UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE & MATHEMATICS

School of Civil, Maritime and Environmental Engineering and Science

Investigating driver's behaviour on approaching a junction at the end of green time

by

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ABSTRACT

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Doctor of Philosophy

INVESTIGATING DRIVER'S BEHAVIOUR ON APPROACHING A JUNCTION AT THE END OF GREEN TIME

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The DFT statistics (2010) revealed that red light running behaviour causes approximately 10 casualties per day in the UK, which is 3.4% higher than the previous year (2009). There has been uncertainty about the reasons for these violations; past literature has suggested that it could be due to insufficient amber duration or factors associated with the road environment, drivers and driving behaviour. Despite the underlying causes of these violations, red light running behaviour has been found to be more prevalent amongst younger drivers. A driving decision behaviour framework that captures continuously driver speed and acceleration performance, and their decisions was proposed. This research identifies contextual variables that can be used to predict driver's decisions at junctions during the amber onset (such as presence of pedestrians and heavy vehicles). In particular, drivers were more likely to cross the junction when there was a vehicle directly ahead of them. Studies of drivers were conducted in a STISIM driving simulator. A methodology was developed to categorise driver responses as safe or unsafe, and to systematically assess the performances of different interventions. The advanced signal intervention (with a set of advanced signals placed upstream on the same approach of the original traffic light displaying the impending signal status from the next second) was the most effective intervention to increase stopping decision (with maximum deceleration rate < $4.9m/s^2$) without elevating driver uncertainty at junctions. The flashing amber intervention (with a standalone flashing amber light adjacent to the original traffic light activated 1s prior to the amber onset) however seemed to encourage drivers to stop early. Drivers braked significantly earlier when compared to other interventions and the control condition (i.e. baseline scenario). The extended amber intervention (with 4s amber phase) has slightly reduced unsafe stopping behaviour when compared to the control condition, but the intervention also increased driver uncertainty. 70% among the stopping decisions were categorised as unsafe (with maximum deceleration rate > $4.9m/s^2$), and therefore may not be recommended. The positive effects of the interventions to reduce violations were negated at urban junctions, which suggest that red light countermeasures may not be required at urban junctions. The findings also revealed a slower braking response time to the interventions when the drivers were within close proximity to another vehicle, thus highlighting the contextual effects of their preceding vehicle as suggested from the observational study. Future research should be extended to assess the performance of the advanced signal intervention to different levels of traffic flow and turning manoeuvres. Larger sample of drivers should be employed for improved reliability.

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DECLARATION OF AUTHORSHIP

I, **Shiaw Yin Yong**,

declare that the thesis entitled **Investigating driver's behaviour on approaching a junction at the end of green time**

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidate for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
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1. Introduction

1.1. Problem description and motivation

Signalised junctions are locations of high accident concentration. On average, 10 casualties per day have been reported as the consequence of running red lights in the U.K. in 2010 (Dft, 2010); which is 3.4% higher than the previous year (Dft, 2009). Vehicle accidents are also more prevalent (i.e. 52%) amongst the vehicles going ahead at junctions than other vehicle manoeuvre (Dft, 2010). Past literature (Gazis, et. al., 1960) has emphasised that red light running behaviour is related to the formation of a problem zone caused by improper settings of the amber signal duration, whilst more recent research (e.g. Urbanik and Koonce, 2007) has suggested that the violations are mainly caused by the formation of an option zone, which is associated with the road environment, drivers and driver behaviour. These two zones have been explained on different concepts. Problem zone, as defined in this thesis, is "a range within the signal approach with inappropriate traffic engineering measures or traffic environment that make both stopping and crossing actions more difficult". If the driver chooses to accelerate to cross the junction, they may be more likely to run a red light; alternatively the driver may have to brake abruptly to stop. Both stopping and crossing decisions within a problem zone demonstrate unsafe responses to the amber signal. Option zone however, is the range within the signal approach where both safe crossing and safe stopping are possible (e.g. Mahalel and Prashker, 1987). The latter has been shown to increase the occurrence rates of rear-end accidents, due to the conflicting decisions between two consecutive drivers approaching the junction at the amber onset.

A number of interventions have been proposed and implemented as the solution to the problem and option zones; however, variations in effects seem to be inconsistent between study sites (e.g. Chin, 1989; Liu, et. al., 2007). Some interventions seem to have a lasting period, after which the positive effects would begin to dissipate (e.g. Retting and Greene, 1997; Lum and Halim, 2006); some are even reported as deleterious over time (e.g. Mahalel, et. al., 1985, Köll, et. al., 2004). Many of the interventions which have been reported as successful in reducing red light violations actually increases rear-end accidents (e.g. Hakkert and Mahalel, 1978; Mahalel and Zaidel, 1985; Retting, et. al., 2003). An elimination of problem zone seems to extend an option zone; therefore, drivers are more likely to experience higher uncertainty on their decisions (e.g. Rakha, et. al., 2007). An intervention to effectively reduce the road hazards (i.e. red light violations and rear-end accidents) caused by the amber and red signals without elevating driver uncertainty is therefore required. An index is also needed to systematically evaluate between different levels of driver uncertainty.

There are certain driving conditions that have a tendency to encourage drivers to make a crossing decision during the signal change interval. For example, when they are closer to the junction or when they are travelling at higher speed. Less predictable behaviour however can happen in an option zone where driver decision is not only dependent on their physical variables (i.e. speed, distance from the junction) but also on their driving contexts. As an example, drivers may be more cognizant of vehicles immediately ahead of them and proceed through the intersection at red onset under the influence of a non-stopping preceding vehicle (Bonneson, et. al., 2002; Elmitiny, et. al., 2010). Identification of the contextual issues in the driving environment that are associated with higher crossing or stopping propensities may therefore enable a better understanding of driver behaviour in problem and option zones, and the causes of red light running. A normative approach to study the impact of these contextual issues to driver behaviour and responses is therefore needed from the study site.

Driver decision in response to the amber onset is not instantaneous, but a complex reaction to the driving environment. When the driver perceives the signal change, they then conceive an action plan and perform it over length of time. The literature has suggested that a delay to the amber and red signal can be avoided or at least be reduced if they are alert of their driving environment and surroundings (e.g. Demirarslan, et. al., 1998; Akçelik, 2008). A systematic way to study driver decision in response to the amber onset is therefore to develop a driver decision behaviour model that describes their decision making processes with respect to their vehicle movement (i.e. physical variables) in different driving contexts (i.e. contextual variables). For example, driver speed and acceleration behaviours associated with the frequency of violations may provide better indication of the safety level at a junction than the frequency alone. As there has been no standard (and reliable) testing protocol to assess the effectiveness of different traffic interventions to reduce driver unsafe decisions in response to the amber onset, a methodology to measure and assess their behaviours in comparable metrics is needed.

Methods proposed for improving red light compliance at junctions need to be calibrated with different traffic situations and repeatedly tested for their effectiveness. A feasible but inexpensive method to evaluate the effectiveness of these interventions is therefore to perform laboratory-based experiments. In contrast to the field experiments which are limited by the inability to control the road conditions, the STISIM driving simulator (research tool) enables experiments to be set up in controlled environment, including the generation of potentially risky situations such as a problem zone. The impact of the strategies of different interventions can be carefully modelled through the response of individual drivers to the driving simulator controls.

1.2. Research objectives

The main objective of this research is to improve the modelling of driving decision behaviour during the amber onset and in particular to seek for potential interventions that are more likely to reduce unsafe decisions at junctions. This research seeks to

- identify potential factors which contribute to the reduced safety at junctions (i.e. red light violation, abrupt braking, early stopping);
- develop more in-depth understanding of driver decision behaviour to different driving environment/contexts;
- recommend appropriate interventions to improve driver decisions at junctions.

1.3. Research aims

This thesis presents an investigation into driver decision behaviour approaching signalised junctions at the end of green phase. For this purpose, data are gathered from three sources: a literature review, an observational study and a set of laboratory-based experiments. The literature review was undertaken with the aim of identifying the contributory factors to reduced driver safety at junctions (such as red light violation, abrupt braking, and early stopping) and understanding the characteristics of the problem and option zones. An observational study was conducted to study the likely variations in driver's stopping propensity under different conditions and to identify the impact of physical variables (speed, distance, and turning movement) and contextual variables (pedestrians, road users and distance respect to other road users) to driver's decision. A laboratory-based experiment comprises a pilot study and a series of four main driving tests was conducted using the driving simulator. The pilot study aimed to validate the use of the STISIM driving simulator to replicate a problem zone; and to set the focus driver group (with potentially unsafe behaviours) among a diverse sample of drivers. The four driving tests were conducted to assess the performances of the three recommended interventions (i.e. extended amber, flashing amber and advanced signal interventions) and the baseline scenario (without intervention). An evaluation of the interventions was performed to identify the most effective intervention to reduce potentially unsafe decisions at junctions, and therefore may provide an insight into future development of safety interventions at junctions.

1.4. Thesis outline

In Chapter 2, a literature review of the problem and option zones, including their contributory factors and their effects is presented. Chapter 3 reports on an observational study to identify the effects of the physical and contextual variables to predict driver decision at signalised junctions by describing the structure of the logistic regression model; data analysis and its results are also presented in this chapter. A validation of driving simulator study to model a problem zone and to identify the focus driver group is presented in Chapter 4. The design and setup of the main driving simulator study, and the methodology used to extract the required information from the simulator output (raw data) are presented in Chapter 5. Evaluation results of the extended amber intervention are presented in Chapter 6. Evaluation results of the flashing amber intervention are presented in Chapter 7. Evaluation results of the advanced signal intervention are presented in Chapter 8. Evaluation between different interventions and the results are presented in Chapter 9. Finally, conclusion and directions for future research are presented in Chapter 10.

1.5. Research contributions

This thesis contributes to the state-of-the-art driving decision behaviour modelling in the following aspects:

- A framework for modelling driving decision behaviour to the amber onset is proposed (as shown in Figure 1.1). Drivers are not limited to make instantaneous decisions based on their position at the amber onset, but also on anticipated conditions. This behaviour framework captures driver's speed and acceleration performance from the amber onset until their final decision.

- A logistic regression model of driver decision approaching a signalised junction is developed, which considers other road users, turning manoeuvre, and the effect of close following vehicles. The model identifies the significant impact of contextual variables to improved accuracy in predicting driver decision at signalised junction.

- A methodology to categorise driver responses as safe or unsafe is proposed, based on multiple driving performance parameters. Identical parameters are used for assessment between individual drivers. Driver's decision, speed and acceleration behaviour, and their uncertainty level as a whole enable prediction of driving skills in laboratory-based experiments.

- An evaluation of the effectiveness of different interventions to reduce unsafe decisions (and increase safer decisions) is assessed using the methodology. The most effective intervention is identified if there is greatest improvement in safe decisions and no elevation of driver uncertainty at signalised junctions. Simulation results also assert the important effect of the vehicles directly ahead of the vehicle (i.e. effect of contextual variables).

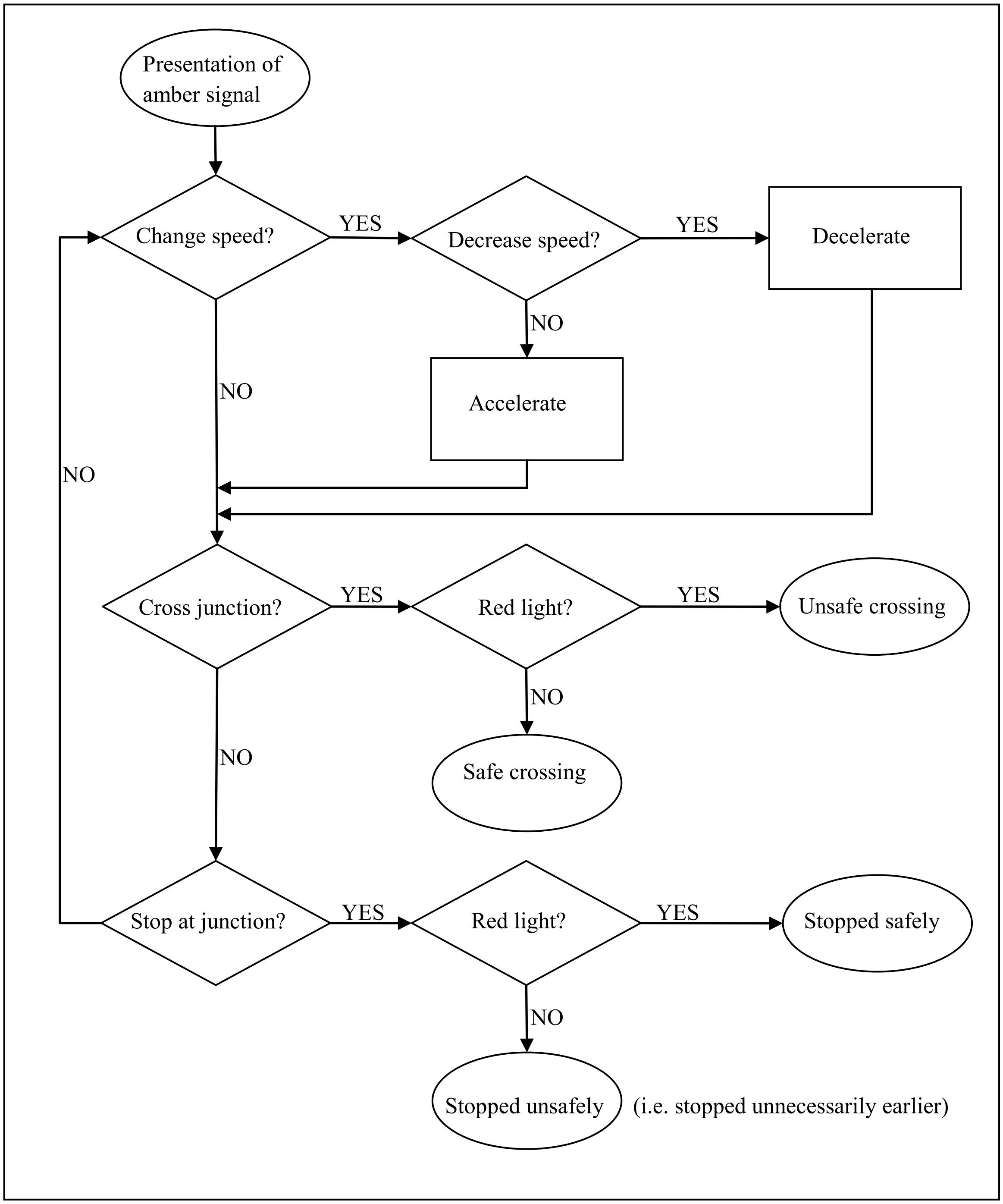


Figure 1.1: Conceptual framework of driver decision behaviour model

2. Literature review

This chapter reviews past research on the problem zone and option zone. Problems with the two zones which occur during the onset of amber light are discussed with varying concepts. The effects of the contributory factors to driver decision are also discussed. This chapter concludes with the suggestion for adaptation of engineering interventions to improve driver's decision making at signalised junctions.

