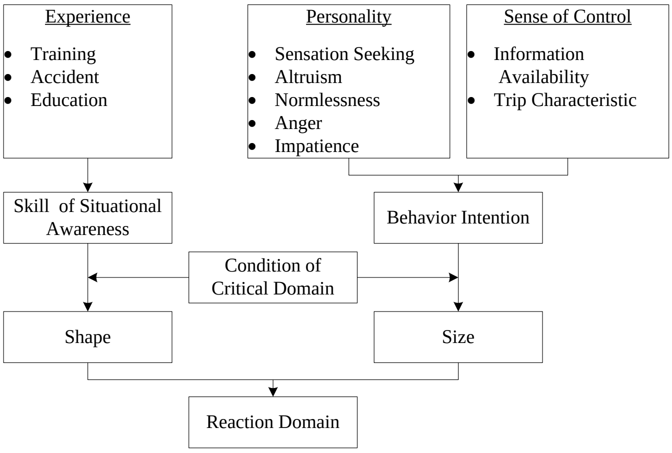


Figure 3-4 Important factors of reaction domain

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 crash rate decreased with increasing exposure and driving experience, since positive experience accumulation and training can help drivers predict and control uncertainties. In other words, experienced drivers are more likely to make better decisions when facing safety threats. Additionally, previous research indicated that experience, personality, attitude, and other psychological factors were important in affecting one's driving behavior (Ulleberg and Rundmo 2003, Taubman-Ben-Ari *et al.* 2004, Chang and Yeh 2007, Wong *et al.* 2010a, Wong *et al.* 2010b). 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 Ng 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 critical 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.

An important purpose of defining these three domains is to simplify the alternatives of visual glances. Objects located in different domains should attract different levels of attention and activate different reactions due to varying levels of risk. Closer threats induce greater risk of collision and require more attention. Another advantage of adopting vehicle driver's domains is to simplify the complex interaction of factors in locating drivers' visions. Different settings of contributing factors, such as a driver's reaction capability under different psychological and physiological conditions, individual intention, weather and speed, may create different attention allocation results. By adopting the concept of the vehicle driver's domain, it is possible to represent the complex interaction of various factors based on the size and shape of the three proposed domains, although each domain's size and shape may change with the driving environment and driver status. Therefore, in modelling attention allocation, the problem is reduced to derive the probability of choosing a specific domain without the concern of different drivers' characteristics.

In addition to the vertical distance, another dimension for characterizing focal points is the lateral location. This study adopted a simplified scenario. Drivers were assumed to drive on a divided four-lane freeway without interferences of intersections. Based on the setting, threats would appear in either the same lane or the adjacent lane when moving forward. Moreover, drivers are able to observe the rear traffic by looking in the side mirrors, and collecting information via roadside signs. Combining the vehicle driver's domains and their relative location generates eight focal points (F_1 to F_8).

F_1: The critical domain on the same lane
F_2: The reaction domain on the same lane
F_3: The perception domain on the same lane
F_4: The critical domain on the adjacent lane
F_5: The reaction domain on the adjacent lane
F_6: The perception domain on the adjacent lane
F_7: Mirror on the left side
F_8: Roadside

3.1.2 Methodology: Multinomial logt model (MNL)

A MNL model is a generalized model of logistic regression with more than two discrete alternatives. Outcome of the MNL is the probability of an individual choosing an alternative based on a set of independent variables. The MNL is widely adopted in the field of transportation, such as the analyses of vehicle ownership analysis (Choo and Mokhtarian 2004, Loo *et al.* 2006, Matas and Raymond 2008, Ritter and Vance 2013), mode choice (Habib *et al.* 2009, Kato *et al.* 2010, Basu and Hunt 2012, Can 2013, Paha *et al.* 2013) and route choice (Sener *et al.* 2009). In addition to the "driver's choice", the MNL was also applied in modeling the safety related issues, including crash type (Neyens and Boyle 2007b, Chimba *et al.* 2010, Pai 2011) and severity (Bennett and Passmore 1985, Ulfarsson and Mannering 2004, Khorashadi *et al.* 2005, Lee *et al.* 2005, Kim *et al.* 2007, Savolainen and Mannering 2007, Kim *et al.* 2008, Malyshkina and Mannering 2009, Gkritza *et al.* 2010, Moore *et al.* 2011, Rifaat *et al.* 2011, Patil *et al.* 2012, Xie *et al.* 2012, Castro *et al.* 2013). In this study, aiming to obtain the probability of drivers transiting vision to specific focal point along a specific path, the MNL was adopted for modeling drivers' choices of vision transition.

A detailed description of the method can be found in, Discrete Choice Analysis: *Theory and Application to Predict Travel Demand*, by Ben-Akiva and Lerman (1985). Followings are the brief introduction of this method. The probability derived through MNL is based on individuals' utilities of all alternatives. The model is expressed as Eq. (1):

$$P_{in} = \frac{e^{V_{in}}}{\sum_{j \in C_n} e^{V_{jn}}} \tag{1}$$

where P_{in} is the probability of an individual n choosing alternative i; V_{jn} is individual n‘s utility of alternative j from a feasible alternative set C_n. In such way, the probability of choosing a specific alternative would be lower than 1 while the total probability would equal to 1.

The utility function of each alternative consists of an observed (deterministic) component and a random component. Based on the random utility theory, the utility function of an individual n choosing alternative i can be expressed as Eq. (2):

$$U_{in} = V_{in} + \varepsilon_{in} \tag{2}$$

where V_{in} represents deterministic part of the utility function; and ε_{in} is the random error. The random error are assumed to follow Gumbel distribution, and be independently and identically distributed (IID) among alternatives and individuals. The observable deterministic utility can be specified as a series of contributing factors, suggesting that these factors would affect the utility of a specific alternative. The utility function is expressed as Eq. (3):

$$V_{in} = \alpha_{in} + \sum_k \beta_k \mathrm{X}_{ink} \tag{3}$$

where α_{in} is the alternative specific constant of alternative i for individual n; X_{ink} are the contributing factors of alternative i for individual n; and β_k is the estimated parameters of respective contributing factor.

After specifying the model, the maximum likelihood method can then be used to estimate the model parameters with the likelihood function shown in Eq. (4):

$$L = \prod_{I=1}^{i} \prod_{N=1}^{n} (P_{in})^{f_{in}} \tag{4}$$

where N is the number of individuals (number of samples); I is the total number of alternative; and f_{in} is a dummy variable indicating whether the alternative i is chosen in time stage k.

3.1.3 Model specification

This study proposes a probability based discrete choice model to analyze the attention allocation process from a microscopic perspective. Thus, the continuous process of attention allocation must be converted into discrete counterparts and treated as successive focal point choices. The resulting probability of choosing a focal point must reflect the fact that a driver would glance to one focal point for a while, and then shift their vision to another focal point. In other words, a glancing at a focal point should be treated as successively choosing the same alternative (focal point).

To simplify the demonstration of a microscopic attention allocation model, this study included only two variables in the model, including the constants and the glance duration spent on a focal point. Equation (6) defines the attention demand function of spare attention.

$$A_{i,j,k} = Asc_{i,j} + \beta_{Dur,i} Dur_{i,k} + \varepsilon_{i,j,k} \tag{5}$$

$A_{i,j,k}$ is the attention demand function of shifting attention demand from focal point i to focal point j in time stage k; $Asc_{i,j}$ is the constant term of shifting attention from focal point i to focal point j, and should reflect attention demand without any motivation from other vehicles on the roads.

The alternative specific constants represent two dimensions of attention demand. The first one is the intrinsic attention demand, which reflects the *Value* of each focal point under specific maneuver intentions (remain in the lane and drive forward). The second effect of constants comes from the *Effort* of shifting attention from one focal point to another. The scan path observed in previous study indicated that drivers allocate their attention based on the function of the previous focal point (Underwood *et al.* 2003b). To extract the scan path of a driver shifting attention around the vehicle, the proposed model included eight sub-models that represented the given associated previous focal points. If scan paths exist, the calibrated results of the alternative specific constants in the eight sub-models should be different and should illustrate distinct patterns of vision transition from one focal point to another.

The other element of attention demand is the glance duration, $Dur_{i,k}$, the number of time stages that a driver has been continuously glancing at the focal point i before time stage k. To reflect the behavior of glancing at one focal point for more than one time stage, the attention demand of choosing the same focal point would be highest among all alternatives at the beginning of each glance. The coefficients of $Dur_{i,k}$ should negatively affect the probability of the same focal point being chosen; that is, the probability of shifting attention away to other focal points increases over time.

The output of the driver attention allocation model is the probability of choosing a specific target being glanced. Given the driver's previous focal point, this probability can be further expanded into the form of a transition matrix that determines the probability of transiting vision from one focal point to another, which enables the analysis of attention allocation from a microscopic perspective.

3.2 Numerical Data

The purpose of this numerical study is not to investigate real driving behavior, but to illustrate the appropriateness of the proposed choice-based driver attention allocation model. Thus, a set of hypothetical data was generated for demonstration purposes. Working with hypothetical data, generated data based on certain rules and characteristics, can effectively illustrate how the model works and how its results can be applied. To be effective, the estimated model results should be able to recover the rules and parameters of data generation.

Two types of parameters must be identified, which are the glance duration and the transition probability. This study treated the process of attention allocation as the successive choices of the next focal point. Therefore, continuous data of attention allocation must be transferred into discrete counterparts (time stages) every 250 ms. Figure 3-5 shows the data generation procedure. The three outputs of data generation used to estimate the proposed attention allocation model were the focal point chosen in time stage k ($F_{j,k}$), the glance duration of glancing at each focal point ($Dur_{i,k}$) and the focal point chosen in the time stage k - 1 ($Prev_k$).

The duration of glancing at each focal point (T) was randomly generated from a normal distribution. Under normal conditions, the mean glance duration of each focal point is between 400 ms to 700 ms (Chapman *et al.* 2002, Underwood *et al.* 2002a, Underwood 2007, Konstantopoulos *et al.* 2010). When driving in a demanding situation with heavy traffic, the sampling rate of each glance will be higher due to psychological pressure. This means that the glance duration would be shorter than that in normal conditions, which is about 400 ms to 500 ms (Chapman *et al.* 2002, Underwood *et al.* 2002a). When driving in hazardous situations in which crashes may occur, the mean glance duration would increase significantly to one second, since drivers must pay close attention to hazardous objects (Underwood 2007).

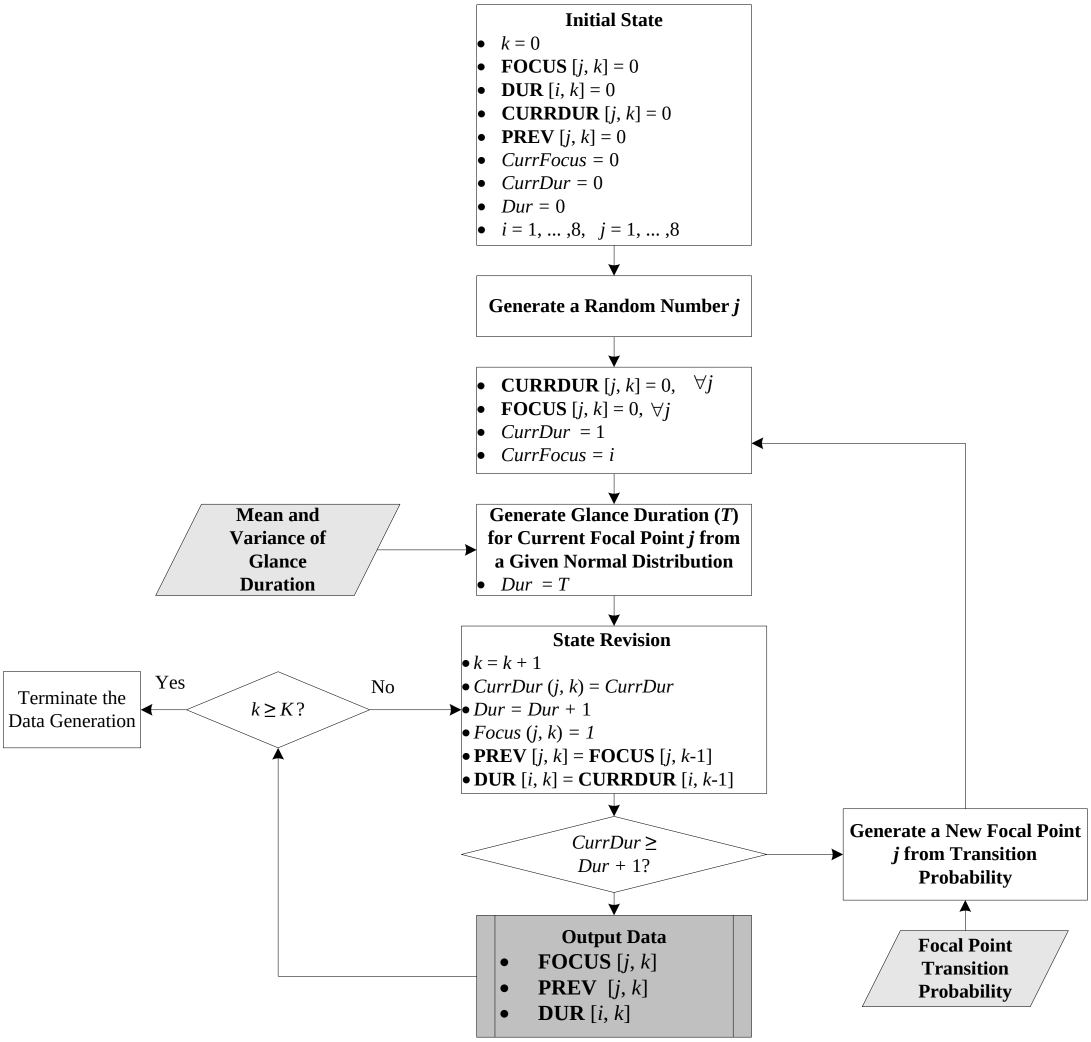


Figure 3-5 Data generation procedure

Table 3-1 outlines the mean and standard deviation of the glance duration hypothesized in this study. Since the level of attention attracted in different focal points is not identical, the mean glance duration was set between 1.5 to 3 time stages (375 ms to 750 ms). Among the focal points, the frontal side (perception domain of the current driving lane) attracted the most drivers' attention (Underwood *et al.* 2002a, Underwood *et al.* 2003b, Underwood 2007, Levin *et al.* 2009). Therefore, the mean duration of glancing at F_3 was set as three time stages. By contrast, drivers pay less attention to the perception domain of the adjacent lane (F_6), and the critical domains of the current driving lane (F_1) and adjacent lane (F_4). Drivers usually glance at these areas quickly, and then shift their visions to other focal points. Therefore, the mean durations of glancing at F_1, F_4 and F_6 were set as 1.5 time stages. In addition, glancing at mirrors and roadside signs required more effort to identify the object in the mirror and the message on the sign. Previous research illustrated that drivers spend an average of 400 ms to 650 ms glancing at roadside signs and mirrors

(Underwood *et al.* 2002a, Crundall *et al.* 2006). Therefore, the mean durations of glancing at mirrors and roadside signs were set to 2 time stages.

Table 3-1 Parameters for data generation

Origin Focal Point	**Glance Duration (250 ms)**		**Probability of Focal Point Transition (%)**							
	Mean	*Std.*	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8
F_1	1.5	0.75	0	5	**70**	5	5	5	5	5
F_2	2	1	7	0	**50**	7	**15**	7	7	7
F_3	3	1.5	2	**30**	0	2	**30**	**32**	2	2
F_4	1.5	0.75	5	5	**40**	0	**10**	5	**30**	5
F_5	2	1	6	**20**	**40**	7	0	6	**15**	6
F_6	1.5	0.75	8	8	**45**	8	8	0	**15**	8
F_7	2	1	5	5	**70**	5	5	5	0	5
F_8	2	1	5	5	**70**	5	5	5	5	0

When drivers end the glance at a current focal point, they must choose a new focal point. Table 3-1 illustrates the probability of shifting attention from one focal point to another that was hypothesized in this study for data generation. The hypothetical driver was assumed as an experienced driver who fits the "normal driving pattern". The hypothesized driver was considered as having no particular intention, such as looking for road signs. Figure 3-6 shows the three types of scan paths considered in this study. Each block represents a focal point that a vision glance can cover. The arrows between blocks represent the origin and destination focal point of scan paths.