2.1. The problem with traffic signals

Despite the implementation of traffic signals to improve traffic efficiency and safety; particularly at junctions by separating conflicting traffic movements in time and space, junctions with traffic signal lights continue to be one of the main accident points (Hanna, et. al., 1976; Hakkert and Mahalel, 1978; Short, et. al., 1982; Retting, et. al., 1995). Red light running crashes are the most frequent type of accident (Retting, et. al., 1995); which occurs when drivers cross the stop line after the red light has appeared (Baguley, 1988). Among these accidents, right angle collisions have received considerable attention because of the severity and casualties involved (Mahalel and Prashker, 1987; Datta, et. al., 2000). On average, 10 casualties per day had been reported as the consequence of red light violations in the U.K. in 2010 (Dft, 2010). This figure has increased by 3.4% since 2009 (Dft, 2009). Red light violation had also been reported to have killed 676 people and injured an estimated 113000 people in the U.S. in 2009 (IIFHS, 2011).

There is a considerable body of literature which shows positive effects of some red light countermeasures in reducing right angle collisions; however, they also increase rear end accidents (Hakkert and Mahalel, 1978; Mahalel and Zaidel, 1985; Retting, et. al., 2003). Both right angle and rear end accidents are common consequences of the problem zone and option zone (Mahalel and Zaidel, 1985; Mahalel and Prashker, 1987; Baguley, 1988; Retting and Greene, 1997; Datta, et. al., 2000). The purpose of this chapter is to review the literature on the relationship between the underlying factors of the two zones, and their contributions to driver's decisions under different circumstances.

There are researches which suggest that red running is affected by the duration of the change interval (Zador, et. al., 1984; Retting and Greene, 1997; Datta, et. al., 2000; Bonneson and Zimmerman, 2004), driver's behaviour (Baguley, 1988; Chang, et. al., 1984; Chang, et. al., 1985; Retting, et. al., 1995; Retting, et. al., 1999) and junction factors (Mohamedshah, et. al., 2000). The interactions of these causes and factors were also used to describe intentional (Baguley, 1988; Retting, et. al., 1998) and unintentional red light running (Retting and Williams, 1996; Bonneson, et. al., 2002; Bonneson and Zimmerman, 2004). Intentional red running is associated with aggressive driving behaviour (Olson and Rothery, 1961; Williams, 1977; Van der Horst and Wilmink, 1986; Retting, et. al., 1999) and the latter is associated with driver's decision in a problem zone which has been defined in literature as the 'dilemma zone' (Gazis, et. al, 1960; Zegeer and Deen, 1978; Sheffi and Mahmassani, 1981).

2.2. Definition of a problem zone

The problem zone is defined in this thesis as a range within the signal approach with inappropriate traffic engineering measures or traffic environment that make both stopping and crossing actions more difficult. Figure 2.1 illustrates the problem zone a driver faces when approaching a signalised junction at the end of the green time. d_i (i = 0, 1, 2) denotes the distance from the stop line. The driver is assumed to travel with constant speed on the approach; when confronted with an amber signal, the driver will be able to stop safely at or before the stop line d_0 if their vehicle doesn't go beyond d_1. Alternatively, the driver travelling beyond d_2 will be able to clear the junction before the end of the amber phase. A problem zone exists when the driver is not in a favourable situation of performing either action of stopping or crossing (Gazis, et. al., 1960; Tarko, et. al., 2006) without adjusting their speed, i.e. when the driver travels beyond d_1 but still remains behind d_2. This 'problem zone', as illustrated in Figure 2.1 between d_1 and d_2, is described as the zone within which *'a driver may neither be able to stop safely after the onset of amber indication nor be able to clear a junction before the end of the amber duration'*. (Gazis, et. al., 1960, pp. 116; Sheffi and Mahmassani, 1981, pp. 50-51; Zador, et. al., 1985, pp. 36).

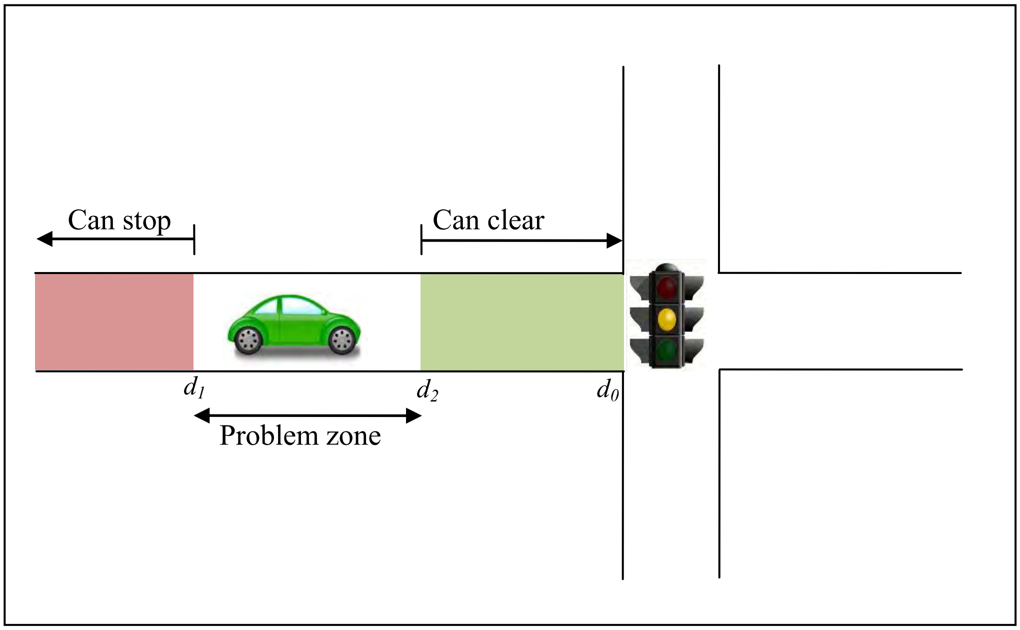


Figure 2.1: Illustration of problem zone in terms of distance to stop line

The distances (d_1-d_0) and (d_2-d_0) illustrated in Figure 2.1 above were defined by Gazis, et. al. (1960, pp. 114-116) as 'x_c' and 'x_0' respectively as '*the critical distance to stop safely*' and '*the maximum distance to cross without acceleration*'. Critical distance x_c is an important quantity widely used in the literature (Gazis, et. al., 1960; May, 1968; Mahalel and Prashker, 1987) to describe the relationships between problem zone and the distance to the stop line. Previous literature revealed that problem zone exists when $x_0 < x_c$, a problem caused by insufficient amber light duration (Gazis, et. al., 1960; Liu, et. al., 1996).

2.2.1. Problem zone as a problem of amber duration?

The problem zone was described as a problem of improper setting of amber time, particularly when the amber duration is set too short (Gazis, et. al., 1960). Apart from its duration, the ambiguous meaning of the amber light has also been raised as a problem (Bissell and Warren, 1981). Assuming full compliance of driver's action to stop on red and cross on green for safety improvements, the effect is negated by the ambiguity of the amber light. In contrast to the unambiguous meaning of the green and red signals, drivers may perform either action of stopping or going on perceiving an amber phase signal, depending on an individual driver's understanding of the meaning of the amber phase (Zegeer and Deen, 1978; Bissell and Warren, 1981; Mahalel and Prashker, 1987; Köll, et. al., 2004; Palat and Delhomme, 2012). A driver approaching the junction during the amber phase may decide to decelerate and stop if they interpret the amber phase as an indication of preparing to stop; or the driver may accelerate to rapidly pass through the junction otherwise (Zegeer and Deen, 1978; Van der Horst, 1988; Urbanik and Koonce, 2007).

2.2.2. Identification of option zone

Extending the amber signal duration has been effective in reducing the chances of drivers to be within the problem zone (Stimpson, et. al., 1980; Chang, et. al., 1985; Wortman and Fox, 1986; Bonneson and Zimmerman, 2004), trade-off was however found in the substantial increase in the chances of drivers facing an option zone (May, 1968; ITE, 1974a). An option zone or indecision zone (Urbanik and Koonce, 2007) is a situation when both stopping and crossing manoeuvres can be executed (Mahalel and Prashker, 1987) with a probability of stopping between 10 and 90 percent (ITE, 1974b). The option zone, when measured in terms of the distance upstream of the stop line, is estimated to lie within the distance where 10% - 90% of vehicles stop. A longer amber duration in general provides a larger option zone for the driver (May, 1968; Prashker and Mahalel, 1989) and the safety benefits were not shown on all study sites (May, 1968; Jourdain, 1986; Van der Horst and Wilmink, 1986). In particular, the number of rear end accidents at urban junctions is significantly higher with longer amber duration (May, 1968; Hakkert and Mahalel, 1978; Mahalel and Zaidel, 1985). The option zone *"exists at the onset of every amber phase indication, regardless of the amber interval duration"* (Urbanik and Koonce, 2007, pp. 4; Liu and Özgüner, 2007, pp. 642).

Figure 2.2 illustrates an option zone a driver faces when approaching a signalised junction at the end of green time. An option zone exists when the driver has a choice of stopping safely or crossing the junction before the end of the amber signal (May, 1968). This happens when $x_0 > x_c$ (c.f. section 2.2). May (1968) replaced 'x_0' and 'x_c' by 'X_C' as the clearing distance and 'X_S' as the stopping distance respectively in his study.

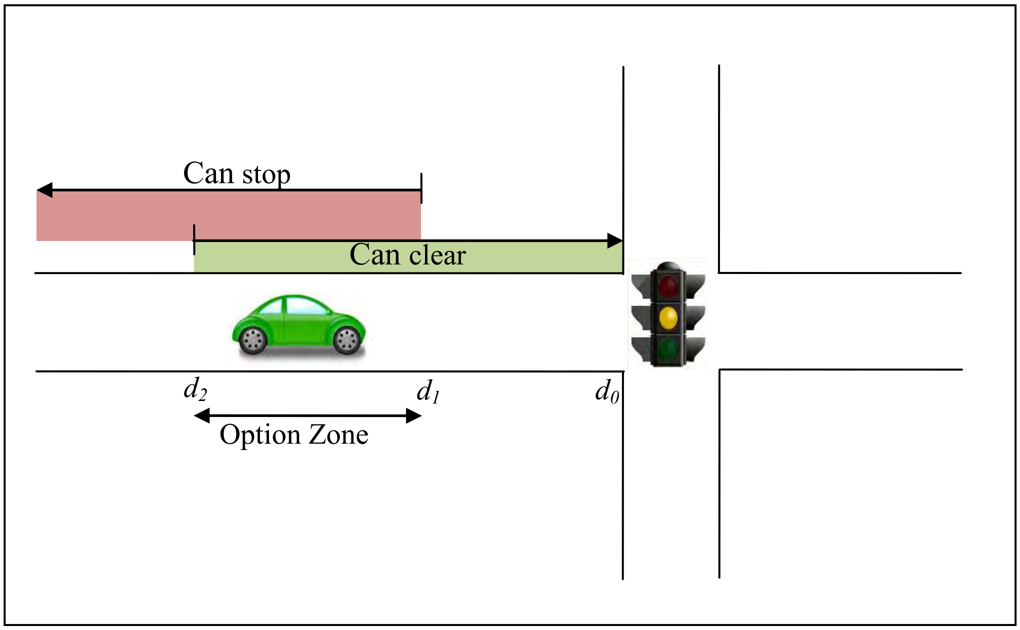


Figure 2.2: Illustration of option zone in terms of distance to stop line

Figure 2.3 illustrates the variation of the size of problem zone and option zone a driver might encounter when travelling in different approach speeds of 50km/hr and 70km/hr respectively. Driver's reaction time is assumed to be 1 second (Chang, et. al., 1985; ITE, 1989) with a deceleration rate of 3.7m/s^2 (Olson and Rothery, 1972; Maxwell and Wood, 2006). As illustrated in Figure 2.3 below, vehicles with approach speed of 70km/hr might encounter a problem zone of 12m if the amber duration was set at 3 seconds or an option zone of 7m with 4-seconds amber duration. The range of option zone for vehicles with approach speed of 50km/hr was shown to enlarge from 2m to 16m as the amber duration increases from 3 to 4 seconds; this illustrates an example of the amber duration being set too long and hence encourages the drivers to continue moving on the amber onset (May, 1968; Stimpson, et. al., 1980; Jourdain, 1986). The calculation of the minimum stopping distances for vehicles with approach speed of 50km/hr (i.e. 13.9m/s) and 70km/hr (i.e. 19.4m/s) is presented as follows:

Assuming a maximum deceleration rate of 3.7m/s^2 (Olson and Rothery, 1972; Maxwell and Wood, 2006), minimum stopping distance s is calculated as $s = \frac{v^2}{2a} = \frac{v^2}{7.4}$. Therefore minimum stopping distance for vehicles with approach speed of 50km/hr (i.e. 13.9m/s) and 70km/hr (i.e. 19.4m/s) are approximated as 26m and 51m respectively to the nearest metre.

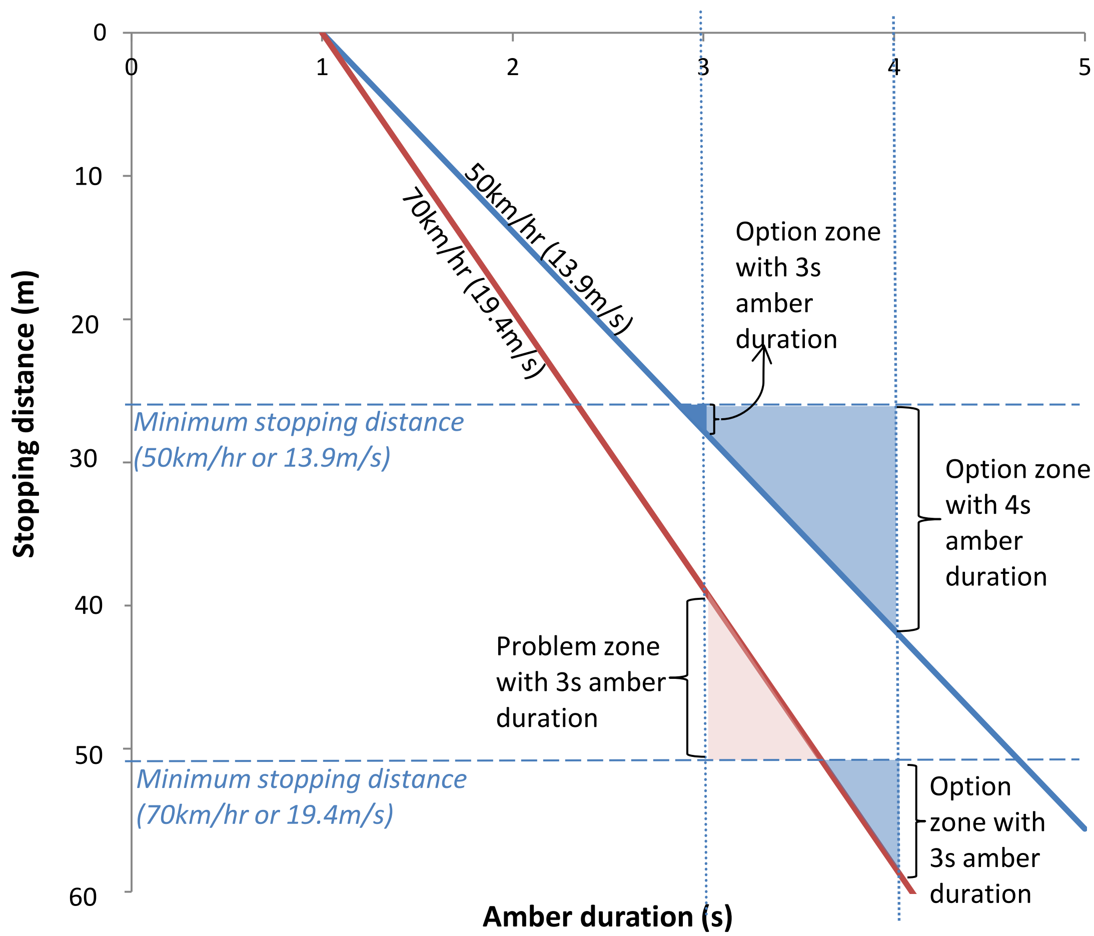


Figure 2.3: Variation of the size of problem zone and option zone for different values of the approach speed when allocated with two different amber durations. (The deceleration rate is assumed to be 3.7m/s^2)

2.2.3. Problem zone as an aggregated problem of amber duration and driver behaviour

According to the Highway Code (2007), 'amber' means 'stop' at the stop line. *"Drivers are supposed to go on only if the amber appears after the drivers have crossed the stop line or the drivers are so close to the stop line that to pull up might cause an accident"* (c.f. The Highway Code, 2007). The meaning of 'amber' is relatively common around the world, although the definition for 'amber' and its duration may vary among different countries. A summary of the definitions for 'amber' and their durations are shown in Table 2.1.

Table 2.1: Definition for 'amber' and its duration in different countries

Country	**Definition for the Amber light**	**Duration of the Amber light**
Australia	Stop if driver can safely do so.	3 to 5s depending on speed limit
Austria	Stop, unless the driver cannot do so safely given their current speed.	3s or 4s depending on cities and speed limit (eg. 3s in Salzburg, 4s in Linz)
Belgium	The stop line should not be crossed unless when the light changes the driver is so close to the line or to the signal that they could not stop with sufficient safety.	3s
Bahrain	Stop, or slow down if car cannot be stopped safely.	3s
Brunei	Prepare to stop.	3s
Canada	Caution, stop if possible.	3 to 5s depending on speed limit and width of junctions
China	Stop behind the stop line.	3s or 4s depending on cities (eg. 3s in Hong Kong, 4s in Beijing)
Cyprus	Stop, unless it is unsafe to do so.	3s
Czech Republic	Attention to stop. However, when the vehicle is very close while the amber light is triggered and the driver cannot stop the vehicle safely, they may continue to drive.	3s
Denmark	Slow down and prepare to stop.	4s
Estonia	Prohibits going ahead; going ahead from the stop line is permitted only if halting is impossible, without endangering other road users. If the amber light illuminates at the moment when the driver is on the junction, they must continue to drive.	3s
Finland	Stop.	3s

France	Stop, unless the driver is not able to stop safely.	3s
Germany	Prepare to stop.	3 to 5s depending on cities and speed limit
Greece	Stop, unless driver has already passed the stop line.	3s
Hungary	Drivers must stop if it can be done safely.	3s
India	Be alert. Drivers caught in the amber signal must not press the accelerator in panic but do continue with care.	3s
Indonesia	Caution.	3s
Ireland	Stop, unless the driver has crossed the stop line or the driver is too close to the stop line to stop safely.	3s
Italy	Prepare to stop short of the junction, if it is safe to do so.	3s
Japan	Vehicles must not move further than the stopping point. However, if a vehicle is rapidly approaching the stopping point when the signal changes to amber, and cannot stop safety, the driver may continue to proceed.	4 to 5s
Korea	Drivers must come to a complete stop before reaching the stop line. If the driver is already in the junction, they must proceed as quickly as possible when safe.	4s
Kuwait	Caution.	4s
Latvia	Stop.	3s
Luxembourg	Stop.	3s
Macedonia	Stop if possible.	3s
Malaysia	Ready to stop.	3s
Malta	Prohibited to cross.	3s
New Zealand	Lights are about to turn red. Stop if driver can do so safely.	4s and above.
Netherlands	Stop; drivers who are so close to the traffic lights that they cannot reasonably be expected to stop safely should proceed.	3s or 4s depending on regions and speed limit.
Norway	Caution.	3s
Philippines	The vehicle should be stopped safely if it's still within a considerable distance from the junction. Otherwise, the driver must proceed to the intersection with caution.	3s
Poland	Driver is not allowed to pass the traffic light unless a sudden braking would cause some danger in road traffic.	3s
Portugal	Stop, except if the car is too close to the traffic light and cannot stop safely.	3s
Romania	Stop.	3s
Serbia	Stop.	3s

Singapore	Stop, unless driver is too close to the *lights* to stop safely.	3s
Slovenia	Stop, unless driver cannot safely stop because at the moment the light turns on the vehicle is too close to the traffic light.	3s
South Africa	Slow down and stop.	3s
Spain	Stop, except if the car is too close to the traffic light and cannot stop safely.	3s
Sweden	The vehicle must not pass the traffic light or the stop line unless it is much forward when the signal changes from green to amber and unless it cannot stop safely, without any danger.	4s
Switzerland	Stop if possible	3s
Taiwan	Warning.	3s
Thailand	The driver shall prepare to stop the vehicle behind the stop line. If the driver has passed the stop line when the traffic light turns amber, they may go through.	3 to 5s, depending on cities.
Turkey	Slow down to stop.	3s
UAE	Stop.	3s
UK	Stop at the stop line. Driver may go on only if the amber appears after the driver has crossed the stop line or the driver is so close to the stop line that to pull up might cause an accident.	3s
US	Caution, stop if possible.	3 to 6s depending on regions and speed limit.
Viet Nam	Stop behind the stop line, except for road users who have passed the stop line and may keep moving.	3s

Driver's reaction to the onset of amber light was extensively researched after Gazis, et. al. (1960) raised a problem of insufficient amber duration at junctions. Percentages of drivers stopping after the amber onset were found inconsistent dependent on their approach speed and distance from the junction (May, 1968; Olson and Rothery, 1972; Williams, 1977). This suggests that the percentage of drivers stopping after the amber onset does not depend on the amber duration (Stimpson, et. al., 1980; Chang, et. al., 1985) and the ability of a driver to stop is based on some deterministic normative values (May, 1968; Mahalel and Prashker, 1987). Hence the use of a constant amber duration has been suggested in the past studies (Olson and Rothery, 1972; Chang, et. al., 1985; Jourdain, 1986) with different proposed time based on their statistics of crossing and stopping vehicles. A constant amber duration of three seconds is used in the UK, with the evidence of being appropriate for most drivers to stop safely (Mahalel and Zaidel, 1985; Chang, et. al., 1985; Jourdain, 1986). Figure 2.4 illustrates 80% and 85% of drivers in different speed ranges stopped when they were three seconds to reach the stop line.

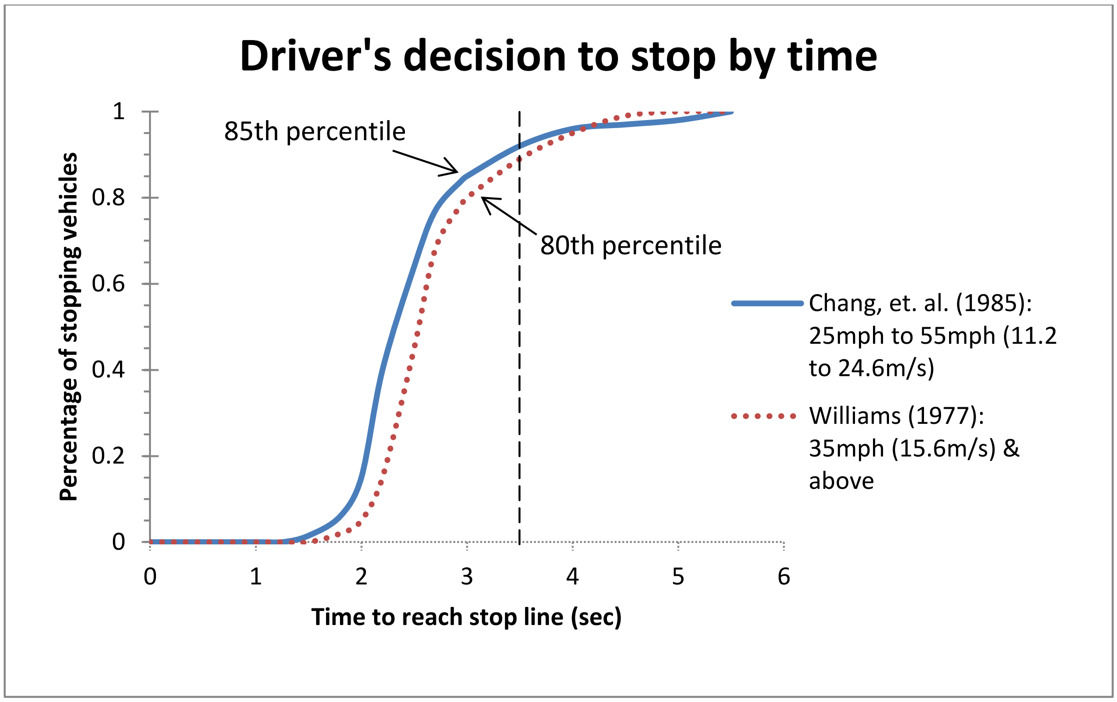


Figure 2.4: Driver's decision to stop by time
(adapted from Williams, 1977, pp. 77; Chang, et. al, 1985, pp. 27)

The frequency of stopping and crossing vehicles and their violations of traffic lights has been the most common measure to indicate the safety level they face with the problem zone and the option zone. Driver's decision in response to the amber light has been studied using different methods: analytical model, statistical model, experimental method, simple comparison tests and before-and-after comparison tests are some research methods used in practice. Some examples of these studies are tabulated in Table 2.2. Given the non-identical samples, research methods, study sites and traffic conditions, the significant effect of each contributory factor to driver's decision may differ. Some factors were also found to overlap between different studies.