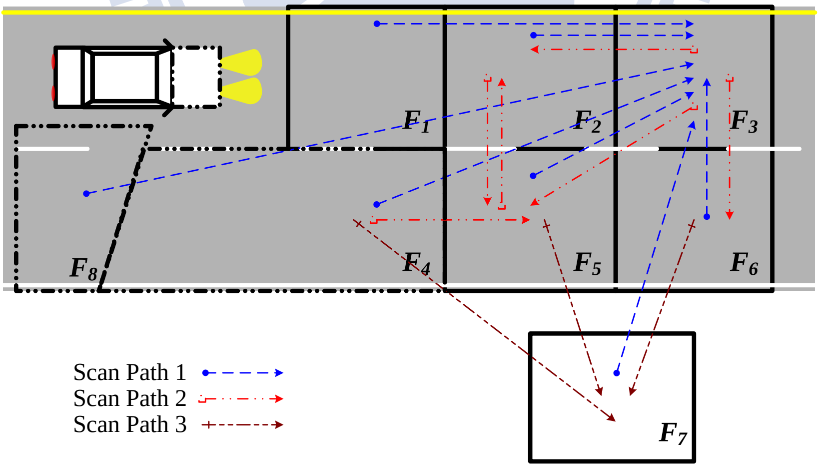
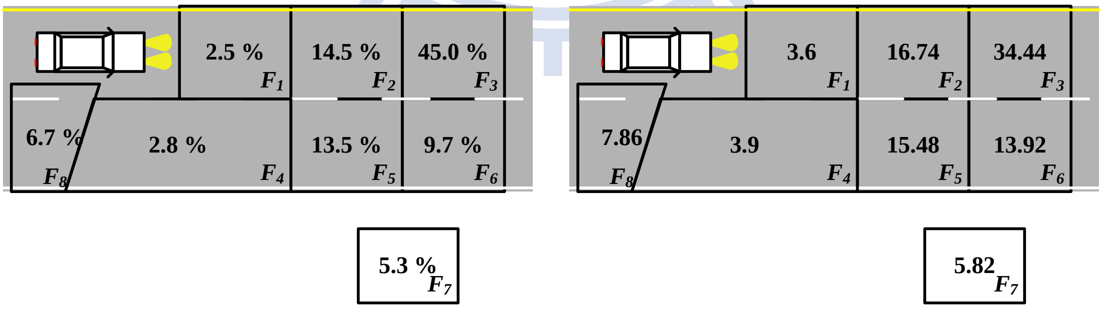


Figure 3-6 Hypothetical scan paths

The first type of scan path represented the frontal area dominating the attention allocation. Drivers usually focus on the farthest point of the current driving lane (F_3). Since the driving task discussed in this case study is driving forward without changing lanes, shifting attention away from this focal point will cause the unawareness of leading traffic and increase the risk. Therefore, drivers will have a higher probability to shift attention back to F_3 after shifting away. Hence, seven paths originated from the other seven focal points to F_3 were created. The second type of scan path illustrated the attention demand of the neighboring transition. Considering that the invested effort increases with the distance between consecutive focal points, drivers tend to transit vision between neighboring areas. This study considered 6 neighboring transition paths, as shown in Figure 3-6. The third type of scan path represented the attention allocation for roadside areas and information acquisition from road signs. In this study, drivers did not have an intention to search the roadside actively for information. However, roadside areas are occasionally glanced due to situational awareness or neighboring search. Since the driver was assumed to drive on the inner lane, the three focal points on the adjacent lane (F_4 to F_6) are closer to the roadside than the other focal points. Therefore, the three scan paths of neighboring transitions from the adjacent lane to the roadside (F_7) are generated.

In total, 8,001 samples were generated. The first sample was removed due to data unavailability for the previous focal point. The average glance duration was 590.1 ms, which was within the reasonable range obtained from previous studies. Figure 3-7 illustrates the percentage of time and frequency of transiting vision on the 8 focal points in this hypothetical case. As shown in Figure 3-7 (a), the farthest area of the current driving lane attracted the most attention. Meanwhile, drivers paid the least attention to the area closest to the vehicle. The proportion of time spent on each focal point, including the length of the glance duration fits well with the general driving behavior. Figure 3-7 (b) illustrates that the number of glances (101.76 per minute) was similar to the results in Underwood *et al.* (2003b).



(a) Percentage of time spending on focal points

(b) Number of glances per minute

Figure 3-7 Statistics of a hypothesis data set of drivers' glances

3.3 Model Estimation

Based on the hypothetical data set, 8 multinomial logit models were estimated by adopting NLOGIT 3.0. Table 3-2 presents the estimation results. Each model represents a path shifting from a specific focal point. For example, model 1 represent the focal point choices when drivers were glancing at F_1 in current stage. The major outcomes of model estimation are the alternative specific constants and the duration glancing at focal points. To illustrate the applicability of the proposed attention allocation model, the estimated results should be consistent with the hypothetical characteristics of the generated data, including the behavior of glancing and vision transition.

Table 3-2 Estimation results of attention allocation model

Alternatives	**Estimated Coefficient *(t-statistics)***									
	Alternative Specific Constant (*Asc*)									
Models	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	*Dur*	$\overline{\rho^2}$
Model 1	**0**	-6.67 *(8.32)*	**-3.35** *(5.91)*	-6.16 *(8.63)*	-6.16 *(8.63)*	-5.98 *(8.66)*	-6.38 *(8.53)*	-5.37 *(8.49)*	-2.68 *(5.79)*	0.40
Model 2	-5.43 (19.53)	**0**	-3.02 (15.96)	-4.99 (20.19)	**-4.09** (19.56)	-4.96 (20.21)	-4.75 (20.28)	-5.08 (20.10)	-1.34 (12.81)	0.35
Model 3	-7.51 *(21.78)*	**-3.94** *(36.95)*	**0**	-6.42 *(30.15)*	**-3.86** *(36.58)*	**-3.78** *(36.18)*	-6.72 *(27.82)*	-6.02 *(33.03)*	-0.77 *(22.83)*	0.45
Model 4	-5.33 (9.56)	-5.58 (9.54)	**-3.23** (7.00)	**0**	**-4.82** (9.34)	-5.91 (9.36)	**-3.67** (7.82)	-5.73 (9.47)	-2.26 (6.02)	0.28
Model 5	-6.06 *(20.19)*	**-4.24** *(21.01)*	**-3.54** *(18.70)*	-5.80 *(20.96)*	**0**	-5.18 *(21.97)*	**-4.29** *(21.13)*	-5.56 *(21.50)*	-1.43 *(14.35)*	0.37
Model 6	-5.32 (17.65)	-5.23 (17.63)	**-3.34** (13.39)	-4.92 (17.41)	-4.90 (17.38)	**0**	**-4.42** (11.67)	-5.04 (16.57)	-2.18 (17.52)	0.26
Model 7t	-5.17 *(12.27)*	-5.62 *(12.21)*	**-2.96** *(4.09)*	-5.22 *(12.21)*	-5.62 *(12.23)*	-5.62 *(10.37)*	**0**	-5.86 *(12.01)*	-1.40 *(10.59)*	0.45
Model 8	-5.82 (12.07)	-5.95 (11.89)	**-3.12** (9.17)	-5.82 (12.07)	-5.60 (12.29)	-5.95 (11.89)	-5.82 (12.07)	**0**	-1.55 (8.16)	0.48

Glancing at one focal point can be presented by the attention demand of repeatedly choosing the same focal point. As shown in Table 3-2, compared to constant of base alternative (such as F_1 in Model 1), the other alternative specific constants were all negative. This indicates that the probability of maintaining a glance on the same focal point was higher than transiting to other focal points. Hence, without considering other factors, drivers would glance at the current focal point in the next stage. The estimated coefficients of the variables *Dur* suggest that glance duration provided negative effect on drivers' attention of staying at the current focal point. Hence, the probability of maintaining a glance to the current focal point kept decreasing with time. Eventually, a driver's vision would transit to other focal points.

In addition to glance duration, the scan paths of shifting attention around the driving environment can be extracted through model estimation. The estimated coefficients of constants represent the relative level of attention demand for each focal point. In Model 1, in which F_1 was chosen in the previous stage, the constant of F_3 is higher than those of the other focal points. In other words, there is a scan path of shifting attention from F_1 to F_3. Table 3-2 illustrates that the model is able to recapture the three types of scan paths in this hypothetical case. Obtained paths (boldface constants) were found consistent with the parameters used in the data generation.

Based on the estimated model, Table 3-3 presents the transition probability that the hypothesized drivers held in this study. Since the duration of glancing at the current focal point was included, the probability of staying at current focal point and that of leaving for other focal points under different conditions of glance duration. Taking F_3, for example, after glancing at on F_3 for a time stage (250 ms), drivers have an 87% chance of staying at the current focal point; after glancing for 5 stages, the probability of choosing to maintain glancing to F_3 drops to 24 percent. Meanwhile, with increases in the glance duration, drivers are more likely to end the glance on F_3 and transit vision to other focal points, especially to F_2, F_5 and F_6. The right lower part of Table 3-3 shows the transition matrix when the glance duration is infinite, which suggests the situation that the driver must end the glance and transit their eyesight to other focal points. This matrix is relatively consistent with the parameter of data generation illustrated in Table 3-1 for the hypothesis case.

Table 3-3 Focal point transition matrix for different levels of glance duration (%)

$Dur_i = 1$	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	**$Dur_i = 3$**	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8
F_1	**58**	1	30	2	2	2	1	4	F_1	**1**	3	70	4	4	5	3	9
F_2	1	**73**	14	2	5	2	2	2	F_2	4	**15**	42	6	14	6	7	5
F_3	0	4	**87**	0	4	4	0	0	F_3	0	11	**59**	1	12	13	1	1
F_4	3	2	21	**54**	4	1	13	2	F_4	5	4	44	**1**	9	3	29	4
F_5	1	5	9	1	**77**	2	4	1	F_5	3	17	34	4	**16**	7	16	5
F_6	3	3	18	4	4	**59**	6	3	F_6	6	7	44	9	9	**2**	15	8
F_7	2	1	16	2	1	1	**76**	1	F_7	6	4	56	6	4	4	**16**	3
F_8	1	1	16	1	1	1	1	**77**	F_8	4	4	62	4	5	4	4	**13**
$Dur_i = 5$	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	**$Dur_i = \infty$**	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8
F_1	**0**	3	71	4	4	5	3	9	F_1	**0**	3	71	4	4	5	3	9
F_2	4	**1**	49	7	17	7	9	6	F_2	4	**0**	49	7	17	7	9	6
F_3	1	21	**24**	2	23	25	1	3	F_3	1	28	**0**	2	30	33	2	3
F_4	6	4	45	**0**	9	3	29	4	F_4	6	4	45	**0**	9	3	29	4
F_5	3	20	40	4	**1**	8	19	5	F_5	3	20	40	4	**0**	8	19	5
F_6	6	7	45	9	9	**0**	15	8	F_6	6	7	45	9	9	**0**	15	8
F_7	7	5	67	7	5	5	**1**	4	F_7	7	5	68	7	5	5	**0**	4
F_8	5	4	71	5	6	4	5	**1**	F_8	5	4	71	5	6	4	5	**0**

3.4 Discussion

The most important advantage of the proposed approach is its ability to present an attention allocation strategy, including both the glance and vision transition process, microscopically. Previous studies used glance duration (Chapman *et al.* 2002, Underwood *et al.* 2002a, Underwood 2007, Konstantopoulos *et al.* 2010), proportion of time spent on a particular target (Nabatilan 2007, Levin *et al.* 2009, Borowsky *et al.* 2010) and the scan path (Brown *et al.* 2000, Underwood *et al.* 2003b), to present an attention allocation model. Providing only the proportion of time spent on a specific object cannot reflect the glance and vision transition simultaneously. Allocating the same percentage of attention to a specific focal point may represent very different behaviors and induce different levels of crash risks. A short glance with a high frequency and a less frequent glance with a long duration can produce the same percentage of time spent on one target. Obviously, the two scenarios imply very different strategies and may result in different crash risks. Comparing with the aggregated results in Figure 3-7, the microscopic transition matrix shown in Table 3-3 can provide deeper insight into driving behavior and crash occurrences.

However, one major disadvantages of connecting two focal points for representing attention allocation is limited numbers of focal point included. These scan paths have contained only two or three sequential points and have shown that the most common paths were heading toward or shifting away from the frontal area. Moreover, the forward area, as the most attractive focal point, usually dominates the process of attention allocation. Using the aggregated scan path method may obscure the characteristics of other non-forward focal points. For example, Underwood *et al.* (2003b) analyzed drivers' sequential glanced points and found novice drivers holding a path of transiting vision from mid-right directly to left-middle on suburban expressway. Such a path did not exist in experienced drivers' glance data. By contrast, they held two paths of shifting attention from mid-right to the frontal side and from frontal side to mid-left. Yet, these two distinct path jointly could represent a path of transiting vision from mid-left, to frontal side, and finally to mid-right. Clearly, connecting the related scan paths together may offer rigorous meanings that correlate to the associated driving activities. Examining the deeper characteristics of such paths facilitates understanding of the behavioral patterns of drivers allocating attention in various conditions. Therefore, to analyze the whole process of attention allocation, a new method is needed.

Additionally, the microscopic model proposed in this section provided only a simple task for demonstrating the concept. To reach the goal of analyzing drivers' attention allocation against real driving tasks in realistic environment, the model should be able to include the contributing factors affecting the attention demand, and to analyze the individual contribution of each factor.

CHAPTER 4 RENEWAL CYCLE FOR ATTENTION ALLOCATION ANALYSES

Seeing the limitation of presenting vision transition in path containing only two focal points, it is necessary to propose a refined representation of attention allocation for analyzing drivers' naturalistic behavior. In this chapter, the concept of *renewal cycle* was proposed. Based on the concept, a set of naturalistic glance data was adopted for analyzing and modeling drivers' attention allocation process.

4.1 Definition of Renewal Cycle

To describe the complete process of attention allocation more clearly, this study expanded the concept of the scan path to analyze attention allocation using *renewal cycles*. A *renewal cycle* represents the process of shifting vision from a reference point, transiting to other points, then shifting back to the reference point. Identifying a renewal cycle requires determining its beginning and ending points. Moving forward is a major activity of driving; thus, this study regarded the forward area as the focal point at which drivers look naturally and comfortably. The forward area is also the point to which drivers eventually return their attention after shifting it away (Crundall *et al.* 2006). Therefore, using "forward" as the initial reference point, this study defined a renewal cycle as the driver directing his or her attention forward, transiting to other focal points, and then returning the gaze again to the forward area.

This approach not only distinguishes on- and off-road glances but also represents a complete chain process of the driver shifting attention from one point to another and transiting their vision back to the front. Using the renewal cycle as the basic component of attention allocation facilitates in-depth exploration of drivers' visual transition characteristics among focal points, especially the transition among non-forward focal points. In addition to the extracted paths transiting toward or from the forward area, this method enables the inclusion of additional serial focal points as a pattern to reflect the entire process of drivers allocating their attention during certain tasks or events. Analyzing renewal cycles can help clarify the interactions between forward and non-forward glances. For instance, drivers employing different strategies of attention allocation by varying the durations of forward and non-forward glances in one renewal cycle may indicate their various ways of searching information.

4.2 100-car Naturalistic Driving Data

This study used the 100-car naturalistic glance data collected by the Virginia Tech Transportation Institute (VTTI) (Neale *et al.* 2002, Dingus *et al.* 2006, Klauer *et al.* 2006). It has been applied in several studies regarding the exploration of drivers behavior and attention allocation (Bagdadi 2013, Dozza 2013, Wu and Jovanis 2013). The dataset contained 241 drivers in United States driving 100 instrumented cars, on which the sensors, data processors, eye trackers and GPS were installed. There was no experimenters presented during the data collection period. No special instructions were given, except of asking them to drive as they usually did. Detail information regarding the sensors and the data processing could be found in (Dingus *et al.* 2006).

In total, approximately 2,000,000 vehicle-miles of driving and 43,000 hours of data were collected by VTTI. Two datasets among these data were released online: event database and baseline database. The baseline database contained only 6 s of glance data in each record, which is insufficient for this analysis. Therefore, this study adopted the event database, which contains 68 crash and 760 near-crash incidents (VTTI 2012). In each incidents, drivers' visual glances and related attributes for the 30 s before crash or near-crash incidents were recorded. The 30-s duration was divided into two parts according to the precipitating events that were determined as causing the crash or near-crash incidents. Data collected after the precipitating events were related to emergency evasion and crash prevention. Such actions do not represent typical driver behavior. By contrast, data collected before precipitating events could be assumed to contain the time period that drivers were driving without being consciously affected by dangers and should be similar to the sample drivers' habitual behavior. Therefore, the data before the precipitating event (on average 25 s) were applied for the analyses.

However, the drivers in the 100-car event database ultimately experienced crashes or near-crashes. The results derived in this study only represent the common patterns of a limited sample of drivers' behavior, which might include potentially risky behaviors. Moreover, the data were collected in United State, where the driving environment, complexity of traffic flow and driving culture are different from ones in Taiwan. Therefore, the pattern observed in this study may not be able to explain the driving behavior in Taiwan. Table 4-1 shows the attributes of the 100-car event database used in this study. Four types of attributes were used: roadway and traffic, driving tasks, environment and eye-glance data.

Table 4-1 Attributes of 100-car event database

Attributes	**Category**
Roadway and Traffic	
• *Relation to junction*	Non-junction, Intersections (Intersection, Intersection－related, Driveway, alley access), Other (Entrance/exit ramp, Rail grade crossing, Interchange Area, Parking lot)
• *Traffic density*	Level−of−service A (less than 12 pc/mi/ln), B (12~20 pc/mi/ln), C (20~30 pc/mi/ln), D (30~42 pc/mi/ln), E (42~67 pc/mi/ln)
Driving tasks	
• *Pre-event maneuver*	Driving straight (Going straight in constant speed, accelerating, but with unintentional "drifting" within lane or across lanes, Decelerating in traffic lane, Starting in traffic lane or Stopped in traffic lane), Lane Change (Passing or overtaking another vehicle, Changing lanes or Merging), Turning left and Turning right
• *Distraction (time series data)*	Cognitive, cell phone, in-vehicle devices, external clutter, activity
• *Turning signal (time series data)*	Recorded when turning signal (left, right and both) were on.
• *Driving speed (time series data)*	mph
Environment	
• *Time of day*	Day time (including dawn and dusk), Night time with light
• *Weather*	Clear, Poor (cloud, rainy, mist, snow)
Eye-glance data	
• *Focal point (time series data)*	Forward, Left forward, Right forward, Rearview mirror, Left window, Left mirror, Right window, Right mirror, In-vehicle distractions (Instrument Clutter, Center stack, Interior Object, Passenger, Cell Phone)
• *Duration of glancing at forward and other focal points*	Continuous variable

The drivers' glance locations, including *Forward* (*F*), *Left Forward* (*LF*), *Right Forward* (*RF*), *Left Window* (*LW*), *Left Mirror* (*LM*), *Right Window* (*RW*), *Right Mirror* (*RM*), *Rear-view Mirror* (*ReM*), and *In-vehicle Distractions* (*InvD*), were recorded every 0.1 s. The period of continual glances to the same focal point is considered the glance duration. Among these focal points, *InvD* refers to all glances inside the vehicles, including the center stack, interior objects, cell phone, passengers, and instrument cluster. Each focal point received varying degrees of attention from different drivers. To simplify the analysis, this study first analyzed only the areas where drivers glance, i.e., the *InvD*. Detailed characteristic differences among multiple locations or objects inside the vehicles were not considered. Moreover, this study excluded the first and final glances of each event in the glance data since these two glances may not be complete ones. Any events with a glanced area recorded as "eyes closed" or "no video" were also excluded.