Table 2.2: Some studies to evaluate the factors affecting driver decision in response to amber signal

Author(s)	Country	Study design	Traffic control system	Measures of effectiveness	Factors
Gazis, et. al. (1960)	US	Analytical model	Fixed-time	Frequency of red light violation	-Amber duration
Sheffi and Mahmassani (1981)	US			Frequency of stopping vehicles	-Speed
May (1968)	US	Before-after comparison	Fixed-time	Frequency of stopping and crossing vehicles	-Amber duration -Demographic areas -Driver Awareness
Prashker and Mahalel (1989)	Israel				-Speed -Distance -Other vehicles
Hulscher (1984)	Australia			Frequency of red light violation	-Driver Behaviour
Bonneson and Zimmerman (2004)	US				-Amber duration -Driver attention -Junction sight distance
Zegeer and Deen (1978)	US		Actuated signal	Frequency of red light violation, abrupt stopping, acceleration through amber	-Traffic volumes -Grade of approach
Van der Horst and Wilmink (1986)	Netherlands			Frequency of red light violation	-Amber duration -Traffic control System
Stimpson, et. al. (1980)	US	Experimental study	Fixed-time	Frequency of stopping and crossing vehicles	-Amber duration -Traffic condition -Road condition
Rakha, et. al. (2007)	US				-Distance -Age -Driver uncertainty
Caird, et. al. (2007)	Canada				-Age -Deceleration rate -Compliance to Signals
Elmitiny, et. al.	US	Experimental	Fixed-time	Frequency of	-Distance

(2010)		study		stopping and crossing vehicles	-Speed -Amber duration
Chang, et. al. (1985)	US	Statistical model	Fixed-time	Frequency of stopping and crossing vehicles	-Speed -Distance -Grade of approach -Junction width -Driver's response time -Deceleration rate
Kikuchi, et. al. (1993)	US				-Driver Aggressiveness
Maxwell and Wood (2006)	UK			Frequency of red light violation	-Speed -Vehicle type -Deceleration rate
Liu (2007)	Taiwan	Statistical model	Fixed-time	Speed limit violation	-Speed -Demographic areas -Traffic conditions -Vehicle type -Gender
Gates, et. al. (2007)	US		Fixed-time and actuated signal	Frequency of stopping and crossing vehicles	-Amber duration -Travel time -Approach speed -Vehicle type -Other vehicles -Other road users
Mohamedshah, et. al. (2000)	US	Statistical model and comparison tests	Fixed-time and actuated signal	Frequency of red light crashes	-Traffic volume -Traffic control system -Junction width
Koh and Wong (2007)	Singapore	Comparison tests	Fixed-time	Frequency of stopping and crossing vehicles	-Acceleration rate -Deceleration rate

2.2.4. Factorisation of problem zone and option zone problem

Driver decisions to stop or cross are affected by approach speed, distance from the junction at the amber onset and the time to reach the stop line (Sheffi and Mahmassani, 1981; Chang, et. al., 1984). Differences between driver's response times to apply the brake were also revealed at different road geometrics (May, 1968; Chang, et. al., 1985), traffic conditions (Zegeer and Deen, 1978; Stimpson, et. al., 1980; Mohamedshah, et. al., 2000) and signal control type (Van der Horst and Wilmink, 1986; Van der Horst, 1988; Mohamedshah, et. al., 2000). All these factors which affect driver decisions and performance were known to have a direct relationship with capacity (Niittymäki and Pursula, 1997; Bester and Meyers, 2007; Akçelik, 2008). Saturation flow indicates the potential capacity of a junction when operating under ideal conditions (ITE, 1982; Turner and Harahap, 1993; Long, 2007), therefore all factors affecting the saturation level would respectively affect the way a driver responds to the respective signal times. For instance, drivers accepting smaller gap would allow higher saturation flow rate, and inversely. Figure 2.5 below illustrates the main factors and elements that affect the saturation flow of a junction (ITE, 1974a, 1974b; Zegeer, 1986; Stokes, 1989; McCoy and Heimann, 1990; Hossain, 2001; Minh and Sano, 2003; Long, 2005; Hounsell, 1989). The remainder of the chapter will consider each of these factors and their effects to driver's decision at the onset of the amber light.

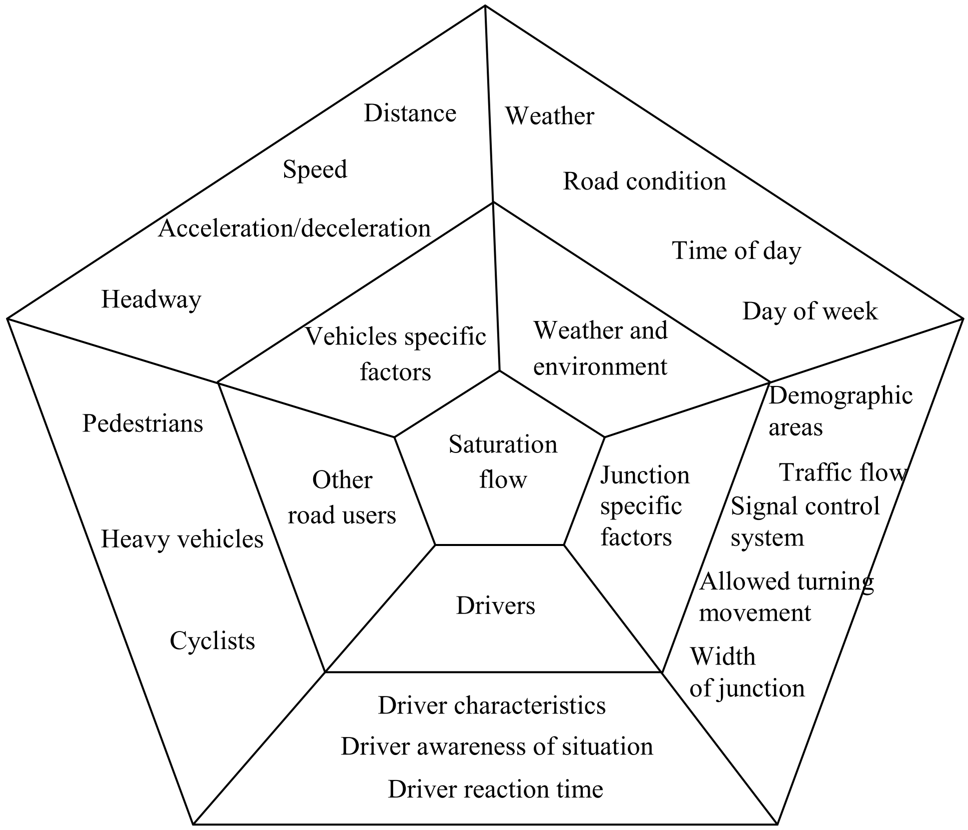


Figure 2.5: Factors and elements affecting saturation flow
(adapted from Stokes, 1989, pp. 35)

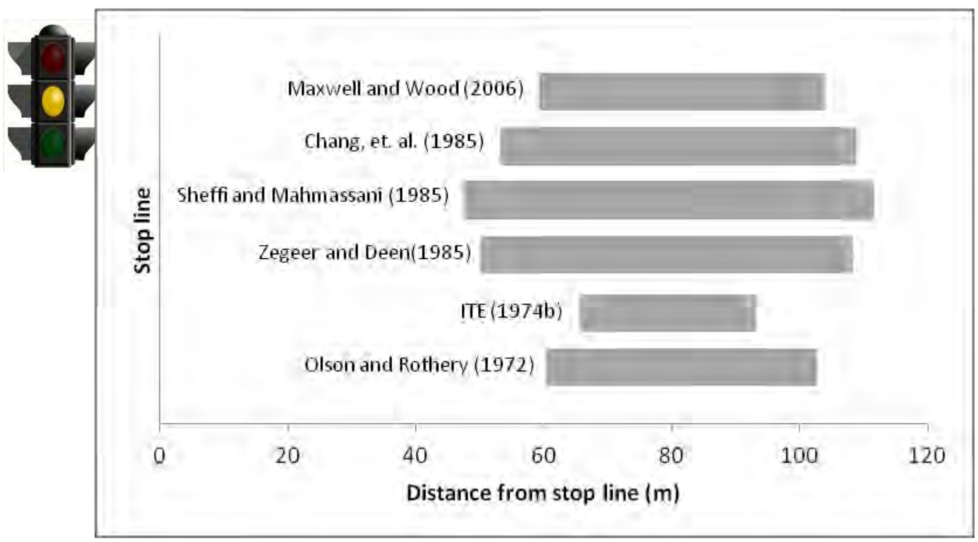
The most common measure of driver's performance is captured at their position on the road relative to the junction and other road users on transition of green to red signal (Gazis, et. al., 1960; Zegeer and Deen, 1978; Van der Horst and Wilmink, 1986; Prashker and Mahalel, 1989; Maxwell and Wood, 2006; Elmitiny, et. al., 2010). Previous studies have shown that driver's possibility to cross a junction without violating any traffic rules is dependent on their distance from the stop line and their travelling speed (Gazis, et. al., 1960; May, 1968; Van der Horst, 1988; Elmitiny, et. al., 2010); and their decision is an interaction between observation and adjusting their position on the road (Van der Horst and Wilmink, 1986; Koh and Wong, 2007). The magnitude of driver's decision problem requires better understanding of the following vehicle specific factors either individually or as a whole.

2.2.4.1(i). Distance

Distance has been used as an important quantity to explain the problem zone and option zone (see section 2.2 and 2.2.2.). Previous studies reported that driver decision is dominated by the distance from the junction at the amber onset (Mahalel and Prashker, 1987; Prashker and Mahalel, 1989; Rakha, et. al., 2007); the probability of stopping decreases as distance decreases (Williams, 1977; Chang, et. al., 1985). Driver's reaction times to brake were shown to increase as the distance to the junction increases and decrease as the distance to the junction decreases (Chang, et. al., 1985). In terms of engineering measures, no drivers were observed to stop at less than 25m from the stop line at the amber onset with approach speed between 30 and 60mph (Maxwell and Wood, 2006), i.e. between 13.4 and 26.8m/s. There is, however, a trend showing that when approach speeds are high, the distance at which drivers are willing to stop also increases (Prashker and Mahalel, 1989; Maxwell and Wood, 2006).

Based on the propensity of driver's decision to stop in response to the amber light onset, the boundaries and sizes of the option zones estimated in terms of their distance from the stop line were dynamic (Olson and Rothery, 1972; ITE 1974b; Williams, 1977; Chang, et. al., 1985; Sheffi and Mahmassani, 1985; Zegeer and Deen, 1985; Maxwell and Wood, 2006). As shown in Figure 2.6(a) and 2.6(b), differences in boundaries and sizes of option zones were found for the same approach speed between different studies. It was also shown that the boundaries of the option zones were located further upstream of the stop line for higher approach speed (Olson and Rothery, 1972; ITE 1974b; Chang, et. al., 1985; Maxwell and Wood, 2006).

(a) 30mph (13.4m/s)



(b) 50mph (22.4m/s)

Figure 2.6: Boundaries of the option zone based on the propensity of driver's decision to stop in response to the amber light at approach speed of (a) 30mph (13.4m/s) and (b) 50mph (22.4m/s)

Higher approach speed has been shown to decrease the critical distance x_c (x_c is the critical distance to stop safely, as in section 2.2) rapidly in the problem zone and the option zone (c.f. section 2.2.2). As speed decreases (Gazis, et. al., 1960; May, 1968) however, no strong linear relationship was found between the approach speed and the amber interval (Lin, et. al., 1987); driver's response time to brake were observed to increase as speed decreases

(Chang, et. al., 1985), revealing the enlarged option zone at lower approach speed (Chang, et. al., 1985; Prashker and Mahalel, 1989). On the other hand, where the mean speed of all crossing vehicles was higher (Olson and Rothery, 1972; Bonneson, et. al., 2002) there would be a higher chance of problem zone at higher speed (Baguley, 1988; Bonneson, et. al., 2002). No significant result on driver's decision in response to amber light could be drawn on measuring speed alone; however, a trend of deliberate red light running has been observed beyond the problem zone (Baguley, 1988; Allos and Al-Hadithi, 1992; Retting and Greene, 1997).

2.2.4.1(iii). Acceleration and deceleration

As the critical distance x_c decreases when the approach speed decreases (Gazis, et. al., 1960; May, 1968), the problem zone can be avoided theoretically if the driver travels lower than the speed limit and accelerates to the speed limit or higher at the amber onset to proceed through the junction (Gazis, et. al., 1960; Liu, et. al., 1996). The maximum possible acceleration in this case is dependent on the approach speed; acceleration capability reduces with increasing speed (Gazis, et. al., 1960; Long, 2000).