4.3 Attention Allocation Analysis from a *Renewal Cycle* Approach

4.3.1 Research framework

Figure 4-1 shows the research framework for analyzing attention allocation from a renewal cycle perspective.

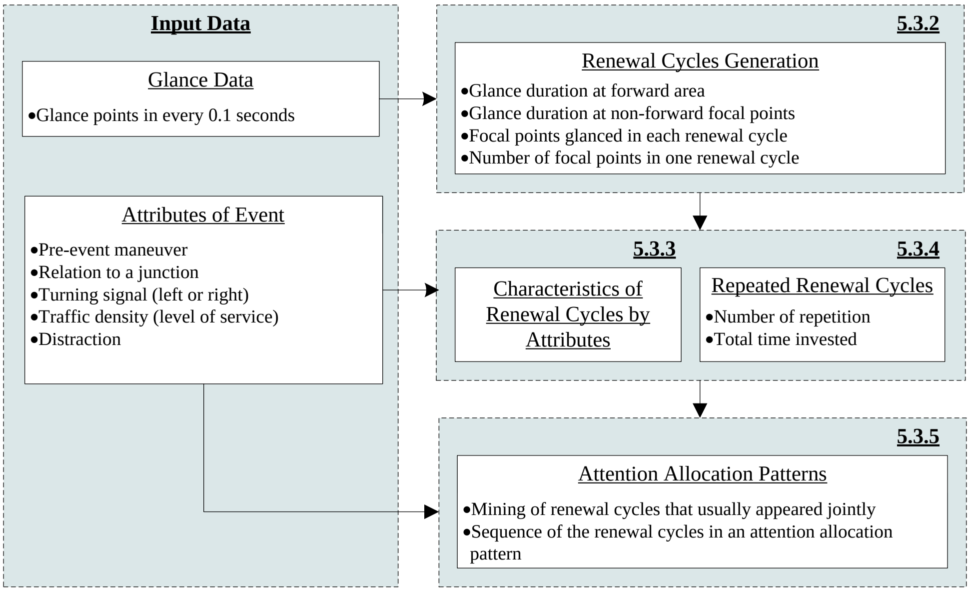


Figure 4-1 Research framework for attention-allocation analysis

In the following sections, this study first processed the glance data that recorded every 0.1 s into glances for each specific focal point. Then the glances were grouped into renewal cycles anchored by forward glances in section 4.3.2. The purpose of generating renewal cycles was to generate the basic component of the attention allocation patterns. However, not all of the cycles were equally important. To identify the minimum number of commonly used renewal cycles that explain the majority of attention allocation processes, section 4.3.3 evaluated the importance of each cycle. The indicator of importance adopted was the recurring frequency of a renewal cycle. If a specific type of renewal cycle occurred more frequently than others, it was considered a crucial cycle typically employed by drivers. Then, characteristics of renewal cycles by attributes were analyzed.

Among the generated renewal cycles, several identical cycles were undertaken by drivers repeatedly before beginning another renewal cycle (Metz *et al.* 2011). This repetitious behavior is probably intended to prevent the risk caused by long glances off-road by transiting vision back and forth between road ahead and a non-forward focal point. Repeated renewal cycles likely result from the intention to complete an activity or continual monitoring the potential threats. To gain deep insight, section 4.3.4 bundled these repetitious renewal cycles as a single repeated one. Finally in section 4.4, grouping renewal cycles helps elucidate the associated driving activities. After the common renewal cycles were identified, this study charted the regular patterns of attention allocation by combining the renewal cycles that usually occur jointly. This study adopted the sequential rule mining method to mine the patterns of attention allocation composed of sets of jointly occurring renewal cycles.

4.3.2 Renewal cycle generation

In total, 2,256 renewal cycles with 91 types were generated. The shortest renewal cycles contained only two glances: one forward and one non-forward focal point. The longest cycle contained 12 glances.

As shown in Table 4-2, the most frequent renewal cycles were 2-glance cycles, with 90.74% of the data falling into this category. A markedly smaller number of cycles were 3-glance, at 7.18%; and 4-glance cycles accounted for only 1.24%. Renewal cycles with 5 or more glances accounted for 0.85% of the data. This finding suggests that, rather than looking sequentially at various focal points within a single renewal cycle, the sample drivers usually separated their lapses from the forward direction into several sequences, directing their vision back to the forward direction after each visual shift.

Table 4-2 Number of glances in renewal cycles

	Number of glances				
	2	3	4	5 or more	Overall
Frequency (%)	2,047 (90.74%)	162 (7.18%)	28 (1.24%)	13 (0.85%)	2,256 (100%)
Duration of forward glance (s)					
Mean	4.01	3.52	3.04	3.16	3.95
Standard deviation	4.91	5.04	4.19	3.15	4.89
Maximum	29.2	23.4	17.7	11.6	29.2
Duration of each non-forward glance (s)					
Mean	0.96	0.96	1.00	0.98	0.96
Standard deviation	0.93	0.71	0.48	0.70	0.91
Maximum	10.50	5.20	2.40	2.50	10.50
Mean duration of a renewal cycle (s)	4.96	5.43	6.04	8.25	5.05

The mean glance duration revealed that the sample drivers spend 3 to 4 s glancing forward and 1 s looking elsewhere. An increased number of non-forward glances per renewal cycle resulted in a longer cycle but a concomitant decrease in time spent looking forward, i.e., decreased mean, maximum, and standard deviation for forward-glance. The mean duration of each glance at non-forward focal points did not vary substantially across renewal cycles with varying numbers of glance points. However, the total time that drivers spent glancing off-road dramatically increased from 0.96 s in 2-glance renewal cycles to 3.00 s in 4-glance renewal cycles, where 3 focal points were non-forward ones with a mean duration of 1.00 s. This result indicates that a higher proportion of attention spent on multiple non-forward focal points in a renewal cycle was not compensated for by shorter cycle duration.

Nevertheless, there is a decrease in maximum and standard deviation of duration on both forward and non-forward focal points in 3- and 4-glance renewal cycles. This suggests that these drivers tried to avoid abnormal renewal cycles that involved dangerously long glances. The findings might illustrate the driver’s uneasiness when additional focal points were glanced at in a renewal cycle. The drivers who showed more glances in a renewal cycle were certainly less aware of the frontal area and incurred a higher risk of an accident. Thus, the 2.09% renewal cycles that showed more than three glances might have striking implications for accident prevention. This area of study deserves further attention.

4.3.3 Distribution of renewal cycle under varying conditions

Table 4-3 shows the distribution of the common renewal cycles under various attributes. There were ten types of renewal cycles with more than a 1% frequency share, whereas eight types of 2-glance renewal cycles accounted for 90.74% of the frequency. Among the 2-glance renewal cycles, those involving in-vehicle distractions and rear-view mirror glances accounted for almost half of the generated renewal cycles.

To analyze the characteristic differences among various attributes, the distribution of these common renewal cycles under different conditions was examined. The recorded maneuvers and their relation to a junction were referred to the final pronounced action and associated location before a precipitating event. Such attributes did not necessarily exist throughout the entire 30-s data period. Certainly, the generated renewal cycles might occur before or during the maneuvering. Thus, it seems that a mismatch of time exists between eye-glance data and certain driving circumstances. Nevertheless, before implementing maneuvering intentions, drivers tend to look in the directions of future vehicle trajectories. That is, the entire maneuver includes searching for information, decision-making, and the final action. Analyzing only the exact period of the maneuver does not represent the entire attention allocation process. Thus, from this view point, the mismatch problem is ignored.

The attributes of a relation to a junction and maneuver were important for determining a driver’s expectations of potential threats. In these cases, of a relation to a junction, road segments and intersections were the two main elements in the driving environment. When the drivers encountered intersections within 30 s, more renewal cycles of *RF* and *RW* would occur, probably because of the associated possibility of increased conflicts from the intersected roadway.

Table 4-3 Distribution of renewal cycles by attributes

Attributes	Sample size	Distribution of renewal cycles (%)										
		F-InvD	F-ReM	F-LW	F-LM	F-RF	F-RW	F-LF	F-RM	F-LM-LW	F-RF-RW	Others
Pre-event maneuver												
Driving straight	1827	26.4	22.3	13.5	9.6	8.1	6.2	3.9	1.4	1.0	0.8	6.8
Changing lanes	306	12.4	29.1	10.5	16.3	7.2	6.5	2.9	2.0	2.6	2.6	7.8
to left lane[*]	44	2.3	20.5	15.9	38.6	2.3	0.0	6.8	0.0	9.1	0.0	4.5
to right lane[*]	43	7.0	23.3	4.7	7.0	9.3	18.6	0.0	4.7	4.7	7.0	14.0
Turning	116	17.2	19.8	22.4	0.9	16.4	2.0	6.0	0.9	0.0	0.9	10.3
left[*]	24	25.0	4.2	25.0	0.0	12.5	4.2	16.7	0.0	0.0	0.0	12.5
right[*]	21	0.0	23.8	23.8	0.0	19.0	9.5	4.8	0.0	0.0	0.0	19.0
Others	7	28.6	42.9	0.0	0.0	14.3	0.0	14.3	0.0	0.0	0.0	0.0
Relation to a junction												
Road segment	1336	26.5	25.1	12.7	10.5	6.2	5.6	3.7	1.6	1.3	0.8	5.9
Intersection	582	24.2	20.1	13.9	6.5	12.5	7.2	4.0	1.2	0.3	1.5	8.4
Others	338	13.9	20.4	15.7	14.5	10.1	6.8	5.0	1.5	1.8	0.9	9.5
Traffic density												
Level of service: A	599	27.7	19.5	16.5	5.3	8.8	6.7	4.0	0.8	0.8	0.8	8.8
Level of service: B	822	22.7	22.3	14.8	8.9	9.7	6.1	4.0	1.1	1.5	1.6	7.3
Level of service: C	536	23.3	25.9	10.8	14.0	8.0	6.7	3.2	2.2	0.7	0.2	4.9
Level of service: D	232	19.0	26.3	9.1	16.4	5.2	5.6	6.0	2.6	1.3	1.7	6.9
Level of service: E	67	29.9	32.8	6.0	13.4	3.0	1.5	1.5	1.5	3.0	0.0	7.5
Level of service: F	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Distraction												
Driving with distraction	572	45.3	16.1	9.1	6.6	5.9	4.4	1.6	1.2	1.4	0.3	7.0
Driving without distraction	1684	16.8	22.5	15.0	11.2	9.3	6.8	4.4	1.5	1.1	1.2	7.1
Total	2256	24.0	23.1	13.5	10.1	8.4	6.2	4.0	1.5	1.2	1.0	7.1

[*] The renewal cycles related to directions of turning and changing lane were only recorded while the turning signal was turned on.

Lane changing and turning were the two primary maneuvers that naturally directed the drivers' attention to directions critical for preventing conflicts. Meanwhile, drivers decreased the attention invested in non-safety related areas, such as *InvD*. The percentage of the renewal cycles in which the drivers transited attention to *InvD* decreased from 26.4% when driving straight to 12.4% when changing lanes, and to 17.4% when turning left or right. While changing lanes, the sample drivers increased their attention to the *ReM* and *LM* to observe the traffic conditions behind them.

In particular, the drivers transited their vision more frequently to the left side (*LW* and *LM*) when changing to the left lane, and to the right side (*RF* and *RW*) when changing to the right lane. The main difference between changing to left or right lanes was the use of the side mirrors. The *RM* was seldom used when changing to the right lane. One reason might be the faster driving speed in the inner (left) lane. Vehicles located in the right rear area were usually traveling relatively slowly. Once the drivers had successfully passed those vehicles, they had good information for where the vehicle was and could easily begin changing lanes to the right side without glancing at the *RM*. By contrast, vehicles in the left lane usually traveled more rapidly and required drivers' close attention to ensure a safe margin for changing lanes to the left.

Turning at intersections was indicated to have an increased risk of crashing with traffic from an intersecting roadway in front of the subject vehicles. An increased number of renewal cycles involving *LF*, *RF*, and *LW* glances were found. For maneuvering a left turn, the *LW*, *LF*, and *RF* were the most common focal points for checking the potential threats coming from opposite traffic. Glancing at those focal points implied that threats were expected from the traffic passing through intersections. Another unique characteristic of turning left was the high percentage of the path from *Forward to InvD* (*F-InvD)*. Turning was usually associated with complex tasks and few chances of shifting one's attention to *InvD*. However, the drivers were more likely to stop and wait at the intersection when turning left than when turning right and changing lanes. In the absence of immediate crash risks, drivers may be inclined to use in-vehicle devices or interact with passengers while waiting. For a right turn, more potential conflicts were related to the traffic from the intersected roadway, pedestrians on the crosswalk, and cars following behind. Thus, the sample drivers paid greater attention to monitoring the *ReM*, *LW*, and *RW*.

Traffic density determined interactions with other vehicles. When traffic density increases from Level of Service (LOS) A to D, the sample drivers allocated more attention to the ReM and LM, probably checking traffic from behind or for lane changing. Moreover, the necessity for frequent speed adjustments and the shorter available reaction time associated with heavy traffic discourages drivers from engaging in non-driving-related tasks, such as transiting their vision from the forward areas to the roadside areas (*LW*, *RW*, and *RF*) or attending to *InvD*. When traffic density increased to LOS E, the sample drivers were unable to operate their vehicles freely but were forced to remain in the traffic stream. Under such conditions, drivers had ample opportunities to use in-vehicle devices because of the slow traveling speed and limited gaps available to merge with other vehicles. Thus, the percentage of *InvD* climbed sharply from 19.0% under LOS D to 29.9% under LOS E.

Among the common cycles, *InvD* were the main focal points on which the drivers spent a large portion of their non-forward attention time. As shown in Table 3, when distractions were present, *F-InvD* contributed 45.3% of the extracted renewal cycles. However, in the absence of distracting activities, 16.8% of the renewal cycles were still related to *F-InvD*. These findings suggest that engaging in distracting activity was not the only reason that the drivers transitioned their vision to in-vehicle focal points. At times, drivers transited vision inside their vehicles, despite doing nothing with in-vehicle devices. Because the sample drivers represented by this data set eventually experienced crashes or near crashes, it is reasonable to presume that defective behavior might have occurred in their daily driving operations.

4.3.4 Repeated renewal cycle

An evident portion of 2-glance renewal cycles were found repeatedly occurred; that is, the drivers repeatedly transiting vision between forward side and an identical non-forward focal point. Occurrence of repeated renewal cycles could be considered an intention to complete a single task of obtaining information from specific focal points, continually checking the area of interest, or reconfirming traffic situations before maneuvers. Thus, the times of repetition and total duration provide meaningful measures that represent the different approaches of drivers in allocating their attention. Table 4-4 shows the duration of each non-forward glance in commonly found 2-glance renewal cycles, for both individual and repeated renewal cycles. The individuals ones are the renewal cycles that were counted individually without considering the repetitions. The repeated renewal cycles were the ones that occurred immediately before or after an identical renewal cycles.

Table 4-4 Glance duration for non-forward focal points

	Duration and frequency of each glance in 2-glance renewal cycles					
	Individual renewal cycle		Repeated renewal cycle			
Focal point	Frequency	Duration (s) Mean / Std.	Frequency (%)	Duration(s) Mean / Std.	Times of repetition [a]	Average total duration (s) [b]
InvD	542	1.14 / 1.04	429 (79.15%)	1.19 / 1.10	3.58	2.68
ReM	522	0.64 / 1.03	312 (59.77%)	0.66 / 0.54	2.90	1.05
LM	227	0.85 / 1.02	134 (59.03%)	0.86 / 0.64	2.91	1.37
RM	33	0.82 / 0.38	14 (42.42%)	0.84 / 0.38	2.80	1.13
LW	304	1.00 / 0.50	156 (51.31%)	0.96 / 1.04	2.59	1.50
RF	190	1.08 / 0.68	69 (36.32%)	1.01 / 0.98	2.48	1.37
RW	140	1.10 / 1.00	50 (35.71%)	1.12 / 0.88	2.27	1.39
LF	89	1.16 / 0.95	26 (29.21%)	0.97 / 0.79	2.36	1.44

[a] The calculation of repeated times included only the repeated renewal cycles.

[b] Both individual and repeated renewal cycles are included.

The focal point showing the highest percentage of repeated renewal cycles was *InvD*, of which 79.15% occurred repeatedly. Among the repeated samples, on average, drivers repeated the renewal cycles 3.58 times. For the total duration of glancing at *InvD*, the sample drivers spent 2.68 s on average. Because *InvD* represented all glances inside the vehicle, the repeated renewal cycle may contain different types of distractions. Consequently, accurate interpretation could be difficult. Fortunately, only 94 out of 429 repeated renewal cycles of *InvD* mixed with other types of distraction. These findings suggest that *InvD* tend to be rule- and knowledge-based activities that consume substantial attention resources to complete certain non-driving related activities, such as making a phone call.

InvD were followed by *ReM*, *LM*, and *RM* glances, which respectively showed 59.77%, 59.03%, and 42.42% of the renewal cycles being repeated, with each repeating approximately 2.8 to 2.9 times. These repeated renewal cycles relating to mirrors showed almost identical mean durations, but less variance when compared to the mean durations of the individual renewal cycles. These results suggest that drivers were aware of the risk of paying inadequate attention to the forward direction by repeatedly searching and reconfirming activities. However, the stable duration of glances implied a required minimum time for the drivers to transit their vision and process information. Consequently, when facing tasks that pose a high information load, drivers might be unable to increase their sampling rates by decreasing the duration of each glance.

The sample drivers also frequently repeated the renewal cycles for the *LW*, *RF*, *RW*, and *LF*, and spent approximately 1.4 s to complete the search activity. Among these four focal points, the *LW* and the *RF* field, representing the roadside areas, showed a larger standard deviation for glance duration in repeated renewal cycles than that for individual ones. This phenomenon might be associated with the drivers' reaction to the different targets along the roadside. They might glance at those areas longer and repeat more frequently if interesting objects on the roadside attract their attentions. In the absence of interesting objects, drivers tended to transit their vision to the roadside areas briefly.

The sample drivers glanced at the *RW* for shorter intervals and repeated less frequently than the glances to the *LW*. Differences between glances to these two windows were probably related to the location of the driver's seat. Drivers sit beside the *LW* and can easily and comfortably transit their attention to enjoy scenic views through this window. Thus, the *LW* focal point showed an increased number of repeated renewal cycles and longer glance durations when compared to that of the *RW*. Finally, unlike the *RF* view, the *LF* field could be largely covered by the driver's peripheral vision of forward glances. Consequently, the percentage of renewal cycles for the *LF* field was the lowest among all focal points and showed the least repetition.

In addition to gathering/confirming identical information, repeated renewal cycles might also represent the task of continued observation of an area for new circumstances. In such cases, the renewal cycles that occurred repeatedly might be unrelated and simply reflect a common manner of driving. The question is how to tell the unrelated ones from the related ones. The inter-glance intervals of the non-forward focal point in the repeated renewal cycles could be good for judgment. Figure 4-2 shows the results of the inter-glance intervals. As seen in this figure, a big portion of the repeated renewal cycles related to *InvD*, *RW*, *RM*, and the *LM* had relatively short inter-glance intervals (3.2 to 3.5 s) and were more likely for collecting and reconfirming information from the same target. On the other hand, some of the repeated renewal cycles related to the *ReM* had relatively long inter-glance intervals (4.5 s), suggesting probably just a common manner of driving.

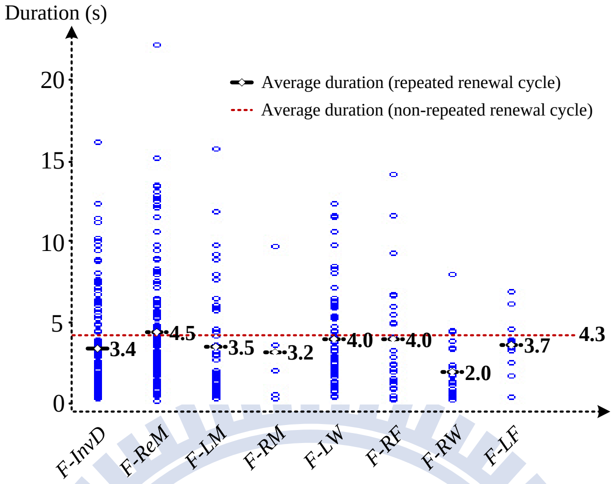


Figure 4-2 Distribution of time between non-forward glances in repeated renewal cycles

4.4 Pattern analysis

4.4.1 Methodology: Sequential association rule mining

Thus, this study adopted the technique of *sequential association rule mining* to mine the patterns of attention allocation composed of sets of jointly occurring renewal cycles. This method has long been effectively applied to examine factors contributing to crash occurrence (Geurts *et al.* 2005, Pande and Abdel-Aty 2009, Montella 2011, Montella *et al.* 2012). The association rule mingling is the technique of identifying the co-occurrence relation among several items. Set of item that usually appear jointly can be extracted. In addition to the co-occurrence relation, the sequential association rule mining includes the time dimension. That is, this method did not only explore the items that jointly appear, it also identifies the sequence of item appearing. Following sections will introduce a brief concept of the sequential rule mining. A detailed description of the method can be found in, *Introduction to Data Mining*, by Tan *et al.* (2006).

Before the introduction of the method, terminologies used in this study and in sequential rule mining must be defined and differentiated. Table 4-5 shows the three terminologies used in the sequential rule mining and driver attention allocation model.

Table 4-5 Definition of sequence, element and event

	Sequential Rule Mining	**Driver Attention Allocation Model**
Event (Item)	The basic component of rule. Purpose of this method is to identify the sequence of event appearing.	Focal points are the basic component for exploring pattern of attention allocation.
Element (Transaction)	A set of event appearing at specific time.	The element refers to the glance in driver attention allocation. Since drivers can only glance at only one focal point, an element can only include one event.
Sequence	An order list of elements. Is can be characterized by its size. A *k-sequence* indicated a sequence with *k* items.	A pattern of attention allocation, which is a sequence of focal points that drivers glance.

The sequential rules are generated by merging the existing sequence. The *a priori* principle stated that a *k-sequence* can be derived by combining two *(k-1)-sequence*. Assuming that there are *(k-1)-sequence*$_1$ and *(k-1)-sequence*$_2$ exist in the rule set. If the sub-sequence of dropping the last event of *(k-1)-sequence*$_1$ is identical with another sub-sequence of dropping the first event of *(k-1)-sequence*$_2$, these two *(k-1)-sequences* can be merged as a new *k-sequence*. Then, the newly generated sequences are included in the rule base, if they satisfy the minimum performance requirement. Otherwise, the sequences are pruned.

In the sequential association rule mining method, two performance measurements, support and confidence, are often used. Support value determines how often a combination of renewal cycles (a rule or pattern) can be found in the entire data set. As shown in Eq. (5), it is the percentage of events in entire data set covered by the rule of X → Y.

$$s(\mathrm{X} \rightarrow \mathrm{Y}) = \frac{\sigma(\mathrm{X} \rightarrow \mathrm{Y})}{\mathrm{N}} \tag{6}$$

$s(\mathrm{X} \rightarrow \mathrm{Y})$ represents the support value of a renewal cycle X appearing before a renewal cycle Y; $\sigma(\mathrm{X} \rightarrow \mathrm{Y})$ represents the number of events that fit the rule of $\mathrm{X} \rightarrow \mathrm{Y}$; and N is the total number of events. Higher support value suggested important patterns that appear more frequently and explain more about the data set.

As shown in Eq. (6), confidence value is the percentage of events having renewal cycle X that also contains a renewal cycle Y.

$$c(\mathrm{X} \rightarrow \mathrm{Y}) = \frac{\sigma(\mathrm{X} \rightarrow \mathrm{Y})}{\sigma(\mathrm{X})} \tag{7}$$

$c(\mathrm{X} \rightarrow \mathrm{Y})$ is the confidence of rule $\mathrm{X} \rightarrow \mathrm{Y}$; $\sigma(\mathrm{X} \rightarrow \mathrm{Y})$ is the number of events which fit the rules $\mathrm{X} \rightarrow \mathrm{Y}$; $\sigma(\mathrm{X})$ is the number of events containing a renewal cycle X in the data set. This research, the maximum gap between two renewal cycles was set at one. That is, the renewal cycle Y appears right after X.

The confidence value was used in this research to derive the sequential rules of renewal cycles. Higher confidence suggested the higher strength between the renewal cycles. However, some rules with high confidence may have only few samples and cannot efficiently explain the entire data set. Therefore, a minimum support should be set to filter the rules. Referring to previous research (Geurts *et al.* 2005, Pande and Abdel-Aty 2009, Montella 2011), this study set the minimum support at 5% and the minimum confidence at 10%.

4.4.2 Pattern generation

One might ask whether the generated renewal cycles were interrelated or not. To answer this question, the Sequential Association Rule Mining package in SAS Enterprise Miner 6.2 was used to mine the sequential association between renewal cycles and combine related cycles into patterns of attention allocation. As stated, drivers displayed different renewal cycles under various road conditions and with various driver intentions. Hence, driving straight on a segment, passing through an intersection, and changing lanes on a segment were separated to mine the respective sequential association rules. Other types of maneuvers were not included because of the small sample size. Table 4-6 shows the derived attention allocation rules of the sample drivers for the three maneuver intentions.

Table 4-6 Attention allocation patterns of various maneuver intentions

Patterns of renewal cycles	Driving straight on a segment		Passing through an intersection		Changing lanes on segment	
	Support*	Confidence*	Support*	Confidence*	Support*	Confidence*
F-InvD → F-ReM	9.23	24.51	5.97	18.18	9.09	42.86
F-ReM → F-InvD	8.49	16.43	8.21	23.4	-	-
F-LW → F-ReM	5.54	18.75	-	-	-	-
F-ReM → F-LW	5.54	10.71	-	-	10.61	20.59
F-LM → F-ReM	6.64	29.51	-	-	9.09	27.27
F-ReM → F-LM	-	-	-	-	9.09	17.65
F-ReM → F-RF	-	-	-	-	6.06	11.7
F-RF → F-ReM	-	-	-	-	7.58	35.71
F-RF → F-LW	-	-	5.22	20.59	-	-
Number of crashes or near crashes	271		134		66	

*The confidence and support values are expressed as percentages
- No pattern found

The renewal cycles that included the *ReM* occurred in almost all extracted patterns of attention allocation. This finding suggests that paying attention to the front and rear areas of the vehicle were the two most crucial components for observing the surrounding traffic and maintaining situational awareness. The sample drivers usually transited their vision to these two areas immediately before or after shifting their attention elsewhere.

Driving straight on a road segment is relatively simple and has a light information load. In addition to the mentioned crucial renewal cycles, the drivers traveling straight on a road segment displayed the pattern related to *InvD* and *LW* glances. These cycles containing non-driving related information and, when combined with the above-mentioned crucial cycles, formed the attention allocation pattern for driving straight on a road segment. Such an attention allocation pattern can be described as drivers comfortably focusing on the front and rear areas, but intermittently and casually directing their attention to distractions on the roadside or inside the vehicles. The drivers also displayed the cautious behavior of transiting their vision from the *LM* to the *ReM* to maintain their situational awareness of the rear area, probably to monitor the blind zone on the left side.

For the maneuver intention of passing through an intersection, the drivers experienced a relatively heavy task load because of possible threats arising from the intersecting traffic. Compared with driving straight on a road segment, fewer notable patterns of renewal cycles were evident because the drivers were more cautious and concentrated on a few critical focal points when passing through an intersection. Apart from concentrating on forward and backward areas, the renewal cycle pattern *F-RF*→*F-LW* showed that the drivers did not transit their vision far from one side of the vehicle to the other side, i.e., renewal cycle *F-RF-LW*. An intermediate glance at the forward side was adopted. The sample drivers usually looked to *RF* field initially, where conflicts with right-turning traffic would occur. Afterward they turned their vision to the *LW* to check for possible traffic emerging from the intersected road.

When changing lanes, drivers may encounter threats from multiple directions and must expend heightened effort to prevent possible conflicts, particularly conflicts from the adjacent lanes. Under these intense circumstances, the sample drivers' *InvD* were minimized and attention to the rear and side areas was strengthened. This finding suggests that the *ReM* was used in an auxiliary manner to enhance the drivers' situational awareness of the rear area, and that the *LM* was used to monitor the blind zone. Compared with the intentions of driving straight on a segment and passing through an intersection, the drivers evidently considered changing lanes to be a more mentally demanding task. Thus, after a renewal cycle for *InvD*, a relatively high proportion (42.86%) of the drivers immediately transited their vision to the *ReM* to gain information of the rear area relevant to changing lanes.

4.5 Modeling Attention Allocation

Noting that the aggregated results of attention allocation characteristics provided mostly the patterns that drivers generally held, there is still a gap between crash occurrences and the attention allocation. To further identify drivers' attention allocation mechanism against dynamic environment and driving tasks, this section adopted the discrete choice technique and modeled the attention allocation in a microscopic choices level. Additionally, the model also enabled including the contributing factors and extracting their individual contributions to attention demand.

4.5.1 Model specification

Purpose of the microscopic attention allocation model is to derive the probability of transiting vision from one focal point to another; i.e. the representation of scan path. Owing to the limitation of forward side dominating the attention allocation, one major purpose of this study is to elucidate the path of shifting vision between non-forward focal points. In other words, the alternatives of the microscopic attention allocation model should be able to represent different types of vision transition.

To capture the path of transiting vision between two non-forward focal points, this study investigated the focal point choices after each non-forward glance. The focal point choice is a loop process that drivers will always have to choose the focal point to glance in the next stage on the basis of the current glanced point. Based on the concept of renewal cycle, three types of vision transition after glancing at a non-forward focal point can occur. Figure 4-3 illustrates an example of vision transition after glancing at non-forward focal point *A*.

The first type is the direct vision transition to other non-forward focal point. It is still a part of the current renewal cycle since drivers have not yet transit vision back to the frontal side. The other types are the transitions to forward direction, which end the current renewal cycle and begin a new one. Within the new renewal cycles, drivers may choose to look at the non-forward focal point *A* again. Such a type of renewal cycle, the second type, is named as the repeated renewal cycle. Additionally, drivers may transit vision to other non-forward focal point after sequentially glancing at non-forward focal point *A* and the forward side. This type of vision transition requires drivers to determine a non-forward focal point to glance in the new renewal cycle, which will form a vision transition from one non-forward focal point, to forward side and then to another non-forward focal point.

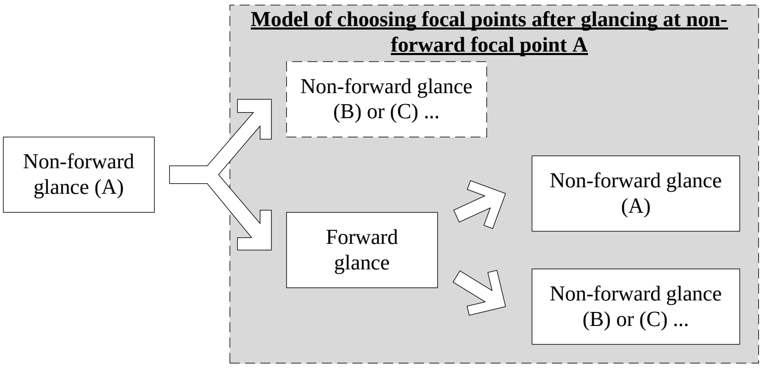


Figure 4-3 Major types of vision transitions

Attention allocation is a continuous process of choosing focal points. The Multinomial Logit Model (MNL) can be a suitable tool to determine the probability of choosing a specific focal point. Additionally, to represent the path between two non-forward focal points, the model consists of several sub-models; each represents the vision being transited from a specific non-forward focal point. Figure 4-4 shows the research framework of a MNL sub-model representing vision transition from the specific non-forward focal point *A*.

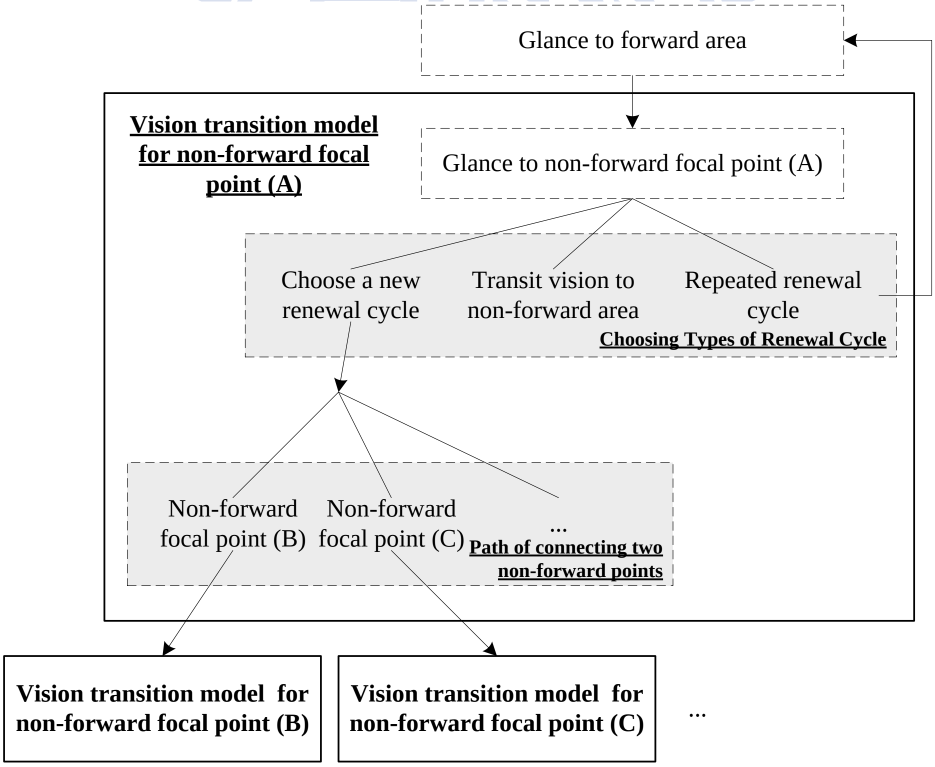


Figure 4-4 Framework of vision transition model

The focal point choices are done in two sequential steps, which were represented by the two separated MNLs specified in Figure 4-4. In the first layer, after glancing at a non-forward focal point, drivers' vision shift will be one of the following three types, transiting vision back to forward side for starting a new renewal cycle, transiting vision back to forward side for repeating the current renewal cycle, or continuing the current renewal cycle by transiting vision directly to another non-forward focal point. Results of layer 1 model will illustrate the probabilities of new renewal cycles, repeated renewal cycles and multiple-glance renewal cycles.