Driver selected deceleration rate is affected by the distance from the junction at the amber onset, the time available to reach the stop line, driver response time and particularly the approach speed (Chang, et. al., 1985, Wang, et. al., 2005; Gates, et. al., 2007). Stopping drivers who approached the junction at higher speed greater than 40mph (i.e. 17.9m/s) were found to use greater deceleration rate than those approaching at lower speed (Chang, et. al., 1985; Gates, et. al., 2007). A maximum deceleration rate of 16 ft/sec^2 or 4.9m/sec^2 was initially proposed (Gazis, et. al., 1960; May, 1968; Williams, 1977; ITE, 1985), but this value was found to be unrealistic high (Olson and Rothery, 1972; Stimpson, et. al., 1980); the maximum deceleration rate was then adjusted to 12ft/sec^2 or 3.7m/sec^2 (Olson and Rothery, 1972; Maxwell and Wood, 2006). Other factors affecting deceleration rate includes drivers' decelerating capability (Taoka, 1989; Bonsall, et. al., 2005), perception time (Demirarslan, et. al., 1998; Akçelik, 2008) and reaction time to brake (Chang, et. al., 1984; Kikuchi, et. al., 1993). Among all studies, there has been no indication of driver's willingness to accept higher average deceleration (Maxwell and Wood, 2006). On the contrary, higher acceleration rates and deliberate speeding were found among young drivers in vehicles with large engine capacities regardless of the time of day (Clarke, et. al., 2006).

2.2.4.1(iv). Headway

Time headway is the elapsed time between successive arrivals of two consecutive vehicles at the same point (HCM, 2000). On transitions from green to red signal, drivers may be more cognizant of vehicles immediately ahead of them and proceed through the junction under the influence of a non-stopping preceding vehicle (Bonneson, et. al., 2002; Elmitiny, et. al., 2010). This effect is particularly noticeable for time headways of two seconds or less (Quiroga, et. al., 2003), an unsafe headway stated in the Highway Capacity Manual (2000). As a result, following a vehicle in an unsafe headway is more likely to participate in rear end crashes at signalised junction (Harbluk, et. al., 2007).

2.2.4.2. Junction specific factors

Several studies have shown that geometric differences between junctions and demographic areas contribute to the change in traffic flow, saturation flow and driving behaviour (Clark and Cushing, 2004; Eiksund, 2009; Nordfjærn, et. al., 2010). Significant differences in driver's choice of speed and headway were found among junctions from different regions and countries (Liu, 2007; ITE, 1974a, 1974b; Vogel, 2002; Chliaoutakis, et. al., 2005; Nordfjærn, et. al., 2010). In particular, cultures between demographic areas constitute a difference in risk taking concept when confronted with an amber signal (Ulleberg and Rundmo, 2003; Chliaoutakis, et. al., 2005; Papaioannou, 2007).

2.2.4.2(i). Demographic areas

Drivers tend to behave differently between rural and urban areas (May, 1968; Hanna, et. al., 1976; Van der Horst and Wilmink, 1986; Bennett and Dunn, 1995). Significantly higher deceleration rates (Bennett and Dunn, 1995) and higher risk-taking behaviours (Eiksund, 2009) have been observed in rural areas than urban areas. This observation is consistent with the prediction of accident rates in rural areas when traffic flow is low (Hanna, et. al., 1976; Clark and Cushing, 2004). Accident rates in rural areas were found inversely related to the traffic flow density, but accident rates in urban areas remained unchanged regardless of the traffic flow density (Clark and Cushing, 2004). The effects of applying the same red light countermeasure in rural and urban areas were also found to be different; an increased amber duration in rural areas has been shown to be effective in reducing vehicles entering the junction after red onset (May, 1968), but no significant improvement was found in urban areas (May, 1968; Van der Horst and Wilmink, 1986). The reason for this variation is likely to be due to a combination of factors including imposed speed limits (Baguley, 1988), traffic flow, road geometrics (Van der Horst and Wilmink, 1986; Mohamedshah, et. al., 2000; Clark and Cushing, 2004) and regional culture (Jourdain, 1986).

2.2.4.2(ii). Width of junction

The width of junction is particularly important for crossing vehicles. Figure 2.7 below illustrates the total distances required for a vehicle of length L to cross and to stop. The width w of the junction varies between sites. Referring to Figure 2.7 below, a safe crossing requires covering the distance $W = w + L$, where W is the minimum distance for the rear of a vehicle to cross the junction completely. Drivers tend to stop at wider junctions but go through at narrower junctions (Chang, et. al., 1985; Bonneson, et. al., 2002) probably because there is greater exposure to hazards on red with wider junction (Bonneson, et. al., 2002). The relationship between exposure and injury accidents appears to be almost proportional and this exposure rate decreases as traffic volume increases (Fridstrøm, et. al., 1995). Wider junction however, does not have a significant effect on red light running crashes when traffic volume is low, which suggests that the effect on red light crashes is a combination of longer junction width and higher traffic volume (Mohamedshah, et. al., 2000).

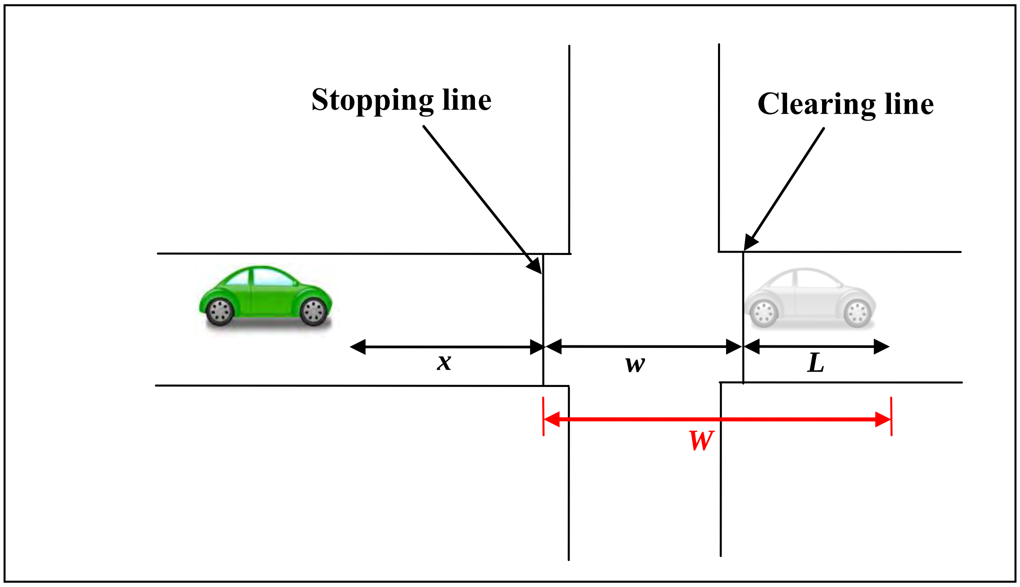


Figure 2.7: Distances required for a vehicle to stop and cross a junction
(adapted from Gazis, et. al., 1960, pp. 114)

2.2.4.2(iii). Signal control system

In terms of traffic control intervention, drivers approaching signal-actuated junctions have been found less likely to stop compared to approaching junctions with fixed-time signals (Van der Horst and Wilmink, 1986; Mohamedshah, et. al., 2000). Extending the amber time from 3 to 4 seconds at signal-actuated junctions in the Netherlands has been found to effectively reduce the frequency of red light violations (Van der Horst and Wilmink, 1986; Van der Horst, 1988). The effects were persistent even after six months, in contrast to a similar study conducted at junctions with fixed-time signal control in Australia, where the author found a gradual deterioration of red light compliance over two years (Hulscher, 1984). It is evident that the signal-actuated control system is more effective than the fixed time signal in reducing potential intentional red light running by eliminating unnecessary red waiting time and lowering the chance of drivers getting exposed to red light (Van der Horst and Wilmink, 1986; Van der Horst, 1988). Whether the difference of the effects of extended amber duration between the two signal control systems was due to other factors, such as differences in driver's attitudes in different countries, remains unclear; this is as a result of the lack of relevant studies.

2.2.4.2(iv). Traffic flow

Due to the average speed level being forced down in denser traffic, average severity of red light running accidents is shown to reduce with increased traffic volume (Fridstrøm, et. al., 1995). The frequency of intentional red light running, in particular, has been shown as the consequence of heavy flow rate and delay at junctions (Liu, et. al., 1996; Mohamedshah, et. al., 2000; Bonneson and Son, 2003; Bonsall, et. al., 2005). A higher probability of red running has been found in high traffic flow conditions near end of the green phase due to the effects of platooning (Bonneson, et. al., 2002) as drivers are more willing to accept crossing actions even with a higher risk after a long waiting time at a junction (Shinar, 1998; Bonsall, et. al., 2005). This high risk red light running behaviour was found to be elicited by a higher level of frustration (Shinar, 1998; Ulleberg and Rundmo, 2003) due to longer waiting time in congestion and longer duration of red light (Shinar, 1998).

2.2.4.2(v). Allowed turning movement

Vehicle accidents are more prevalent (i.e. 52%) amongst the vehicles going ahead at junctions than other vehicle manoeuvre (Dft, 2010). Differences in driving behaviour have been observed between drivers making different manoeuvres in many aspects; for instance, drivers tend to decelerate when making a turning movement (Chin, 1989; Lenné, et. al., 1997; Liu, et. al., 2002) and hence their mean speed remains lower than the vehicles travelling straight across the junction (Lenné, et. al., 1997). The standard deviation of speed on a turning lane is however higher (Lenné, et. al., 1997), which reveals a potential interaction between speed and lateral position. Turning at a junction with a greater speed would produce higher lateral forces as compared to turning at lower speed (Kaptein, et. al., 1996; Shechtman, et. al., 2007) and greater turning radii at junctions would in return increase the turning speeds of drivers (Tarawneh, et. al., 1998). Driver's acceptable gap in a turning manoeuvre is also dependent on their vehicle size, with light vehicles accepting smaller gaps than heavy vehicles (Mason, et. al., 1990; Hossain, 2001).

In general, drivers attempt to maintain longer headways when following a turning vehicle (Mason, et. al., 1990) and are less likely to run red lights when turning at junctions (Chin, 1989; Liu, et. al., 2002). Vehicles' turning speed is however dependent on driver's characteristics; for instance, older drivers make turns at junction at slower speeds than younger drivers (Tarawneh, et. al., 1998).

2.2.4.3. Other road users

The physical size of vehicles contributes to driver's gap acceptance and the time required for completing a crossing movement at junctions (Hossain, 2001). Variations in driver behaviour while approaching a junction at amber onset have been found to be associated with the proportion and positions of heavy vehicles (Hossain, 2001; Liu, 2007; Su, et. al., 2009) and interference from pedestrians and cyclists (Virkler, et. al., 1995; ROSPA, 2006; Su, et. al., 2009).

2.2.4.3(i). Heavy vehicles

Although heavy vehicles are known to have lower speed and accelerating capability than passenger cars (Chin, 1989; ITE, 1989; Mason, et. al., 1990), there has been no evidence of heavy vehicles travelling at lower average speed than the passenger cars (Maxwell and Wood, 2006). Heavy vehicles are even less likely than the passenger cars to stop at the end of green phase (Bonneson and Son, 2003; Zimmerman and Bonneson, 2006; Gates, et. al., 2007).

Previous studies show that saturation flow decreases with increased ratio of heavy vehicles (McCoy and Heimann, 1990; Hossain, 2001; Su, et. al., 2009) and the probability of facing a problem zone quandary would increase with higher frequencies of heavy vehicles (Zegeer and Deen, 1978). Due to heavy vehicles being physically larger and having a lower deceleration capability (ITE, 1989; Mason, et. al., 1990), vehicles following a heavy vehicle would have a higher probability of being exposed to hazards at the junction during the red onset if they chose to tailgate or travel in platoons (Bonneson and Son, 2003; Zimmerman and Bonneson, 2006). In comparison with passenger cars, larger headway has been found when following larger preceding vehicles such as heavy vehicles and buses (Tong and Hung, 2002; Su, et. al, 2009).

2.2.4.3(ii). Pedestrians

Driver's awareness of pedestrians at junction has been raised due to the statistics of pedestrian vehicle crashes (Khasnabis, et. al., 1982; Stutts, et. al., 1996) caused by driver's violation, obstructed view from drivers particularly for turning vehicles and also pedestrian's poor compliance with pedestrian signals (Zegeer, et. al., 1982; Hills, et. al., 1993; Stutts, et. al., 1996). As a result, driver's decision on crossing is enforced by the action of pedestrians crossing the street rather than waiting to cross, in particular pedestrians who ignore the signal indications (Retzko and Androsch, 1974; Khasnabis, et. al., 1982; Lord, 1996) and pedestrians with slower than average walking speeds (Virkler, 1982; Virkler, et. al., 1995; Knoblauch, et. al., 1996; Gates, et. al., 2006). The age of drivers was also shown as a contributing factor to their likelihood of yielding, with older drivers more likely than younger drivers to stop for pedestrians (Harrell, 1993; Keskinen, et. al., 1998); the result was more significant for pedestrians with highly visible clothing (Harrell, 1993).

2.2.4.3(iii). Cyclists

The presence of a bicycle lane is more likely to have an impact on driver's behaviour (Hills, et. al., 1993) than the flow of cyclists (Stokes, 1989). Cycle Advanced Stop Lines (ASLs) have been designed to provide a reservoir area for cyclists between the stop line at the junction and a second stop line in advance of the regular stop line (Allen, et. al., 2005; Dft, 2008). Although ASLs have been shown to significantly improve safety for cyclists at signal controlled junctions by segregating them from other vehicles (Dft, 1993; CCC, 1998; ROSPA, 2004; Allen, et. al., 2005; NCC, 2006), no evidence has shown that ASLs could conclusively prevent risk taking by cyclists violating the traffic signals (ATKINS, 2005; Allen, et. al., 2005). The presence of ASLs however contributes to wider junctions and thus might increase the chance of drivers crossing on red (c.f. section 2.2.4.2).

2.2.4.4. Driver

Driver's decision at signalised junctions is strongly correlated with their intention to cross (Williams, 1977), particularly when they are within an option zone independent of the amber light duration (Olson and Rothery, 1961; Van de Horst and Wilmink, 1986). See section 2.2. Significant differences have been found between drivers of different age groups and gender (Yagil, 1998; Lu and Pernia, 1999; Clarke, et. al., 2006), with young male drivers being the prominent group of aggressive drivers (McGarva and Steiner, 2000; Shinar and Compton, 2004) with the highest frequency of speeding and red light violations (Delhomme and Meyer, 1998; Yagil, 1998; Clarke, et. al., 2006). Previous studies show that aggressive driving behaviour is also triggered by driver's higher level of anger and frustration at junction (Shinar, 1998; Underwood, et. al., 1999). See section 2.2.4.2 on Traffic flow.

2.2.4.4(i). Drivers' characteristics

Aggressive driving behaviour is a negative attitude towards traffic safety (Ulleberg and Rundmo, 2003) which contributes to red light violations at junctions (Kikuchi, et. al., 1993; Retting, et. al., 1999). Aggressive driving behaviour has been shown to be encouraged by driving anger and frustration (Lajunen, et. al., 1998; Ulleberg and Rundmo, 2003), particularly when drivers are in a hurry (McGarva and Steiner, 2000) and thus have less time to concentrate on the surroundings (Riemersma, et. al., 1990; Liu, et. al., 2007).

Red light runners are more likely to be male than female based on the statistics of red running frequencies (Retting and Williams, 1996; Shinar, 1998; Retting, et. al., 1999; Liu, 2007); however, gender may not be a good estimator due to the samples dominated by higher percentage of male drivers in all studies.

In terms of the differences of driving behaviour among different driver age groups, younger drivers are in general more willing to take risks (Oltedal and Rundmo, 2006) and less motivated to comply with traffic laws (Delhomme and Meyer, 1998; Yagil, 1998) than older drivers. In particular, risky driving behaviour has been found among younger male drivers (McDonald, et. al., 1992; Lajunen, et. al., 1998; Golias and Karlaftis, 2002) with greater tendency in speeding (Cestac, et. al., 2011) and running red lights (Retting, et. al., 1996; Retting, et. al., 1999; Liu, et. al., 2007; Rakha, et. al., 2007). Some studies also found that driver's age is negatively related to anger (Lajunen, et. al., 1998; Green, 2000; Shinar and Compton, 2004) and risk taking behaviour (Golias and Karlaftis, 2002), which revealed that older drivers are able to better tolerate frustrating driving situations (Lajunen, et. al., 1998) and more willing to accept longer gaps between vehicles than younger drivers (Tarawneh, et. al., 1998). Driving behaviour of older drivers however, is more uncertain based on their driving speed alone. Some studies found older drivers driving frequently with high speeds (Retting, et. al., 1999; Rakha, et. al., 2007; Papaioannou, 2007), although others found the opposite (Green, 2000; DfT, 2001). Previous studies have also shown that older drivers are more involved in right angle collisions at junctions (Retting, et. al., 1999; Lu and Pernía, 2000; Caird, et. al., 2007) due to older drivers having slower responses to hazards (Lu and Pernía, 1999; Retting, et. al., 1999; Dft, 2001; Rakha, et. al., 2007).

Drivers with multiple speeding convictions on driver records have been identified as more likely to run red lights (Retting and Williams, 1996; Retting, et. al., 1999), but there is no evidence to judge drivers without any historical driving conviction. Red light violators were also found less likely to wear a safety belt (Retting and Williams, 1996; Porter and England, 2000) which is indicative of more risk taking in general (Golias and Karlaftis, 2002) but driver's judgment of the level of risk towards safety belt use does not necessarily determine their actual behaviour (Calisir and Lehto, 2002). Use of a safety belt might be a habitual behaviour and therefore may not be a good predictor of red light violation.

2.2.4.4(ii). Drivers' awareness of situation

Sight distance has been raised as a major safety concern at high-speed junctions (Zegeer and Deen, 1978; Retting, et. al., 1999; Bonneson, et. al., 2002) that may cause driver's judgment errors (Yagil, 1998) on the actual distance and the adequate time to complete their action. Driver's judgment ability was found to decline with increased complexity of driving environment (Liu and Wu, 2009) particularly among older drivers, although they are more aware of the negative consequences on potential hazards than younger drivers

(Parker, et. al., 1992). For instance, lack of visibility of signals at junctions has been shown to increase unintentional red light violations (Bonneson, et. al., 2002; Bonneson and Zimmerman, 2004) and this finding is more significant among older drivers (Retting, et. al., 1999; Rakha, et. al., 2007). Improved traffic signal conspicuity has been shown as an effective countermeasure; increasing driver's awareness to brighter signals (Bonneson, et. al., 2002; Sunkari, et. al., 2005) and installation of advanced road markings in urban areas has also improved safe operations in a similar manner (May, 1968). In contrast to the benefits of advanced road markings, the removal of road markings and traffic lights was found to substantially decrease car accidents in Drachten, the Netherlands (Methorst, et. al., 2007). This implementation is however, found to be beneficial only in areas with substantial higher levels of walking and cycling and lower traffic speeds of at most 30km/h, i.e. less than 20mph or 8.9m/s (Methorst, et. al., 2007; Reid, et. al., 2009).

2.2.4.4(iii). Drivers' reaction time

A further aspect to the problem zone exists because driver's perception-reaction time is not instantaneous (Chan and Liao, 1987; ITE, 1989; Prashker and Mahalel, 1989). This perception-reaction time is not identical between all drivers (Green, 2000), and could be reduced when drivers are alert of their driving environment and surroundings (Taoka, 1989; Demirarslan, et. al., 1998; Akçelik, 2008). Driver's aggressive driving behaviour and familiarity with the junction were also found to contribute to shorter reaction time to brake and stop (Chang, et. al., 1984; Kikuchi, et. al., 1993). Older drivers are found more likely to have longer reaction time than younger drivers (Demirarslan, et. al., 1998; Green, 2000; Lu and Pernía, 2002), dominated by their differences in visual activity (Demirarslan, et. al., 1998; Harbluk, et. al., 2007). Hard braking is particularly observed under conditions of limited or reduced driver's vision regardless of the driver's age group (Harbluk, et. al., 2007).

2.2.4.5. Weather and the environment

Previous studies show that weather and the environment factors greatly affect driver's decision and their driving patterns (Retting, et. al., 1998; Shinar, 1998; Ulleberg and Rundmo, 2003). The change in driving behaviour to different weathers is also revealed as a result of driver's awareness of the hazards (May, 1968; Bonneson, et. al., 2002) and their potential negative consequences. (c.f. section 2.2.4.4).

2.2.4.5(i). Time of day/ day of week

Higher red light violation rates have been observed at junctions during morning peak hours on weekdays (Shinar, 1998; Retting, et. al., 1998, 1999; Shinar and Compton, 2004; Yang and Najm; 2007) when the traffic volume is relatively high (Retting, et. al., 1998; Lum and Wong, 2003). Despite the fact that speed and movement of vehicles are more restricted in denser traffic flow (Yang and Najm, 2007), high violation rate remains with drivers being more aggressive at junctions (Shinar, 1998; Ulleberg and Rundmo, 2003). Similar trend is found with lower violation rate and less aggressive drivers observed during uncongested weekends (Retting, et. al., 1998; Shinar, 1998). Driver's performance is also shown to be related to the time of day (Lenné, et. al., 1997); for instance, driver's mean speed has been found lowest at 14:00 in some studies as a likely effect of post-lunch dip which occurs during mid afternoon hours (Smith and Miles, 1986; Lenné, et. al., 1997).

Time of day has been shown to have an effect in visibility at junctions, and hence their driving behaviour. See section 2.2.4.4 on driver's awareness of situation. Accidents occurred at night were shown to be related to the difficulty in performing driving tasks in darkness (Doherty, et. al., 1998), especially in bad weather when darkness hinders perception of road condition and reduces preview distance and time (Summala, 1996; Kilpeläinen and Summala, 2007).

2.2.4.5(ii). Weather

No significant difference in driver's behaviour was observed in different weather conditions, e.g. sunny days or rainy days (Retting, et. al., 1998; Datta, et. al., 2000; Porter and England, 2000). Deceleration and lower speed however, were only observed under conditions of heavy rain or heavy fog with low visibility (Porter and England, 2000) which decreases the effectiveness of driver's visual search of their surroundings (Konstantopoulos, et. al., 2010). Significant slower reaction time was also found at night (Doherty, et. al., 1998; Konstantopoulos, et. al., 2010) when drivers' judgment becomes more difficult (Summala, 1996; Kilpeläinen and Summala, 2007). Drivers were found to adjust their driving habits to keep the risk level constant and to reduce their exposure on road (Fridstrøm, et. al., 1995; Kilpeläinen and Summala, 2007) only under adverse weather conditions.

2.2.4.5(iii). Road condition

Road slipperiness has been shown to contribute to higher accident rates (Norrman, et. al., 2000; Kilpeläinen and Summala, 2007) and higher probability of drivers misjudging the gap and their speed on wet surface (Yagil, 1998; Cooper and Zheng, 2002). Driver's misjudgement of gap and distance is particularly significant among older drivers (Cooper and Zheng, 2002). Driving speed between drivers on dry and wet surfaces has been found to remain consistent (Lamm, et. al., 1990) which suggests that drivers may be less aware of the hazards caused by lower friction on wet surface. A reduction in speed was observed on wet surface only under conditions of limited sight distances (Lamm, et. al., 1990).

2.3. Conclusion

The purpose of this chapter is to review the literature on the relationships between driver decision at the onset of the amber signal at junctions and the contributory factors. The likelihood of drivers driving through red has been shown to increase with shorter distance to the junction when the amber light commences (i.e. junction specific factors) and decrease when their movement are impeded by other road users such as pedestrians and cyclists (i.e. other road users). Drivers have been found to be more cognizant of their preceding vehicle when following closely behind a vehicle's movement. When anticipating the crossing action of their preceding vehicle during green to red signal transition, drivers would be more likely to get exposed to the red onset if following behind a heavy vehicle (synthesis of junction specific factors, vehicle specific factors and other road users).

Driver factors were found to contribute to the likelihood of red light violation in two different manners. Driver's misjudgement on their critical distance to stop, due to obstructed view or limited sight distance (i.e. weather and environment), has been found more likely to result in unintentional red violation. Intentional red light violation was however, triggered by aggressive drivers at junctions with denser traffic flow (i.e. synthesis of junction specific factors and driver factors). Intentional red light violators were found in most cases, among younger drivers.

It seems that people drive through red signals for a variety of reasons, including insufficient amber duration, higher vehicle speed, shorter distances to junction, short headway to leading vehicle in front, and youth of drivers. The reduced likelihood of red light violations was however found in driver awareness of the traffic situations and higher visibility of the driving environment (i.e. driver factors). For instance, raising driver's awareness of the existence of traffic lights by installing an advanced sign upstream of the junction has been shown to reduce the frequency of vehicles getting trapped in a problem zone (May, 1968). The positive effects have been shown in both rural and urban areas. Based on the results from the literature, it is suggested that driver's decision could be improved through junction design and driver training.

3. The impact of contextual variables on driver behaviour at signalised junctions

This chapter describes an observational study to identify the contextual issues in the driving environment that are associated with higher stopping propensity. A logistic regression model based on the physical and contextual variables is presented to make predictions on driver decisions at junctions. Statistical analysis of the observed and predicted data, and their results are also presented.

3.1. Introduction

Red light running occurs when drivers cross the stop line after the red light has appeared (Baguley, 1988). This behaviour has been found to be associated with 'option zone' (Retting, et. al., 1995) and 'problem zone' (c.f. Chapter 2) when a signal turns amber as they approach. The option zone is a situation when both stopping and crossing manoeuvres can be executed successfully (May, 1968; Mahalel and Prashker, 1987; Urbanik and Koonce, 2007), often defined as the range of distances where probability of stopping lies between 10-90% (ITE, 1974). By making the assumption that drivers maintaining constant speed (without any change in acceleration) on and after the amber onset, the range of option zones had been shown to enlarge with longer amber duration (May, 1968; Prashker and Mahalel, 1989). In contrast, the problem zone is defined in this thesis as a range within the signal approach with inappropriate traffic engineering measures or traffic environment that mean that the driver can neither enter the junction before the red light appears, nor stop the vehicle safely before entering the junction. This problem zone has previously been defined as a "dilemma zone", often caused by improper settings of amber duration (e.g. Gazis, et. al., 1960).