If the alternative of transiting vision to the frontal side and starting new renewal cycle is chosen, another model for calculating the probability of choosing a specific non-forward focal point other than point *A* is needed. Thus, the second layer MNL model is formulated to derive the probability of path connecting two different renewal cycles. The results from this layer will tell the drivers' vision transitions among non-forward focal points indirectly.

For the model development, it is important to understand the contributing factors in drivers' attention allocation. In the SEEV model, four constructs of contributing factors were identified, which are salience, effort, expectancy and value. Based on these four constructs (Wickens *et al.* 2003, Wickens and Thomas 2003, Horrey *et al.* 2006, Werneke and Vollrath 2012), Table 4-7 shows our model specification and the contributing factors associated with the four constructs.

Table 4-7 Specification of multinomial logit model

Variable	**Description**
Effort	
•ASC	Alternative specific constants for MNL
Salience	
•Surface	A dummy variable. Equal to one when the driver drove on slippery surface.
Expectancy	
•Speed	Driving speed of the last recorded in a glance. This study set 25 mph as the reference level of speed attributes.
•LOS_B	A dummy variable. Equal to one when the driver drove under LOS B.
•LOS_C	A dummy variable. Equal to one when the driver drove under LOS C.
•LOS_DE	A dummy variable. Equal to one when the driver drove under LOS D to E
Value	
•Intersection	A dummy variable. Equal to one when driver drove through intersection.
•Distraction	A dummy variable. Equal to one when drivers suffered distraction.
Renewal Cycle	
•Off-road duration	Consecutive off-road duration before the current glance. This study set 1 s as the reference level of the off-road duration attributes.
•On-road duration	Duration of last forward glance in current renewal cycle. This study set 4 s as the reference level of the off-road duration attributes.

The alternative specific constants (ASC) reflects the difference in the utility of alternative *i* from that of the base alternative when all other conditions area equal. Thus, it reflects the relative preference of the respective focal point or type of renewal cycle being chosen. For the alternatives of choosing other non-forward focal points in the second layer, the estimated constants can represent the potential paths along which drivers were more likely to follow. Results of such path can be used to reflect the *Effort* of shifting vision from one focal point to another, which is determined by the visual angle difference between two focal points (Wickens *et al.* 2003, Wickens and Thomas 2003, Horrey *et al.* 2006). Usually, drivers were more likely to transit vision to the objects closer to the current glanced point.

The attributes related to the *Salience*, such as color or conspicuity, represent the easiness of targets being differentiated and identified (McIntyre 2008, Gershon *et al.* 2012, Koustanaï *et al.* 2012, McIntyre *et al.* 2012, Dukic *et al.* 2013). Unfortunately, the database did not provide the salience level of each target being glanced. The weather condition (rain fall), however, is used to represent the possible effect of the easiness of targets being identified on drivers' vision shift.

The third type of attribute is *Expectancy*, which represents the expected frequency of threat or information appearing (information bandwidth). High information bandwidth suggests more frequent status changes that drivers need to update. The traffic density and speed could induce interaction and/or potential conflicts among vehicles, and thus, were proper to represent the *Expectancy* of focal point being glanced (de Waard *et al.* 2008, Werneke and Vollrath 2012). Moreover, to simplify the representation of the results, the speed is mean centered based on the reference speed 25 mph. It allows the alternative specific constants representing the visual shift paths in a more likely condition for drivers to drive in.

The last attribute of SEEV model is the *Value* of a target, which represents the importance and safety relevance of a focal point. Areas containing threats with higher crash risk might attract more drivers' attention than other less relevant focal points (Martens and Fox 2007, Koustanaï *et al.* 2012). Generally, drivers paid their attention mostly to the future trajectories where they expected to encounter possible threats (Summala *et al.* 1996, Werneke and Vollrath 2012, 2013). In this study, the intersection was used to determine the possible effect when drivers approached or passed the intersection. Additionally, the distraction was used to capture the value of focal points caused by non-driving related tasks. Usually, the distraction activities are increased with the relevance or importance perceived in collecting information from in-vehicle or off-road distractions (Blanco *et al.* 2006, Kiefer and Hankey 2008).

In addition to the attributes in SEEV model, the ones related to the renewal cycle were also included. It has been stated that the longer consecutive time spent off-road, the higher unawareness of leading traffic and the probability of transiting vision back to the front will be (Brown *et al.* 2000). In addition, previous studies also showed that the duration of glancing forward also influence the focal point choices (Wong and

Huang 2013a). To reflect renewal cycle characteristics, the consecutive off-road duration till the instance of making the next glance choice and the duration of glancing forward in current renewal cycle were included. Both attributes were also mean centered based on the reference of mean on-road (4 s) and off-road (1 s) duration.

4.5.2 Model estimation

Some non-forward focal points, such as left forward and right mirror, were rarely glanced. To satisfy the sample size requirement, grouping similar focal points is necessary. In the renewal cycle generation, the focal points were treated separately to calculate the duration and identify the repetition. However, in the process of model estimation, the three focal points on the left (or right) side were included into one single model dealing with the path shifting from the left (or right) side of a vehicle. In total, 1461 complete renewal cycles without missing value were generated, of which 45.45%, 41.96% and 12.59% were classified as starting a new renewal cycle, repeated renewal cycle and direct vision transition to other non-forward focal point, respectively. Estimation result derived in this study will be divided into four sections for the path of transiting vision from the four non-forward focal points.

(1) Path from left side

Table 4-8 shows the estimated logit models for vision shifting from the left side of vehicles. The results in the first layer shows that the drivers were more likely to transit vision back to the front and, then, begin another renewal cycle after glancing at the left side. The drivers would transit vision to the identical focal point on the left side after the forward glance, particularly under conditions of high speed, distraction and LOS C. It shows a compensatory behavior of which drivers constantly check the frontal side for securing the safety against leading traffic. Driving in such conditions of heavy task load urges drivers to pay less attention to safety irrelevant areas and repeatedly transit vision between left and frontal side more frequently. The type of vision transition that the drivers undertook least frequently is transiting vision from the left side directly to another non-forward focal point, especially in LOS D or E. Meanwhile, the probability of directly transiting vision to other non-forward focal points decreases with the increase of on- and off-road glance durations.

Table 4-8 Estimated logit models for the path from the left side

	Layer 1			Layer 2			
	New renewal cycle ^{a}	Repeated renewal cycle	Direct to other non-forward focal point	Left side ^{b}	Right side	Rearview mirror	In-vehicle distraction^{a}
ASC		-0.79**	-1.03**	0.11	0.41	0.44**	
Off-road duration			-0.03**				
On-road duration		-0.01**	-0.01**	-0.01*	-0.01*	-0.01*	
Speed		0.01**			-0.02*		
Intersection					0.60*	-0.77*	
Distraction		0.62*					
Rain							
LOS B							
LOS C		0.49**			-0.74*		
LOS DE			-1.54**		-1.09**		
Sample size	232	139	77	53	69	63	47
LL(b)	-432.44			-302.55			
LL(0)	-492.17			-321.62			
$\bar{\rho}^2$	0.10			0.03			

^{a}: Set as the base alternative in model estimation

^{b}: Represent a path from any one of the focal points on the left side to another one on the identical side.

**: Significant at the level of 0.05

*: Significant at the level of 0.1

The estimated logit model in layer 2 shows the choice of non-forward focal points when starting a new renewal cycle. The most frequent path observed in these samples is transiting vision from left side, to forward direction and to rearview mirror. Path between these two non-forward focal points indicates a usual manner that drivers adopted to gather information. Additionally, instead of directly transiting vision from one side of vehicle to another side, a substantial path from left to right side via a glance at forward area occurred when drivers approached an intersection. Despite the reduced effort stemmed from connecting two renewal cycles, transiting vision across vehicle is still not a comfortable way for allocating attention and observing surroundings. Such a type of vision transition occurred less frequently than transiting vision to other non-forward focal points, particularly under high speed and heavy traffic (LOS C to E).

Moreover, the duration that drivers glance on-road in the current renewal cycle decreases the probability of the significant paths of shifting attention from left side to rearview mirror and to right side. Meanwhile, the probability of shifting vision to in-vehicle distraction increased. Long glance on the frontal side may represent a relatively stable driving status. Less evident paths would occur after glancing at the left side. The attention allocation may be close to a random pattern rather than following certain paths.

(2) Path from right side

Table 4-9 is the estimated logit model for paths from the right side of vehicles. Comparing with other two types of vision transition, starting a new renewal cycle share highest portion of renewal cycles choices after glancing at the right side. Relatively, drivers less likely transit vision directly to other non-forward focal points immediately after glancing at the right side, particularly in the conditions of high speed, rain, LOS C and long glance off-road. These results stated the drivers' cautiousness behavior of inhibiting possible long off-road glances in such restricted conditions. Moreover, probability of repeatedly transiting vision between right and forward side is lower than that of starting a new renewal cycle. Only when driving in the conditions of restricted speed choices (such as LOS D/E), probability of repeated renewal cycle after a glance to right side will increase.

Table 4-9 Estimated logit models for the path from the right side

	Layer 1			Layer 2			
	New renewal cycle^{a}	Repeated renewal cycle	Direct to other non-forward focal point	Left side	Right side^{a}	Rearview mirror	In-vehicle distraction
ASC		-1.14**	-0.80**	2.13**		0.59**	-0.05
Off-road duration			-0.11**				
On-road duration		-0.01*					
Speed			-0.05**	-0.04**			
Intersection						-1.53**	
Distraction							1.17**
Rain			-1.30**				
LOS B				-1.37**			
LOS C			-1.24**	-1.90**			-2.30**
LOS DE		0.94**		-1.80**			
Sample size	155	58	64	68	29	34	24
LL(b)	-238.15			-176.64			
LL(0)	-304.31			-214.87			
$\bar{\rho}^2$	0.19			0.12			

[a]: Set as the base alternative in model estimation

[b]: Represent a path from any one of the focal points on the right side to another one on the identical side.

[**]: Significant at the level of 0.05

[*]: Significant at the level of 0.1

Similar with the result of paths from the left side, the probability of transiting vision from right side to left side via a forward glance was found significantly higher than the base alternative. Drivers decreased the probability of such a path when driving in high speed and under LOS B to E, possibly owing to the heightened task complexity in these conditions. Moreover, the path of transiting vision to forward and rearview mirror sequentially after looking at the right side occurred. In line with the path from the left side, probability of transiting vision to rearview mirror decreases when approaching intersections; while the path of transiting vision to other three non-forward focal points. As for the distraction, the path from right side to in-vehicle distraction, comparing with the ones to other non-forward focal points, was not significant. Yet, when suffering distractions, probability of transiting vision from right side to in-vehicle distraction increases.

(3) Path from rearview mirror

Table 4-10 shows the estimated logit model for the path from rearview mirror. Unlike the result of left and right side, constant of repeated renewal cycle is insignificant and close to that of choosing a new renewal cycle. The off-road duration provides positive effect on choosing repeated renewal cycles. This result suggests that drivers rely deeply on the rearview mirror and consider it as a focal point that drivers must keep checking. Moreover, comparing with other types of renewal cycle, drivers would increase the probability of the repeated ones with the increasing speed and under rain conditions. These conditions imply a scenario with higher expectancy and lower conspicuity on the leading area. Thus, repeatedly looking at rearview mirror can be seen as a compensatory behavior enabling drivers to constantly check the rear side in harmful situations. Furthermore, the probability of transiting directly from rearview mirror to other non-forward focal point is exceedingly low. It may support the notion of looking at rearview mirror being the important mean of maintaining situational awareness. Driver would rather transit vision back to frontal side (for a new renewal cycle or a repeated one) than allocate attention to other areas.

Table 4-10 Estimated logit models for the path from rearview mirror

	Layer 1			Layer 2		
	New renewal cycle^{a}	Repeated renewal cycle	Direct to other non-forward focal point	Left side	Right side^{a}	In-vehicle distraction
ASC		-0.14	-26.21**	0.35*		0.09
Off-road duration		0.06**	-2.86**			
On-road duration						
Speed		0.02**				
Intersection						
Distraction						
Rain		0.57*				
LOS B						
LOS C						
LOS DE						
Sample size	151	137	21	61	43	47
LL(b)	-208.36			-164.15		
LL(0)	-339.47			-165.89		
$\bar{\rho}^2$	0.36			0.01		

^{a}: Set as the base alternative in model estimation
**: Significant at the level of 0.05
*: Significant at the level of 0.1

Though the result obtained in layer 2, the path of transiting vision from rearview mirror is relatively simple. The only path found through the sample data is transiting vision from the rearview mirror sequentially to forward side and to left side. The path of transiting vision from rearview mirror to right side or to in-vehicle distraction is relatively rare.

(4) Path from in-vehicle distractions

Table 4-11 shows the estimated logit model for the path from in-vehicle distraction. The unique characteristics obtained in this table is the higher probability of repeating current renewal cycles than starting a new one after glancing at in-vehicle distraction, especially in the condition of suffering distraction and high speed. The repetition becomes more evident with the increase of duration glancing off-road and the decrease of duration glancing on-road. In other words, drivers would spent long time on processing the distracted information; meanwhile, they glance back to the frontal side only shortly for checking the conditions ahead. In this condition, unlike the results obtained in other paths, the majority of attention resource seems to be allocated on the distraction rather than the driving tasks.

Table 4-11 Estimated logit model for path from in-vehicle distraction

	Layer 1			Layer 2		
	New renewal cycle[a]	Repeated renewal cycle	Direct to other non-forward focal point	Left side	Right side[a]	Rearview mirror
ASC		0.53^{**}	-3.33^{**}	0.57^{**}		0.82^{**}
Off-road duration		0.03^{**}	-0.35^{**}			0.07^{**}
On-road duration		-0.01^{**}				
Speed		0.01^{*}	-0.05^{**}			
Intersection						
Distraction		0.94^{**}				
Rain				0.81^{*}		
LOS B		-0.53^{**}				
LOS C						
LOS DE						
Sample size	126	279	22	49	23	54
LL(b)	-289.92			-126.28		
LL(0)	-469.107			-138.42		
$\overline{\rho}^2$	0.36			0.06		

[a]: Set as the base alternative in model estimation
**: Significant at the level of 0.05
*: Significant at the level of 0.1

After finishing the interaction with in-vehicle distractions, results in layer 2 shows that the drivers usually transit vision to the left side or rearview mirror rather than the right side. Glancing at these two focal points would help drivers retrieve their awareness of traffic in surrounding areas, which they may not be able to comprehensively update during the distraction. The result also shows significant effect of duration glancing off-road on the probability of choosing rearview mirror. Comparing to the one of left and right side, drivers' peripheral vision can still partially cover these two areas. Thus, the longer time that drivers spent glancing off-road, the more likely drivers would transit vision to the rearview mirror.

4.5.3 Characteristics of vision transition

The pattern of vision transition can be discussed in two folds. The first one is related to the information processing from a non-forward focal point. Summing up the results from layer 1 models, the rearview mirror and in-vehicle distraction are the two focal points where drivers usually need more time to gather and process the respective information. It supports the previous findings that the in-vehicle distraction contained complex information needing to be processed, and the rearview mirror represented an usual mean for constantly checking the rear side traffic (Metz *et al.* 2011, Wong and Huang 2013a). These repeated renewal cycles would be more evident when driving in high speed, which represent higher expectancy owing to the shorter time to collision and higher crash risk against the leading obstacles. Drivers in such conditions need to transit vision back to the frontal side more often for checking the leading traffic.

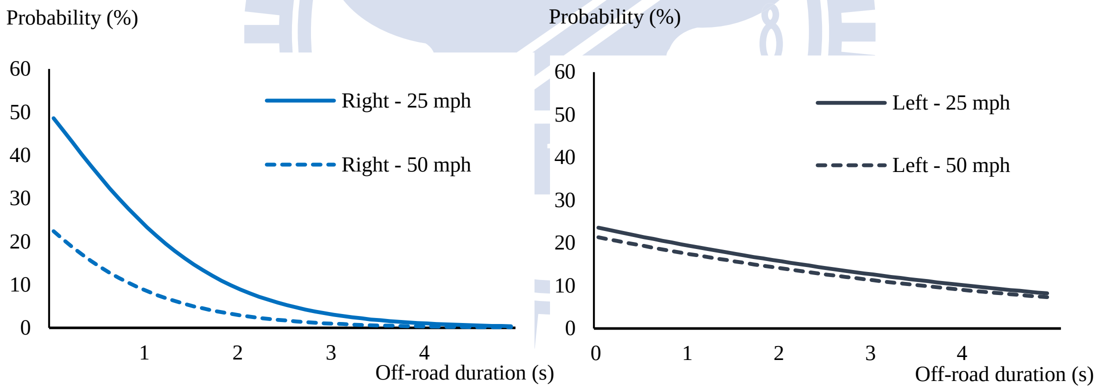
However, it may be questionable that whether renewal cycles repeated for a specific purpose, or they just repeated as a usual manner of driving. The answer may rely on exploring duration of on-road glances between two repeated renewal cycles. The results show that the duration of the forward glance decreases the probability of repeated renewal cycle after glancing at in-vehicle distraction. By contrast, effect of on-road duration does not exist. It shows that drivers focused more on the distraction and transited vision to frontal side shortly to make a brief check on the leading traffic. On the other hand, drivers glanced at forward side as normal when repeatedly checking the rearview mirror, probably because looking at rearview mirror is a routine task of checking the rear side.

In the second part, this study characterized the pattern of drivers transiting vision among different non-forward focal points. The most important focal points that drivers must constantly check are forward side, left side and the rearview mirror. This speculation is supported by the result of the path from in-vehicle distraction. Since in-vehicle distraction is the focal point that distracts drivers’ mental resource, drivers would more likely to transit their vision to the focal points where they perceive as the most critical ones. In this study, left side and the rearview mirror are the two most frequent occurred focal points after an in-vehicle distraction glance.

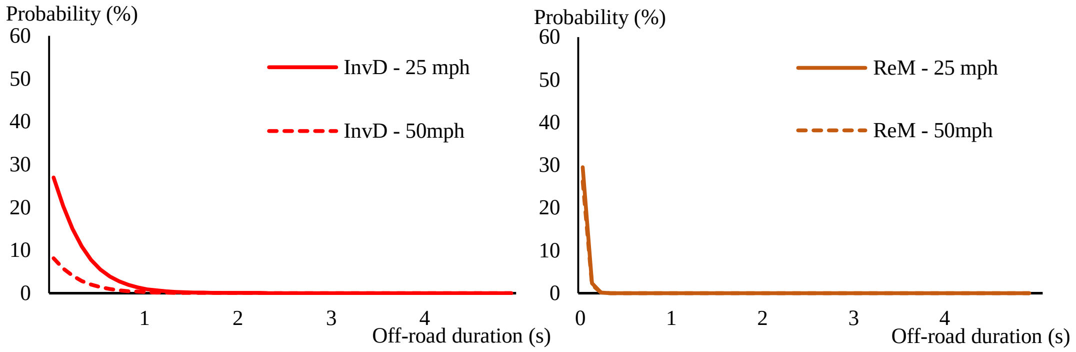
The most evident paths related to these non-forward focal points includes the one from rearview mirror or in-vehicle distraction to the left side, and the one from the right side across the vehicle to the left side. The later type of paths are usually connected two individual paths (from right to forward side, and from forward to left side). Although combining these two paths can reduce the effort required for transiting visions, this type of vision transition is less evident in the conditions of slow driving speed and heavy traffic. Instead, in these worsen driving conditions, drivers would transit vision to the rearview mirror more frequently. That is, the possible path that drivers may held is to transit vision from the right side, sequentially to the forward side, rearview mirror, forward side again and finally to the left side.

4.5.4 Off-road glances with multiple focal points

In addition to the vision transitions of transiting vision back to the frontal side, drivers seldom transit vision directly from one non-forward focal point to another. Such a type of vision transition may be the major cause of crashes owing to the long glance off-road. Figure 4-5 shows the probability of drivers transiting vision to other non-forward focal points immediately after looking at the four non-forward focal points. Driving speed and the time that drivers have spent off-road were included.



(a) Right (b) Left



(c) In-vehicle distraction (d) Rearview mirror

Figure 4-5 Probability of directly transiting vision to other non-forward focal point

The common pattern among the four non-forward focal points is the decreasing probability of direct vision transition to another non-forward focal point. Speed difference is also in line with the notion of higher attention demand owing to the higher expectancy. Shown in Figure 4-5, Probability of transiting vision back to the frontal side is lower under 50 mph than 25 mph. Despite of the rearview mirror case in Figure 4-5, the difference was not clear because the probability drop to the level close to zero after glancing at rearview mirror for approximately 2 s.

However, the decreasing trend is not identical. When looking at the both sides of vehicle, drivers' vision can still cover partial area of the frontal side. There are chances that drivers keep a certain level of awareness of conditions ahead. They may feel safe since no emergent event requiring drivers' attention. Thus, as seen in Figure 4-5 (a) and (b), the probability of transiting vision to other non-forward focal points decrease slower against the time that they have already spent off-road. By contrast, looking at rearview mirror and in-vehicle distraction are the two tasks requiring heightened mental effort. Also, drivers cannot update the timely situations in anyways when glancing at these two non-forward focal points; unless they transit vision back to the front. The nervousness and unawareness would inhibit drivers from transiting to other non-forward focal points.

This section shows an example of using attention allocation model for evaluating driving safety. The sample drivers in this study shows a possible risky pattern that the probability of keep glancing other non-forward focal points is high after glancing at left and right side. Both sides of vehicles may represent possible off-road distraction or close attention to the vehicles close to subject drivers. Yet, the long off-road glances may cause higher crash risk since the leading area were not timely updated.

CHAPTER 5 ROAD SAFETY FROM AN ATTENTION ALLOCATION PERSPECTIVE

Instead of staring only on the frontal side, drivers would occasionally transit vision around or inside vehicles for maintaining situational awareness. Yet, although it is necessary, shifting vision away inhibits drivers from perceiving the status changes ahead (Summala *et al.* 1998, Galpin *et al.* 2009, McIntyre *et al.* 2012). All in all, driving safety relies on an adequate distribution of attention between on- and off-road areas. To evaluate road safety from an attention allocation perspective, this section utilized the Perception Reaction Time (PRT) as a threshold of safety for identifying the risky *renewal cycles* which may cause abnormal off-road glances and possibly unawareness of leading conditions.

5.1 Perception Reaction Time (PRT)

In varying situations, an average driver may require 0.8–1.8 s of Perception Reaction Time (PRT) under normal conditions, and 0.5–0.7 s under emergency conditions (Fambro *et al.* 1998, Davoodi *et al.* 2012). To satisfy most driving experiences, the American Association of State Highway and Transportation Officials (AASHTO) are using a 2.5-s PRT as the minimum roadway design standard for an average driving condition, which includes 1.5 s for perceiving information and forming decisions, and 1.0 s for drivers to perform responses and for vehicles to react to the drivers' actions (Hooper and McGee 1983, Fambro *et al.* 1998). However, numerous researchers have challenged the 2.5-s PRT used by AASHTO as being too low (Hooper and McGee 1983, Neuman 1989, Davoodi *et al.* 2011). The argument is that the current PRT is based on the assumption that drivers can always perceive the obstacles at the instance they present themselves. Such an assumption may not reflect actual driving situations because drivers are not likely to stare in the direction(s) from which threats may materialize. A portion of the 2.5-s PRT frequently elapses before drivers transiting their vision to dangerous threats. Hooper and McGee (1983), incorporating visual transition among focal points, suggested that the 2.5-s PRT only satisfies 57% of driving experience and the adequate level should be 3.5 s.

More importantly, drivers may allocate attention differently in different conditions, including maneuvering, hazardous weather, and inadequate lighting (Martens and Fox 2007, Konstantopoulos and Crundall 2008, McIntyre 2008, Konstantopoulos *et al.* 2010, Koustanaï *et al.* 2012, McIntyre *et al.* 2012). The PRT increases in conditions where the hazard is unexpected, the driving scene is visually complex, or the driver is distracted. In addition, the currently increasing usage of in-vehicle devices is worsening the impairment of PRT owing to attention misallocation. Accordingly, it is essential to analyze the actual PRT under varying driving conditions, particularly, where there may be deteriorated drivers' reaction capability. Therefore, this study investigated the duration of drivers' allocating attention to focal points under varying conditions and examined the robustness of the 2.5-s PRT rule from the attention allocation perspective.

5.2 Analysis Procedure

To evaluate road safety from an attention allocation perspective, this section outlines the procedure of analysis.

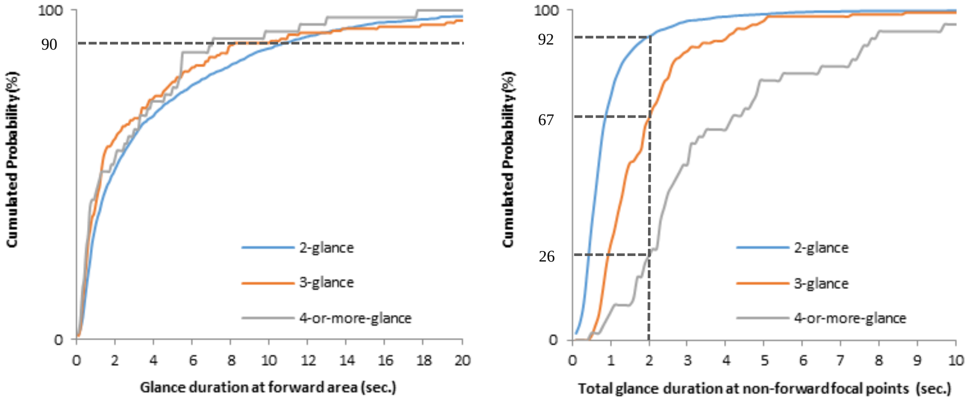
(1) The analysis addresses the duration of glancing at forward and non-forward focal points for renewal cycles with different number of glances. A two-way ANOVA was performed to test the difference of glance duration at focal points under various conditions, including maneuver intentions, traffic densities, distractions, time of day, and weather.

(2) The cumulated probability distribution of the glance duration was calculated to examine the characteristics of drivers distributing their attention resources. Accordingly, the proportion of abnormally long, off-road glances was identified. Considering that drivers require approximately 0.5–0.7 s to apply the emergency brake (baseline PRT) (Fambro *et al.* 1998, Davoodi *et al.* 2011, Davoodi *et al.* 2012), a roadway design based on the 2.5-s PRT rule allows drivers to shift their vision away for 1.8-2.0 s at most. This threshold assumes an obstacle appearing on the frontal side of the vehicle that drivers must take action to prevent conflict. Once shifting their vision away for more than 2.0 s (or 1.8 s under 0.7-s baseline PRT), drivers will not have sufficient time to respond to those obstacles at the edge of their sight. Thus, this study focused on the probability of a driver transiting vision off-road longer than the 2.0-s threshold. Such threshold is close to the one used in other research, which suggested that transiting vision away for longer than 1.6–2.0 s significantly increase crash risk (Caird and Hancock 1994, Cooper and Zheng 2002, Klauer *et al.* 2006, Horrey and Wickens 2007).

(3) To check the robustness of the 2.5-s PRT rule, the 1.8 and 2.0 s margins of duration glancing at non-forward focal points were examined. Moreover, because the 2.5-s PRT was set based on the 90th percentile value, this study also adopted the 90th percentile rule to determine the desired PRT level when taking the behavior of drivers' attention allocation into consideration.

5.3 Duration Analysis

Figure 5-1 indicates the cumulated probability of glance duration to the forward area and non-forward focal points for renewal cycles with different number of glances. Figure 5-1 (a) indicates that the glance duration to the forward area in various types of renewal cycles differs slightly. The 90th percentile glance durations to the forward area are 10.7, 8.2, and 7.2 s for renewal cycles with 2, 3, and 4-or-more focal points, respectively. For the duration of non-forward glances, Figure 5-1(b) indicates that the attention was transited away from the frontal side longer in renewal cycles with more focal points. Using 2.0-s as the threshold, 8% of 2-glance renewal cycles were unsafe. However, 33% of 3-glance and 74% of 4-or-more-glance renewal cycles might be unsafe since the time away from the forward side was more than 2.0 s. This result suggests that drivers glancing at more non-forward focal points consecutively in a renewal cycle were more likely to encounter insufficient time to respond to harmful changes in front of the vehicle. Therefore, to maintain situational awareness, drivers should avoid looking at too many focal points off-road in a sequence.



(a) Forward focal point (b) Non-forward focal points

Figure 5-1 Cumulated probability of glance duration

This section explores the characteristics of attention allocation when facing different maneuver intentions, distractions, traffic densities, time of day, and weather. Because of the small sample size of 4-or-more-glance renewal cycles, the following analyses included only 2- and 3-glance renewal cycles.

(1) Maneuver intentions

Different maneuvers create different future trajectories and unique expectations of potential threats. Thus, drivers may distinctly concentrate on focal points and vary the glance duration at non-forward areas.

Table 5-1 indicates the descriptive statistics and ANOVA results for glance duration to forward and non-forward areas under different maneuver intentions. The duration of the forward glance in each renewal cycle was not significantly affected by maneuver intentions (*F* = 0.93, *p* = .39), the number of glances (*F* = 1.15, *p* = .28), and their interaction (*F* = 1.98, *p* = .14). However, for the total duration of glancing at non-forward focal points in a renewal cycle, the ANOVA results indicate that the maneuver intentions (*F* = 4.16, *p* = .02), number of glances (*F* = 81.93, *p* = .00), and their interaction effects (*F* = 2.80, *p* = .06) are significant.

Table 5-1 ANOVA of glance duration under different maneuver intentions.

	Sample size / Mean duration on forward area (Std.) / Mean duration on non-forward focal points (Std.)		
	2-glance renewal cycle	3-glance renewal cycle	Total
Driving straight on segments	1039 / 4.08 (5.12) / 0.92 (0.79)	62 / 2.38 (2.92) / 2.11 (1.71)	1101 / 3.99 (5.03) / 0.98 (0.91)
Changing lanes on segments	174 / 3.54 (4.64) / 0.81 (0.62)	24 / 4.31 (5.82) / 1.53 (0.86)	198 / 3.63 (4.79) / 0.89 (0.70)
Passing through intersections	415 / 4.19 (4.80) / 1.10 (1.27)	36 / 3.48 (5.16) / 1.90 (1.44)	451 / 4.13 (4.83) / 1.16 (1.31)

	ANOVA of glance duration at forward and non-forward focal points			
Source of variance	Sum of square	Degree of freedom	Mean square	F (*p*-value)
Glance at forward focal point				
Maneuver intention	45.64	2	22.82	0.93 (0.39)
Number of glances	28.23	1	28.23	1.15 (0.28)
Interaction	96.89	2	48.44	1.98 (0.14)
Error	42709.17	1744	24.49	
Glance at non-forward focal point(s)				
Maneuver intention	7.96	2	3.98	4.16 (0.02)**
Number of glances	78.33	1	78.33	81.93 (0.00)**
Interaction	5.36	2	2.68	2.80 (0.06)*
Error	1667.40	1744	0.96	

**: Significant at the level of 0.05

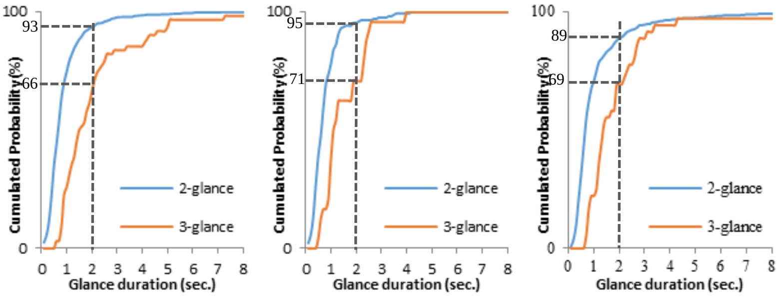
*: Significant at the level of 0.1

Compared with driving straight on segments, both changing lanes and passing through an intersection may be considered to be mentally demanding tasks. Drivers must pay more attention to surroundings against the increased interaction with other vehicles. The higher mental effort resulted in distinct ways of allocating attention. As in the 2-glance renewal cycles, changing lanes on segments indicated decreased glance duration at both focal points, suggesting quick vision transitions between the forward area and the adjacent lanes. Shorter durations enable higher sampling rates for drivers to gather information more efficiently under pressure. Thus, they can reach a balance of distributing their attention to maintain an adequate gap between themselves and the leading vehicle, and to timely observe the adjacent lane(s) for lane-changing opportunities.

As for the 2-glance renewal cycles in passing through intersections, the drivers were cautious and spent more time on both forward and non-forward focal points than on the other two maneuver intentions. When approaching an intersection, drivers would stare at the front area to avoid possible conflicts caused by a sudden deceleration by the leading vehicle. In addition, drivers would also pay close attention to the intersected roadway, particularly when there were vehicles attempting to enter the intersection. The close attention to both sides of the intersected roadway enabled continued observation to check for possible maneuvers by other vehicles constantly. On the other hand, under such circumstances, drivers may not be able to timely check the status of leading vehicles.

In 3-glance renewal cycles, drivers glanced at the forward area for shorter durations and on non-forward focal point for longer durations when driving straight on segments than for the two other tasks. The significant interaction effect shows that the average duration of each non-forward glance was shorter in 3-glance renewal cycles when changing lanes on road segments and when passing through intersections. This result may imply the uneasiness of shifting attention away to more focal points in these mentally demanding situations. The sample drivers speedily glanced at the non-forward focal points to reduce the possible deterioration of awareness of the leading area. Interestingly, driving straight on segments had the shortest forward glances among all maneuver intentions in 3-glance renewal cycles. On the contrary, it also had the longest non-forward glances among all maneuver intentions in 3-glance renewal cycles and the average duration was longer than the one in 2-glance renewal cycles. This unique pattern may be related to leisurely driving, or sometimes probably to distracted activities. Because drivers spent almost half of the time not looking at the front area, such an attention allocation might expose the driver to dangerous risks of conflict with leading traffic.

Figure 5-2 indicates the cumulated probability of the glance duration at other focal points for various maneuver intentions. When changing lanes, only 5% of 2-glance renewal cycles and 29% of 3-glance renewal cycles transit vision away for more than 2.0 s. These results indicated compensatory behavior for fewer abnormal glances being undertaken, probably because of their nervousness in potential conflicts when changing lanes than other maneuver intentions. However, 3-glance renewal cycles accounted for 11% of the renewal cycles in changing lanes on segments, comparing to 5.6%–8.0% for the other two maneuver intentions. Higher percentages of 3-glance renewal cycles when changing lanes, probably more areas needed to be glanced, suggests more opportunities to lose attention to leading traffic. Fortunately, as stated, drivers in general tried to shorten their glance durations for compensation. As for the maneuver of passing through intersections, Figure 5-2 (c) indicates the highest probability of 2-glance renewal cycles exceeding the 2.0-s safety margin occurs when passing through intersections. Accordingly, when passing through intersections, compared to other tasks, drivers are more likely to miss information ahead owing to the observation of intersected road.