Studies of driver's decisions at signalised junctions have received significant research attention since Chang, et. al. (1985) identified the stability of driver's reaction time to a range of approaching speeds, and thus highlighted the fact that a decision to cross at a signalised junction is in most cases strongly correlated to driver's choice of continuing over their ability to stop. Combinations of speed, distance and time to stop line have been long shown as the main estimators of driver's decisions (Gazis, et. al., 1960; Chang, et. al., 1984), with different levels of stopping propensity having also been shown to be caused by the dynamic quantities of vehicle related factors under different scenarios (Olson and Rothery, 1972; Williams, 1977; Chang, et. al., 1985; Prashker and Mahalel, 1989; Bonneson, et. al., 2002; Maxwell and Wood, 2006). Other research suggests that drivers make their decision to cross or stop based on scenarios they perceived as either beneficial or more risky to cross (Hills, et. al., 1993; Delhomme and Meyer, 1998; Datta, et. al., 2000), with the wider driving context also seeming to affect driver's decisions (Yan, et. al., 2005; Archer and Young, 2010).

The emphasis in the current study is therefore placed on quantifying the potential impacts of wider driving context, focusing on the impact of other road users such as cars, heavy vehicles (Zegeer and Deen, 1978; Hills, et. al., 1993; Zimmerman and Bonneson, 2006) and pedestrians. The main aim of the current study is therefore to observe any change in frequencies of stopping decision under different conditions with designated range of junction related factors and other road users directly appeared ahead of the drivers, and to reveal any potential indicator of driver's stopping and/or crossing decision and hence red light running. There currently exists no decision model to study the independent effects of these factors on road users' driving behaviour at signals and therefore the current study represents a substantial step forward in understanding the contributory factors in both stopping behaviour and red light running.

3.2. Methodology

Because the incidence of red light running is rare, the approach taken in the current study is to calibrate distributions of all stopping behaviour in option and problem zones for a typical junction and then use these distributions to quantify the proportions of drivers likely to run red light.

3.2.1. The study site

The site selected for the current study is a three way (T-shape) junction between Burgess Road and University Road in Southampton, UK (see Figure 3.1 for a schematic plan view and Figure 3.2 for a photographic view of the junction). The area of interest is a two lane approach on the Burgess Road which allows either through movement across the junction or left turning movement into the University Road, illustrated as the shaded region in Figure 3.1. Due to its location (close to the University), higher traffic flow remains at off-peak hours and there is also higher than typical number of pedestrian movements. This junction is designated with pedestrian crossings, cycle lanes and advanced stop lines for cyclists (clear markings on the road surface are an advantage for the purpose of data collection and calibration; road markings were used as reference points to record vehicle's distances from the stop line of junction. See Figure 3.3). It should be noted that no traffic enforcement cameras are installed at this junction as such enforcement has been shown to contribute to a substantial increase in the frequency of stopping (e.g. Chin, 1989; Retting, et. al., 1999a, 1999b; Lum and Wong, 2003).

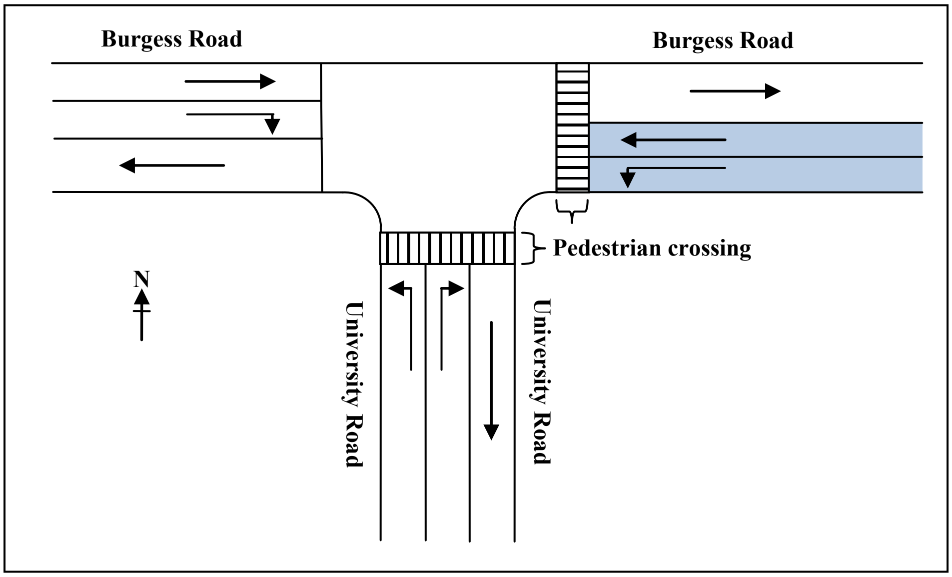


Figure 3.1: Plan view of the junction between Burgess Road and University Road

Figure 3.2: Street level view (from east) of the surveyed approach on Burgess Road

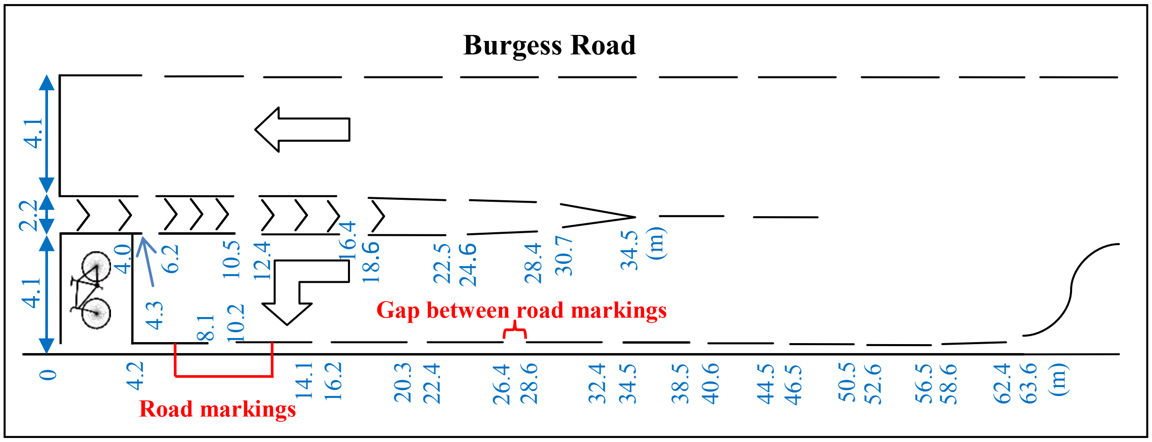


Figure 3.3: Plan view of road markings on surveyed approach

3.2.2. Data collection

This study used video cameras as the main tool for collecting primary data of traffic flow, signals and driver decisions, with video-based data collection having been used in previous research as a cost effective method to collect such information (e.g. Chang, et. al., 1984; Van der Horst and Wilmink, 1986; Liu, et. al., 2007). Video recordings were taken for a total duration of ten hours on three separate dry and clear weekdays: 11am to 12 pm on 21st January 2010, 12pm to 3pm on 22nd December 2010 and 10:30am to 4:30pm on 27th April 2011. Data from short periods caused by the need to quickly change video tapes were discarded prior to data analysis; providing a total of 781 vehicles overall which were recorded as having approached the junction with an amber light displayed.

(a) (b)

Figure 3.4: Video data capture in progress from (a) high level from northwest and (b) street level from west

A total of four time-synchronised video cameras were used in this study; two video cameras were set up (see Figure 3.4 (a)) at the interior of the first floor of a building (i.e. the Gower Building) on the south side of Burgess Road west of the junction to capture an unobstructed view of the junction from the above (the arrow in Figure 3.2 (middle left of the image) shows the location of this window relative to the approach). These two video cameras were placed side by side, allowing a high vantage view of both the overall junction and the status of the pedestrian crossing situated on the University Road. The main purpose of setting up the first video camera was to capture the vehicles approaching the junction inclusive of their final status of stopping or crossing and the presence of pedestrians crossing and/or waiting to cross at and after onset of the amber light on the main road. The second camera was set up to capture the possible interaction observed between the pedestrians on the University Road crossing (see Figure 3.5) and any vehicles making a left turn from Burgess Road into University Road.

Figure 3.5: Street level views showing the pedestrian crossing on the University Road (from west)

Another two video cameras were set up side by side at street level on the south sidewalk pathway beside Burgess Road (see Figure 3.4 (b)); one video camera was set up to directly capture the status of traffic signals and the movement of vehicles approaching the junction while the other video camera was used to capture the vehicle flow at a distance of about 50m upstream of the junction, 10m after the starting point where the single lane approach splits into a two lane approach for the two different turning movements.

3.2.3. Data extraction and manipulation

The videos recorded from field study site are encoded at 25 frames per second, allowing detailed vehicle's movement to be captured every 0.04 second. Reference lines were drawn horizontally on the TV monitor screen (a method adopted by Liu, et. al., 2007) with known locations based on the starting and ending point of each road marking captured on the videos on playback (see Figure 3.6(b) for an example, where the lines have been enhanced for illustration purposes). The measurements obtained on screen were then calibrated with the geometric measurement obtained from measuring the real site (as shown in Figure 3.3) prior to carrying out any the analysis.

Figure 3.6: Video playback with horizontal reference lines

The inter-green period of each phase consists of an amber indication of 3 seconds and an all-red indication of 2 seconds. Only vehicles observed approaching and/or entering the junction at onset of amber lights were extracted as samples, inclusive of the first stopping vehicle at the junction of each traffic cycle. Vehicles arriving at the junction when the signal remained green were not included as samples. Vehicle profiles were set up for each vehicle from the sample data, and each vehicle is assigned a unique Vehicle ID with an alphanumeric string denoting their cycle number of each of the study periods, their lane position between through and turning approach and their position on respective lanes within each cycle. Vehicle's characteristics were also recorded with vehicle types, model and colour for data verification and reference purposes.

The distance of each vehicle from the stop line on commencement of amber light time was measured, as well as the distance of the respective vehicle at one second after the amber onset, i.e. amber time + 1 sec. This unit of distance is used to estimate the speed of a vehicle, i.e. the distance (m) one could travel per second. The traffic flow was captured during the data collection period using two different video cameras set up at two different angles; crossing or stopping decision was recorded in a database.

Time headway was defined as the time interval between two consecutive vehicles travelling on the same approach reaching the same fixed point on the approach. In this study, leading or following vehicles are classified using two different time headways as boundary values: 2 seconds and 3 seconds. Using time headway of 2 seconds, the succeeding vehicle was classified as following when the time headway with its preceding vehicle is less than 2 seconds, and leading if the time headway with its preceding vehicle is at least 2 seconds; similar classification rule was also applied for time headway of 3 seconds. Vehicles queueing at the junction and vehicles remained at the junction as the residues from previous signal cycles were removed from the sample as not truly representative of 'approaching' vehicles.

Road users observed in the study were classified into three major groups: passenger cars (including small cars, sedans and wagons), heavy vehicles (including trucks, buses and large delivery vans) and pedestrians. The frequency of cyclists observed in this study was too low to be included in the analysis. The presence of pedestrians was recorded if pedestrians were observed crossing or waiting to cross the pedestrian crossings on commencement of an amber vehicle light (i.e. the data does not include pedestrian activities not utilising the pedestrian crossings, e.g. walking past the junction without crossing).

In summary, the data recorded on the 781 vehicles were organised into the two groups as follows (along with a result variable stopped taking value 1 if the vehicle stopped and 0 if it continued):

Physical variables (used in existing models):

- *Distance*: the vehicle's distance (m) from the stop line at the onset of the amber light;
- *Speed*: the vehicle's speed (m/s) at the onset of the amber light;

- *Time*: the estimated time (s) needed for the vehicle to reach the stop line from the onset of the amber light without any acceleration (= Distance/Speed);
- *Vehicle type*: whether the vehicle is a passenger car (e.g. small cars, sedans, wagons) or a heavy vehicle (e.g. trucks, buses, delivery vans);
- *Turning Movement (TM)*: whether the vehicle was on a left turn lane (denoted by 1) or on the straight ahead lane (denoted by 0).

Contextual/Situational variables (the focus of the current study):

- *After_HV*: whether the vehicle was driving behind a heavy vehicle (1) or not (0);
- *Position_2 (Psn2):* whether the vehicle was in a leading position (1) or following position (0) in the traffic flow with headway of 2 seconds;
- *Position_3 (Psn3):* whether the vehicle was in a leading position (1) or following position (0) in the traffic flow with headway of 3 seconds;
- *Pedestrian*: whether there was any pedestrian waiting to cross or crossing the Burgess Road (1) or not (0);
- *Pedestrian_LT*: whether there was any pedestrian waiting to cross or crossing the University Road (1) or not (0).

While it maximises the number of data points that can be obtained, it is noted that one limitation of this form of data collection is that the study was unable to reveal all potential indicator variables to driver's stopping propensity, specifically those related to socio-demographic driver and characteristics. As the recorded images were not sufficient to enable assessment of vehicle occupants, potential impacts of age, gender and vehicle occupancy on driver's decision cannot be identified in the current study.

3.3. Analysis and results

3.3.1. Identification of principle variables

Logistic equations are used in the current study to model driver's decision in terms of the probability of stopping at signalised junction, due to their binary result of either crossing or stopping. An initial test on the significance of individual physical variables on predicting driver's decision was carried out, with the most important independent variables (as expected) identified as *Distance* and *Time*, when ranked accordingly to their significance (see Table 3.1) and thus should be treated as potential candidates of the principle factors.