(a) Driving straight on segments (b) Changing lanes on segments (c) Passing through intersections

Figure 5-2 Cumulated probability of glance duration at non-forward focal points under different maneuver

(2) Distraction

Based on the ANOVA in Table 5-2, both distraction and number of glances in a renewal cycle significantly affected the duration of glancing at the forward area (F = 4.87, p = .03; F = 2.84, p = .09), and on non-forward focal points (F = 10.15, p = .00; F = 121.16, p = .00). However, there is no significant interaction effect of distraction and the number of forward and non-forward glance durations (F = 1.42, p = .23; F = 1.96, p = .16). As indicated in Table 5-2, the glance duration to the forward area with distractions was shorter than that of driving without distractions. In-vehicle distractions or clutter located on the roadsides increased the duration of shifting vision away from the front.

Table 5-2 ANOVA of glance duration under different distraction conditions

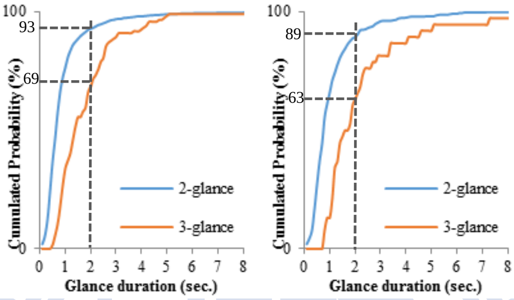
	Sample size / Mean duration on forward area (Std.) / Mean duration on non-forward focal points (Std.)								
	2-glance renewal cycle			3-glance renewal cycle			Total		
Driving with distraction	522	/ 3.65 (4.85)	/ 1.08 (0.96)	38	/ 2.29 (3.75)	/ 2.24 (1.74)	560	/ 3.56 (4.80)	/ 1.16 (1.07)
Driving without distraction	1525	/ 4.13 (4.91)	/ 0.91 (0.92)	124	/ 3.90 (5.33)	/ 1.81 (1.30)	1649	/ 4.11 (4.94)	/ 0.98 (0.98)

	ANOVA of glance duration at forward and non-forward focal points			
Source of variance	Sum of square	Degree of freedom	Mean square	F (p-value)
Glance at forward focal point				
Distraction	117.23	1	117.23	4.87 (0.03) **
Number of glances	68.28	1	68.28	2.84 (0.09) *
Interaction	34.21	1	34.21	1.42 (0.23)
Error	53088.65	2205	24.07	
Glance at non-forward focal point(s)				
Distraction	9.57	1	9.57	10.15 (0.00) **
Number of glances	114.31	1	114.31	121.16 (0.00) **
Interaction	1.85	1	1.85	1.96 (0.16)
Error	2080.38	2205	0.94	

**: Significant at the level of 0.05

*: Significant at the level of 0.1

Figure 5-3 is the cumulated probability distribution of non-forward glance duration associated with and without distractions. When driving with distraction, 11% of 2-glance renewal cycles and 37% of 3-glance renewal cycles transited vision away from the forward area for more than 2.0 s. Specifically, for those 3-glance renewal cycles that exceeded the 2.0-s threshold, a large portion of them were quite long. There were around 5% of 3-glance renewal cycles that even exceeded 7 s. In addition, approximately a quarter of sample drivers in this study were affected by distractions. Undoubtedly, it is a challenging issue deserving of more attention.



(a) Driving without distraction

(b) Driving with distraction

Figure 5-3 Cumulated probability of glance duration at non-forward focal points with and without distractions

(3) Traffic density

Drivers may suffer more complex tasks from frequent interactions with other vehicles under heavy traffic conditions than in free flow conditions. Table 5-3 indicates that traffic density (*F* = 2.33, *p* = .07) and its interaction with the number of glances (*F* = 3.29, *p* = .02) significantly affected the glance duration to the forward area. However, the duration of forward glances were not significantly affected by the number of glances (*F* = 0.01, *p* = .90). The total duration of non-forward glances in a renewal cycle was significantly affected by traffic density (*F* = 3.43, *p* = .02), number of glances (*F* = 148.43, *p* = .00), and their interactions (*F* = 2.40, *p* = .07).

Table 5-3 ANOVA of glance duration under different Levels of Service (LOS)

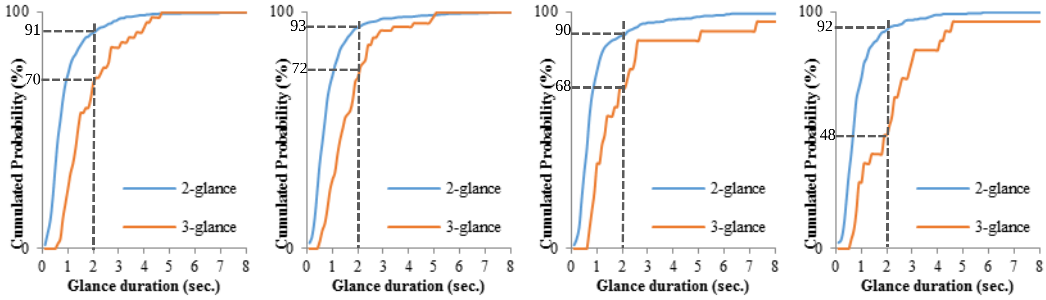
	Sample size / Mean duration on forward area (Std.) / Mean duration on non-forward focal points (Std.)								
	2-glance renewal cycle			3-glance renewal cycle			Total		
Level of service A	536	/ 3.91 (4.68)	/ 0.94 (0.84)	47	/ 3.66 (4.89)	/ 1.83 (1.06)	583	/ 3.89 (4.70)	/ 1.02 (0.89)
Level of service B	737	/ 3.96 (4.72)	/ 0.93 (0.86)	65	/ 2.45 (3.63)	/ 1.70 (1.03)	802	/ 3.84 (4.66)	/ 0.99 (0.90)
Level of service C	505	/ 4.39 (5.33)	/ 1.02 (1.16)	25	/ 3.67 (4.63)	/ 2.19 (2.25)	530	/ 4.36 (5.30)	/ 1.08 (1.25)
Level of service D/E	269	/ 3.62 (4.94)	/ 0.95 (0.79)	25	/ 5.87 (7.72)	/ 2.31 (1.77)	294	/ 3.80 (5.26)	/ 1.06 (0.98)

	ANOVA of glance duration at forward and non-forward focal points			
Source of variance	Sum of square	Degree of freedom	Mean square	F (*p*-value)
Glance at forward focal point				
Traffic density	167.82	3	55.94	2.33 (0.07) *
Number of glances	0.35	1	0.35	0.01 (0.90)
Interaction	237.56	3	79.18	3.29 (0.02) **
Error	52913.78	2201	24.04	
Glance at non-forward focal point(s)				
Traffic density	9.74	3	3.25	3.43 (0.02) **
Number of glances	140.60	1	140.60	148.43 (0.00) **
Interaction	6.81	3	2.27	2.40 (0.07) *
Error	2084.85	2201	0.95	

**: Significant at the level of 0.05
*: Significant at the level of 0.1

The glance duration to the forward area in 2-glance renewal cycles increased with traffic density from LOS A to C. Thereafter, it decreased in LOS D/E, probably owing to the heavy traffic, which seriously restricts drivers' maneuvers. Drivers in these conditions may check the lead traffic quickly, and transit to surrounding areas frequently for possible lane changes or for relaxation. By contrast, the 3-glance renewal cycles indicated that glance duration on both forward and non-forward focal points were the longest in LOS D/E. The interaction effect between numbers of glances and density shows increased average duration non-forward glances in 3-glance renewal cycle under LOS D/E. In contrast with the 2-glance renewal cycles, drivers applying the 3-glance renewal cycles in LOS D/E might drive in a relaxed way without attempting to change lanes. Therefore, they transit vision at a slower pace without urgency. However, long glances away from the front may increase the chances of drivers failing to notice changes in leading traffic. Moreover, the behavior in the 3-glance renewal cycles in LOS B indicated that drivers glanced shortest at both forward and non-forward focal points. This phenomenon suggests that drivers in moderate traffic conditions may drive more speedily and cautiously by increasing the sampling rate of collecting information from various focal points.

Figure 5-4 indicates the cumulated probability of the duration of non-forward glances under various traffic densities. The 3-glance renewal cycles in LOS D/E contained more long non-forward glances than those in LOS A/B density levels. Fifty-two percent of non-forward glances in 3-glance renewal cycles were longer than 2.0 s in LOS D/E, compared to 30%, 28%, and 32% in LOS A, B, and C, respectively. Moreover, 8.5% renewal cycles in LOS D/E were 3-glance, which was approximately the same level as in LOS A/B, and higher than the percentage in LOS C (4.7%). This result suggests that drivers in this study did not decrease their percentage of 3-glance renewal cycles to compensate for the increasing traffic conflicts in LOS D/E. This negligence may result in more incidents in heavy traffic than in other traffic densities.



(a) LOS A (b) LOS B (c) LOS C (d) LOS D/E

Figure 5-4 Cumulated probability of glance durations at non-forward focal points under different levels of traffic density

(4) Time of day

Table 5-4 indicates that the durations of both forward and non-forward glances were not significantly affected by time of day. Unexpectedly, glance patterns exhibited by drivers during the day were similar to those during the night with light.

Table 5-4 ANOVA of glance duration at different times of day

	Sample size / Mean duration on forward area (Std.) / Mean duration on non-forward focal points (Std.)								
	2-glance renewal cycle			3-glance renewal cycle			Total		
Day time	1563	/ 3.99 (4.87)	/ 0.97 (0.94)	132	/ 3.50 (5.08)	/ 1.88 (1.42)	1695	/ 3.95 (4.89)	/ 1.04 (1.02)
Night time (with light)	393	/ 3.70 (4.53)	/ 0.91 (0.89)	25	/ 3.65 (5.35)	/ 2.12 (1.55)	418	/ 3.70 (4.58)	/ 0.99 (0.98)

	ANOVA of glance duration at forward and non-forward focal points			
Source of variance	Sum of square	Degree of freedom	Mean square	F (*p*-value)
Glance at forward focal point				
Time of day	0.38	1	0.38	0.02 (0.90)
Number of glances	5.93	1	5.93	0.25 (0.61)
Interaction	3.98	1	3.98	0.17 (0.68)
Error	49171.12	2109	23.31	
Glance at non-forward focal point(s)				
Time of day	0.64	1	0.64	0.67 (0.42)
Number of glances	88.63	1	88.63	92.54 (0.00) **
Interaction	1.68	1	1.68	1.75 (0.19)
Error	2019.81	2109	0.96	

**: Significant at the level of 0.05

*: Significant at the level of 0.1

(5) Weather

The ANOVA results in Table 5-5 indicate that the durations of both forward and non-forward glances were not affected by weather conditions, which was unexpected. Combining drivers’ similar behavior during the day and night time with light, the results suggest that the sample drivers were slightly aggressive.

Table 5-5 ANOVA of glance duration under different weather conditions

	Sample size / Mean duration on forward area (Std.) / Mean duration on non-forward focal points (Std.)								
	2-glance renewal cycle			3-glance renewal cycle			Total		
Clear	1477	/ 4.19 (4.97)	/ 0.96 (0.95)	111	/ 3.54 (5.14)	/ 1.87 (1.19)	1588	/ 4.14 (4.98)	/ 1.02 (1.00)
Poor	570	/ 3.55 (4.69)	/ 0.96 (0.86)	51	/ 3.48 (4.89)	/ 1.99 (1.83)	621	/ 3.54 (4.70)	/ 1.04 (1.03)

	ANOVA of glance duration at forward and non-forward focal points			
Source of variance	Sum of square	Degree of freedom	Mean square	F (*p*-value)
Glance at forward focal point				
Weather	15.90	1	15.90	0.66 (0.42)
Number of glances	16.43	1	16.43	0.68 (0.41)
Interaction	10.49	1	10.49	0.44 (0.51)
Error	53085.56	2205	24.08	
Glance at non-forward focal point(s)				
Weather	0.47	1	0.47	0.50 (0.48)
Number of glances	122.94	1	122.94	129.33 (0.00) **
Interaction	0.46	1	0.46	0.48 (0.49)
Error	2096.00	2205	0.95	

**: Significant at the level of 0.05

*: Significant at the level of 0.1

5.4 Desired PRT from Attention Allocation Perspective

This section addressed the desired PRT that incorporates latent time of drivers glancing off-road. Table 5-6 presents a summary of the desired PRT at different percentiles of six tasks and environmental conditions. The desired PRT is consisted of two parts. One is the time that drivers spent looking off-road. In this study, three percentiles, 75th, 85th and 90th, were used. The second part is the baseline PRT for emergency reactions, which is around 0.5–0.7 s based on previous studies (Fambro *et al.* 1998, Davoodi *et al.* 2011, Davoodi *et al.* 2012). Moreover, this section includes six tasks and environmental statuses for identifying the desired PRT under different conditions. The percentage of driving experiences covered by 2.5-s PRT is provided to illustrate the gap between current and the desired PRT. In addition, the desired PRT of driving straight on segments during the day, good weather, under LOS A to C flow condition and without distractions (the preferred condition) is used for comparison.

Table 5-6 Desired PRT from the perspective of attention allocation

	Desired PRT at different percentile based on 0.5 / 0.7 s baseline PRT (sec.)			2.5-s PRT coverage (%)
	75	85	90	
Maneuver intention				
Changing lanes on segments	1.6 / 1.8	1.8 / 2.0	2.3 / 2.5	91.18 / 88.73
Passing through intersections	1.8 / 2.0	2.5 / 2.7	3.1 / 3.3	85.50 / 82.68
Distraction				
Driving with distraction	1.8 / 2.0	2.3 / 2.5	2.7 / 2.9	87.68 / 85.36
Traffic density				
LOS D/E	1.7 / 1.9	2.2 / 2.4	2.7 / 2.9	87.96 / 85.95
Time of day				
Night time with light	1.7 / 1.9	2.3 / 2.5	2.8 / 3.0	87.03 / 84.62
Weather				
Poor weather	1.6 / 1.8	2.1 / 2.3	2.6 / 2.8	89.39 / 87.46
Preferred condition (317 samples)	1.5 / 1.7	1.8 / 2.0	2.1 / 2.3	94.34 / 92.45

As expected, the 90th percentile PRT (90-PRT) in the preferred condition (2.1–2.3 s) was lower than that of other conditions. The 2.5-s PRT covers 92.45%–94.34% of driving experiences, which is higher than the 90% stated in AASHTO. Other than the preferred conditions, changing lanes on segments was the only one in which the desired 90-PRT was under 2.5 s. Other conditions indicate that desired 90-PRTs are higher than 2.5 s. The longest one occurred when passing through intersections, in which the 90-PRT is 3.1–3.3 s and the 2.5-s PRT only satisfied 82.68%–85.50% of driving experiences. This result implies that drivers should be very vigilant when passing through intersections.

The core issue of this study is the robustness of the 2.5-s PRT is a robust design standard for naturalistic driving under various environments. The current 2.5-s PRT design standard was not far away from the desired 90-PRTs and indicated acceptable performance in most conditions. Even in the worst conditions examined in this study, the 2.5-s PRT still covered 83% driving experience. It suggests that existing roadways are rather safe even taking attention allocation into consideration.

Nevertheless, the proposed desired 90-PRT was based on the assumption that drivers are able to perceive and react quickly in 0.5–0.7 s, of which the value (baseline PRT) was obtained primarily through laboratory experiments or field studies in controlled environments. The stimuli used in these studies were usually clear and simple for drivers to point out. However, the actual driving environment is more complicated than a controlled environment. Objects with less conspicuity, in a more complex background, have lower chances and require more time to be identified (Gershon *et al.* 2012). That is, obstacles may not be explicit enough for drivers to see and react to within the baseline PRT. Moreover, it has been suggested that drivers react slower if they do not expect the occurrence of stimuli (Fambro *et al.* 1998, Davoodi *et al.* 2012, Gershon *et al.* 2012) or have little driving experience (Underwood *et al.* 2003b, Martens and Fox 2007, Nabatilan 2007, Simons-Morton 2007, Stanton and Salmon 2009, Borowsky *et al.* 2010). Therefore, current PRT settings based on average drivers' capabilities may be insufficient for drivers whose driving and situational awareness performance was below average, particularly, the aging drivers.

CHAPTER 6 CONCLUSION AND RECOMMENDATION

Purpose of this study is to find a proper representation of attention allocation for analyzing drivers' vision transition process, and to identify the usual pattern that drivers held to transit vision around or inside vehicles. Based on the result obtained in this study, the conclusions regarding the contribution of the novel approach proposed in this study and the general pattern observed are summarized in 6.1. Then, the policy implication are addressed in 6.2. Finally, recommendations to future research related to this issue were made in 6.3.

6.1 Conclusion

A novel approach of *renewal cycle* was proposed in this study as the basic element for analyzing attention allocation. This method provide in-depth insight and different view of attention allocation. The contributions of this method are described as follow.

(1) In previous studies, the path related approaches extracted the sequence of drivers transiting vision between two or three focal points. However, such a way may represent only a partial process of drivers allocating attention to multiple areas. Moreover, it is important to identify the focal point where drivers start and end a sequence of vision transition. That is, the basic component of attention allocation must be identified. In this study, the concept of renewal cycle is proposed by anchoring the glance to forward. Considering that the vehicle were moving forward in most of time, the frontal side is the area where drivers must constantly glance. Glancing at the frontal side may also be area where drivers can most comfortably looking at. Therefore, using the concept of renewal cycle can be utilized for distinguishing the forward and non-forward glances. This approach can also transform the sequence of vision transition into several components for analysis.

(2) In previous studies, the forward and non-forward glances were either analyzed as the same focal point, or separately without considering the relation between them. Since the drivers spent most of time looking forward, such ways may obscure the characteristics of non-forward focal points owing to the dominant forward area. Additionally, glancing away from the frontal side may increase the unawareness of leading conditions, and thus, urge drivers to transit vision back to the front. It implies the importance of analyzing the process of drivers shifting vision away from and back to the frontal side. Since each renewal cycle contains a glance to

forward side, using it as the basic component prevents analysis being dominated by the forward glance. It also presents not only the distinction between on- and off-road glances, but also enable the analyses to observe the interaction between these two types of focal points.

(3) Based on the scan path approach, another advantages of using renewal cycle is to provide a clearer understanding of the visual transitions among focal points. The most significant paths comprise visual transitions to or from the frontal area, the most dominant focal point. This method cannot thoroughly reflect all visual transits around the vehicle. By using renewal cycles as the basic component of attention allocation, two seemingly distinct scan paths can be combined in an attention allocation pattern that illustrates the chain processes of drivers glancing at sequential focal points. In other words, a paths containing more than three focal points can be observed, such transiting vision from one non-forward focal point, to forward side, then to another non-forward focal point and finally back to the frontal side again.

(4) Drivers do not always finish the information from a focal point in a glance. As an alternative, they sometimes repeatedly transit vision between an intended non-forward focal point and the forward side for preventing long glances off-road. Using renewal cycle as the basic component of analyzing attention allocation can observe such a characteristics of repeated renewal cycle. Moreover, the duration of repeated renewal cycles may indicate the investment of mental resources in an information source. Because drivers separate lengthy glances on a focal point into several shorter successive renewal cycles, the traditional methods for analyzing the duration of each glance may underestimate the total effort expended on certain focal points. Analyzing the total duration of glances over repeated renewal cycles provides vital insight into the manner in which drivers manage information perception and/or reconfirmation of traffic conditions.

(5) Finally, modeling the process of attention allocation microscopically provided the probability of drivers choosing specific type of renewal cycle or a specific focal point. A two-layer MNL model is proposed based on the concept of renewal cycles, which are the types of renewal cycle choices in layer 1 and the focal point choices in layer 2. Particularly, this study focus on the transition between two non-forward focal points under varying driving tasks or environmental conditions. The contribution of each individual factor affecting attention demand of each focal point can be derived.

Using the naturalists glance data of 100-car dataset, this study explored and modeled drivers' attention allocation. Some patterns of vision transition were found in this study.

(1) More than 90% of the renewal cycles identified in this study contained only one glance away from the forward direction. Moreover, the probability of transiting vision from one non-forward focal point directly to another decreases with the time that drivers has glanced off-road. Particularly in the complex tasks and worsen environmental conditions, drivers tended not to glance at more than one non-forward focal point in a sequence. This result suggests a cautious behavior that drivers would prevent long glance off-road by glancing only one non-forward focal point before transiting vision back to the front. Additionally, transiting vision away from the frontal side would urge drivers to transit vision back to the front for compensating the lost awareness against leading traffic.

(2) As expected, maneuvers that entail different task loads create distinct patterns of attention allocation. Moreover, the drivers exhibited patterns of transiting vision to the roadside or to in-vehicle devices to gain non-driving related information less frequently when they were busy performing maneuvers with higher task loads. This finding suggests the existence of compensatory behavior to prevent crashes by allocating increased attention to where the risk is increased (Liu and Lee 2005, Törnros and Bolling 2006).

(3) Nevertheless, in some risky situations, such as driving under LOS D/E, *InvD* were found to occur most frequently among all non-forward focal points. Drivers who overestimated their ability to handle both distraction activities and driving tasks placed themselves at increased risk of having a crash, especially under poor driving conditions. Hence, managing distraction is clearly vital for improving driving safety. Detailed analysis of distracted behaviors and their implications for designing effective information systems warrant further research.

(4) A large proportion of these cycles occurred successively and repeatedly; that is, the drivers may separate a long glance at one focal point into several repeated short renewal cycles. This finding supports the hypothesis that shifting attention away from the forward area decreases the driver's awareness of the traffic ahead. Thus, the sample drivers generally avoided looking away from the forward area for lengthy durations.

(5) Among all non-forward focal points, in-vehicle distraction and rearview mirror related renewal cycles are the two that drivers would more likely to repeat. It supports the previous findings that the in-vehicle distraction contained complex

information needing to be processed, and the rearview mirror represented an usual mean for constantly checking the rear side traffic (Metz *et al.* 2011). These repeated renewal cycles would be more evident when driving in high speed. Again, the higher speed may represent shorter time to collision against the leading obstacles, which induce higher expectancy. Drivers would be more eager for transiting vision back to the frontal side when driving fast. Therefore, repeatedly transiting vision between rearview mirror and in-vehicle distraction may be a compensatory strategy for balancing the attention resources allocating to on- and off-road areas.

(6) The renewal cycles of rearview mirror and in-vehicle distraction are repeated for different purpose. This study found that the drivers would tended to glance these two non-forward focal points longer in repeated renewal cycles. The duration of forward glance in rearview mirror does not vary between individual and repeated renewal cycle. However, drivers would decrease the duration glancing on-road when repeated transiting vision between in-vehicle distraction and forward side. This distinction implies different purpose of renewal cycles. One is for constantly checking the specific area, such as rear side through rearview mirror, where potential threats may appear. Drivers' main effort is still invested on the frontal side. On the other hand, the other type of repetition is for dividing a long glance on certain information source into several shorter glances. The in-vehicle distraction is fall into this category. Drivers would spent more mental resource for gathering and comprehending the information from the distraction. Meanwhile, to compensate the lost awareness against leading traffic, they would transit vision back to the frontal side shortly.

(7) Regarding the different types of renewal cycle connecting two non-forward focal points, the probability of drivers transiting vision directly to from one non-forward focal point another was the lowest and decreased with the duration being glanced off-road. This result supports the notion of drivers being more stressful when glancing at more than one non-forward focal point in a renewal cycle.

(8) Drivers barely transited vision directly to other non-forward focal points after glancing at rearview mirror and in-vehicle distraction. It may be related to the heightened level of mental resource required for identifying the image through a small mirror reflection or reading the information on the in-vehicle distraction. Such a tense glance may increase drivers' uneasiness more evidently than glancing elsewhere. By contrast, after glancing at left or right side, drivers may feel comfortable to glance another non-forward focal point. Yet, in the

conditions of high density or high speed, the probability of transiting vision directly to other non-forward focal point would decrease, which is related to higher expectancy level of traffic on the frontal side.

(9) Through modeling the attention allocation process, this research is able to extract the path of shifting vision from one non-forward focal point, to forward side, and then to another non-forward focal points. In this type of vision transition, the most frequent occurred path observed in this study is transiting vision from one side of a vehicle to another side through a glance to forward area. Drivers would offset the effort of transiting vision across the vehicle by connecting two renewal cycles. As stated in Underwood *et al.* (2003b), such a combination can be observed in an experienced driver’s scan path, while a novice may directly transit vision from right to left. The renewal cycle concept can help in grouping these distinct paths for better interpreting the pattern of attention allocation. Yet, even though this type of vision transition requires less effort than the one of directly transiting vision from one side to another, it is still a driving tasks with higher effort. While driving in a mentally demanding scenario, such as heavy traffic, drivers would decrease the vision transition across the vehicle, no matter in the form of a direct path or a path containing two renewal cycles.

(10) This study analyzed the duration of each forward and non-forward focal point based on the numbers of glances in a renewal cycle. Applying such a method could identify the duration changes against when drivers are aware of the possible long glance off-road. It is found that drivers would alter the duration glanced at forward and non-forward focal points based on the clues obtained from driving tasks and environment conditions, especially the duration of forward glances in 3-glance renewal cycles. Drivers would glance at forward side shorter in 3-glance renewal cycles than the 2-glance ones, suggesting the drivers’ alertness against possible long off-road glances. However, the duration of off-forward glances did not decrease with the number of off-road glances. It shows that the off-road glances would increase dramatically when drivers intended to look at more than one non-forward focal point in a sequence.

(11) This study, incorporating the potential time loss of drivers not gazing forward, developed a desired PRT for examining the robustness of the current PRT rule. The results revealed that drivers in certain conditions probably have insufficient time to perceive information, form decisions, and initiate reactions. As expected, attributes including maneuver intentions, distraction, and traffic density were found to have significant effects on the durations of forward or non-forward glances. Degradation of safety resulting from attention allocation with two or

more non-forward glances in a renewal cycle is substantial. Seeing that adopting inappropriate renewal cycles evidently deteriorates safety, improving drivers' information searching skills can be beneficial in crash prevention. Drivers must develop defensive driving skills to observe surroundings properly and efficiently, especially when driving in high risk conditions.

6.2 Policy Implications

The ultimate goal of analyzing attention allocation is to improve safety. Based on the results obtained in this study, several policy implication can be made.

(1) Although this study did not represent a "safe" pattern of driver attention allocation, some of the results are still close to a usual pattern can be used as a reference for driver education. It has been stated that experienced drivers have better and more flexible rules for allocating attention in varying conditions. By contrast, novice ones may be affected by their limited rule of vision transition and poor efficiency of processing information. Thus, if adequate prototypes of vision transition in certain critical scenario are available, educating not only skills of controlling vehicles but also the proper situational awareness technique can help improve safety.

(2) Clear-sighted and useful information can be crucial to attract drivers' attention effectively and to drive safely. Providing road information actively and in a timely fashion allows drivers to focus more on driving rather than searching for relevant information on the roadside. Section 2.4 shows different types of ITS devices and their possible impact on driving behavior. Whether these devices can provide positive effect on safety is a vital issue that requires researchers' attention. The effectiveness and possible impact of providing such a specific type of information may be evaluated by the pattern changes of driver's attention allocation.

(3) Additionally, the content of information offered to drivers and the manner in which the information is used are extremely relevant to safety improvement. The negative effects of using in-vehicle devices, such as cell phones or navigators, have been widely discussed (Patten *et al.* 2004, Horrey *et al.* 2006, McEvoy *et al.* 2007, Caird *et al.* 2008, Kass *et al.* 2010, Thompson *et al.* 2012). The longer a driver transits vision away from the roadway to gain extra information, the greater the danger of losing full awareness of the traffic situation ahead. To evaluate the effect of an information system, a threshold for processing

information, such as the rule of 2-s off-road glance proposed by Klauer *et al.* (2006), should be considered. In this study, a large portion of renewal cycles that contained more than one non-forward glance were evidently over the safety threshold.

(4) The information load and manner of obtaining information have clear implications for traffic safety. Remember that the right message is required to change drivers' behavior. The possible side effects of distracting a driver's attention must be considered when designing an intelligent safety information system. Safety performance of an information system should be analyzed based on the dimensions of minimizing repetition, total duration, and duration of each glance when drivers seek information. Moreover, to decrease the negative impact of distraction, the content of information should be dividable and allow drivers to complete the perception in several repetitions. Moreover, since drivers usually transit vision to left side of vehicles after glancing at in-vehicle distraction, locating the in-vehicle information system near the left side of the dash board could help decrease the effort of transiting vision between these two focal points.

(5) Providing information to drivers, from the in-vehicle devices or the off-road sign, can be beneficial in aiding driving safety if it is delivered in a proper way. One major concern is the location of information platform, which should decrease drivers' uneasiness of transiting vision for information gathering and ensure the information being successfully perceived. Taking the Intersection Decision Support Sign (IDS) for instance (Creaser *et al.* 2007), drivers were found transiting vision from left to right when approaching intersection. Therefore, such an information system should be installed on the left side of the driving lane to ensure drivers' perception. With more detail clues of the timing that drivers transit vision to the left side, the distance between the IDS and the intersection can be further clarified for improving the performance.

(6) Meeting the drivers' desired PRT is an essential requirement to design a safe road. As stated in the Highway Safety Manual (AASHTO 2010), assessing the field conditions helps clarify the cause of crashes and possible countermeasures. From the perspective of human factors, the desired PRT must be derived based on the field conditions that drivers actually came across, including driving tasks, environmental conditions, and interactions with other vehicles. Therefore, from the perspective of attention allocation, the current 2.5-s PRT may not be robust enough as a universal rule that satisfies every situation.

(7) Although disturbing driving situations may occur rarely, a safe road should provide enough margin of PRT to ensure safe driving even under deteriorated conditions. Thus, based on the results derived using the 100-car event database, we conclude that a 3.0-s PRT may be better for designing safer roads because it satisfies most of the driving requirements. The desired PRT can also serve as a tool for proactive road safety audits, in design stage and after construction. Sites with insufficient PRT, based on drivers' natural driving behaviors, should be identified and reviewed.

6.3 Recommendations

Results obtained in this study may not be able to represent rules of safe driving from the perspective of attention allocation. Yet, it is still fruitful for improving safety and for further studies. In this section, the recommendations for future studies were addressed in this section.

(1) This study utilized only the event database in 100-car. Sample drivers in this dataset eventually experience crashes. It is clearly that they encounter some undesired situations and allocate attention in an improper way. Therefore, results obtained in this does not necessarily represent a typical driver's attention allocation pattern, nor a crash-free pattern. However, purpose of this study is to propose a method for analyzing attention allocation. Using 100-car data set enables the exploration of drivers' vision transition among focal points. It is still a fruitful research for future application.

(2) The comparisons driver attention allocation patterns among crash, near-crash and baseline data will be needed. This study focus only on the data of which drivers eventually experience crashes or near-crashes. Including more levels of crash severity can help identify the possible pattern that drivers help to observe and prevent crashes. Comparing baseline and crash data in similar conditions can explore the difference of drivers gathering information from multiple sources, and possibly help researchers move one step closer to the causation of crashes.

(3) Crash occurrences are not necessarily resulted from the subject drivers' fault. Meanwhile, driving safely does not mean that the subject drivers did not make mistakes in driving or in attention allocation. Distinguishing these types of possible bias can be an essential issue when researchers intended to identify a risky pattern and a safe pattern. Moreover, in addition to exploring the crash-proneness patterns of attention allocation from the dimensions of

environmental conditions and driving tasks, another way of approaching this issue is to identify the risky driving population, particularly the aging or novice drivers.

(4) Owing to the data limitation, this study was not able to include attributers related to the characteristics of other vehicles on-road. For instance, whether a vehicle is located closely in front of the subject vehicle may vary the duration of glancing at forward side. Moreover, the concept of vehicle drivers' domain cannot not be verified since the dataset did not provide the distance between drivers and the exact glanced point. Particularly, the boundary of reaction domain could be important clues for designing collision warning system. That is, once an obstacle crossing the reaction domain without triggering the changes of drivers' attention allocation pattern, a warning could be delivered before the obstacle getting close to the critical domain.

(5) In addition, approximately 90% of off-road glances were shorter than 2.0 s when adopting 2-glance renewal cycles, which accounted for 90.74% of the generated renewal cycles. Apparently, most of the sample drivers were alert. Their attention was efficiently allocated and not glancing away from the front for too long in deteriorated situations. By contrast, off-road glances in 3-glance renewal cycles were unsafe and significantly different from those in 2-glance cycles, particularly in certain deteriorated conditions. Even the 3-glance renewal cycles accounted for only 7.14% of the generated renewal cycles, such a small proportion of driving patterns might contribute to most of the crash occurrences. Therefore, for crash prevention, further study is warranted for defective attention allocation patterns.

(6) The data adopted in this study was collected in United States. Driving culture, environment, behavior and complexity are different between the US and Taiwan. To gain better insight of localized attention allocation patterns, it is crucial for government and university to develop programs of naturalistic driving for studies of driving behavior. Based on the localized data, concept proposed in this study could be a potential way for identifying the causations of crashes in Taiwan and possibly countermeasures for improving safety.

(7) The sequential glances made by different drivers are panel data. Relation between glances in a sequence and the heterogeneity among different driving conditions may cause the low fitness. In the future, mix logit could be considered for modeling the driver attention allocation.

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CURRICULUM VITAE

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❖ Education

Ph.D.	Institute of Traffic and Transportation National Chiao Tung University Taipei, Taiwan, Republic of China (2013) Advisor: Prof. Jinn-Tsai Wong Dissertation: A Novel Approach for Modeling Driver Attention Allocation
MS	Institute of Traffic and Transportation National Chiao Tung University Taipei, Taiwan, Republic of China (2007) Advisor: Prof. Jinn-Tsai Wong Thesis: Analysis of Two-vehicle Accident at Intersections
BS	Department of Transportation and Communication Management National Cheng Kung University Tainan, Taiwan, Republic of China (2005)

❖ Experience

Assistant Editor	Journal of Chinese Institute of Transportation (2008~2013)

❖ Awards and Fellowship

2011	NSC Dissertation Writing Fellowship
2009	6th CECI Engineering Science Fellowship
2008	5th CECI Engineering Science Fellowship
2007~2010	Ph.D. student Fellowship, ITT, NCTU
2007	NCTU Entrance Fellowship
2007	Honorary member, The Phi Tau Phi Scholastic Honor Society, R.O.C.
2005~2007	Master student Fellowship, ITT, NCTU

❖ Research Interest

Roadway safety, Driving behavior, Human factor

❖ Publication

Journal Papers

Wong, J.-T. and Huang, S.-H. (2013), "Attention Allocation Patterns in Naturalistic Driving," *Accident Analysis and Prevention*, Vol.58, pp. 140-147.

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即時安全資訊系統之建構、分析與應用 (2008-2011)，國科會。

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