Table 3.1: Significance of individual physical variables in predicting stopping behaviour

Variable	R^2	Significance
Distance	**.447**	**<.0001****
Time	**.418**	**<.0001****
Turning_Movement	.004	.075
Speed	.001	.284
Vehicle_Type	.000	.737

**** indicates significance at 0.05 level**
Higher R^2 indicates greater fit of the model

Past studies have suggested that driver's decision to stop or to cross is affected by both the approach speed, as well as the distance from the junction when amber light appears and the time to reach the stop line (Williams, 1977; Sheffi and Mahmassani, 1981; Chang, et. al., 1985). While Table 3.1 showed that *Speed* has a much less significant relationship with driver's decision (compared to *Distance* and *Time*) when treated as a single independent variable, comparison of models based on combinations of the three variables identified that *Distance* and *Speed* together gave the best fit. No improvement was observed by including *Vehicle_Type* within the model, i.e. driver's decision did not appear to be affected by the type of vehicle (heavy vehicle or passenger car) they are driving, beyond impacts already potentially represented by different speeds.

Table 3.2: Comparison between principle variables

Variable(s)	R^2	Significance
Distance	.447	<.0001**
Estimated Time	.418	<.0001**
Speed	.001	.284
Distance & Speed	.479	<.0001 (D)** <.0001 (S)**
Distance & Time	.463	<.0001 (D)** <.0001 (T)**
Speed & Time	.437	<.0001 (S)** <.0001 (T)**
Distance, Speed & Time	.473	<.0001 (D)** <.0001 (S)** .413 (T)

** indicates significance at 0.05 level
Higher R^2 indicates greater fit of the model

3.3.2. Importance of situational variables

With the identification of a basic model containing *Distance* and *Speed* variables, the impact of the different situational variables can then be quantified. To perform this analysis it is necessary to split the sample by *Turning_Movement*, due to the obvious relevance of different pedestrian movements to different turning movements. In each case the impact of following positions and the presence of pedestrians waiting to cross (or actually crossing) the vehicle movement are analysed for inclusion in the model.

For the straight ahead movement the only significant adaptation to the model comes through the addition of *Position_3*. Vehicles leading (or at least 3 seconds behind the vehicle ahead of them when the amber light is displayed) are identified as being more likely to stop than vehicles following within 3 seconds of the vehicle in front of them. Drivers following closely behind the preceding vehicle tend to be more cognizant of the vehicle immediately ahead of them (Harbluk, et. al., 2007; Elmitiny, et. al., 2010) and will be more likely to proceed through the junction if that vehicle does; of course, whether this behaviour represents (for example) a subconscious view of 'safety in numbers' or a subconscious delegation of responsibility to the preceding vehicle could not be identified from an observational study.

For the left turn movement the impact of close following was not significant (although this may be partially be due to lower occurrence rates (12%) of close following events in this movement within the dataset), but a noticeable effect was observed for the presence of waiting pedestrians (*Pedestrians_LT*) which increased the likelihood of the driver choosing to stop. It should be noted however that presence of pedestrians on University Road was recorded in 42 out of 153 left turning observations (31.1%), but on Burgess Road for only 62 out of 628 observations (9.8%) of straight ahead movements.

Using the standard logit model for formulation,

$$Logit(p) = \log\left(\frac{p}{1-p}\right) \qquad [3.1]$$

where p represents the probability of a driver stopping, this inclusion of a close following impact for straight ahead traffic and a pedestrian impact for left turning traffic gives a total of four possible scenarios as tabulated in Table 3.3.

Table 3.3: Logistic Regression scenarios and models

Scenario		***Logit (p)***
I	*Straight and close following*	*-3.309+0.175*Distance-0.37*Speed*
II	*Straight and leading*	*-1.812+0.175*Distance-0.37*Speed*
III	*Left turn with pedestrian(s)*	*0.056+0.14*Distance-0.342*Speed*
IV	*Left turn with no pedestrian(s)*	*-1.208+0.14*Distance-0.342*Speed*

3.3.3. Predictive accuracy

The Logistic Regression models in Table 3.3 enable an overall successful prediction of 87% on all decisions made by drivers on the straight ahead movement and 86% on the left turn movement (see Table 3.4) in the current study. These overall successful prediction rates also include correct prediction of decisions made by 78 out of 102 vehicles (76.5%) in option zones and 11 out of 11 vehicles (100%) in problem zones. If the sensitivity of the prediction is defined as the percentage of correct predictions of stopping vehicles, then for this dataset the values are 83% and 84% respectively for straight and turning vehicles. The accuracy of the model in predicting driver's likelihood of stopping therefore compares favourably to those proposed by Allos and Al-Hadithi (1992) and Gates, et. al. (2007) which yielded respectively 77% and 80% correct prediction rates of stopping vehicles.

Table 3.4: Predictive accuracy of models

		Straight Ahead			*Left Turn*		
		Predicted			Predicted		
Observed		Continue	Stop	Correct	Continue	Stop	Correct
	Continue	357	45	88.8%	75	11	87.2%
	Stop	39	187	82.7%	11	56	83.6%
	Overall			86.6%			85.6%

While the models in Table 3.3 can be used to simply predict the likelihood that a given driver will decide to stop rather than to cross given a defined speed and distance in each of the scenarios using the standard logistic regression transformation; however, an alternative approach is to plot the impact on the stopping decision across a range of realistic speeds and distances by substituting relative distances (ranging from 0 to 70m, the minimum and maximum distance from the stop line are recorded in the sample as 0 and 68.11m respectively) into the equations in Table 3.3 and then transforming the results into probabilities of stopping. Four different approach speeds: 30km/hr, 40km/hr, 50km/hr (the speed limit for the Burgess Road approach) and above 50km/hr (≤ 70km/hr) are shown in Figure 3.7 (parts (a) to (d) respectively) to illustrate the probability of stopping for vehicles in Scenario I (i.e. straight and following vehicles, the largest sample size of 374 vehicles). Equivalent figures for the three other scenarios (Scenario II, III and IV) can be found in the Appendix A.

In each part of Figure 3.7 the lower (darker shaded) part of the column and associated sample size is the vehicles observed as stopping in the sample and the upper (lighter shaded) part of the column represents those vehicles choosing to cross the junction for that combination of *Speed* and *Distance* (including those (if any) choosing to cross, running the red light as they did not enter the junction before the amber signal turned red who are also separately denoted as RLR). The S-curve on each plot is the modeled probabilities from the Scenario I equation in Table 3.3, showing a good fit to the observed data in parts (a) to (c), but less so in part (d) where the observed sample sizes are much smaller.

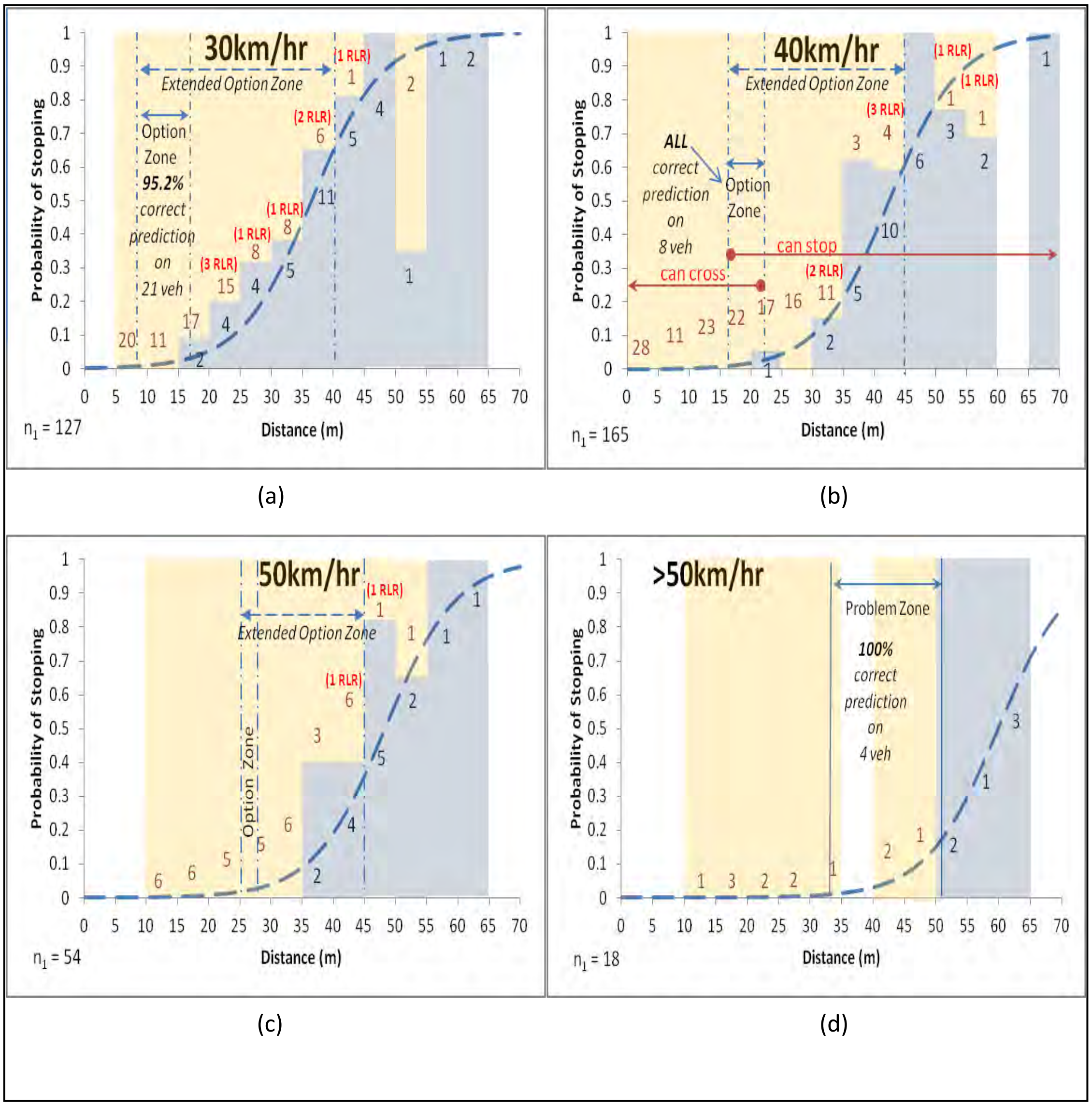


Figure 3.7: Observed and predicted probability of stopping for Scenario I (Straight and close following)

To assess overall model accuracy two approaches are used. Firstly, the overall successful prediction rate of $\frac{321}{374} = 85.8\%$ was found for vehicles in Scenario I and then the observed distances of stopping vehicles (of Scenario I) from the sample were compared with the equivalent predicted distances from model in Table 3.3. The predicted distances (15th percentile, median and 85th percentile) were found similar to the observed data (See Table 3.5).

Table 3.5: Observed and predicted values for distance distribution of stopping vehicles (Scenario I)

Speed								
	30km/h (8.3m/s)		40km/h (11.1m/s)		50km/h (13.9m/s)		>50km/h (>13.9m/s)	
Measurements	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
N	39		30		15		6	
15^{th} Percentile	24.6	26.6	36.2	32.5	39.3	38.4	52.7	50.1
Median	36.9	36.5	43	42.4	46.5	48.3	59.7	57.1
85^{th} Percentile	48.4	46.4	53	52.3	55.7	58.2	62.4	64.1

3.3.4. Redefining the option zone

Assuming a maximum deceleration rate of $3.7m/s^2$ for safe stopping (Olson and Rothery, 1972; Maxwell and Wood, 2006) and reaction time of 1s (Chang, et. al., 1985; ITE, 1989), option zones can be estimated for each approach speed and these are included in Figure 3.7. (As expected, larger option zones are found at lower approach speeds, with zone width reducing as speed increases). It is immediately clear however (see Figure 3.7(b) where the definition of the option zone as those vehicles who can stop and can cross is additionally highlighted) that a substantial number of vehicles at greater distances which would traditionally be defined as unable to cross (Distance/Speed > duration of amber signal) are still managing to cross the junction safely (not red light running).

For the lower (minimum distance) bound on the option zone, drivers were observed most likely to stop for Scenario IV at the left turning movement when pedestrians were present and least likely to stop for Scenario I when they were in a following position on straight lane (this is particularly true when drivers were within 15m from the stop line regardless of their approach speed). In this study (across all four scenarios) 99.5% of vehicles crossed when they were within 15m from the stop line on green to amber transition. Given the variability in speed that exists in the traffic stream due to non-homogenous driver behaviour, the speeds of the drivers and their corresponding distances from the stop line at the amber onset were not normally distributed. The median speed of the drivers and their median distance from the stop line were used respectively as the measures of average speed and the average distance from stop line in the non-parametric test. As a result, there is no significant difference in the average speed (*p-value = 0.099 in Mann-Whitney Test)* between crossing ($\bar{x}_c = 9.56m/s;\ S_{xc} = 2.35$) and stopping vehicles ($\bar{x}_s = 9.36m/s;\ S_{xs} = 2.65$); probably due to the imposed speed limit on Burgess Road. The difference in average distance from the stop line between crossing ($\bar{y}_c = 18.29m;\ S_{yc} = 13.05$) and stopping vehicles ($\bar{y}_s = 27.6m;\ S_{yc} = 17.37$) is however, significant (*p-value* < 0.0001 *in Mann-Whitney Test)*; implying that the crossing or stopping decision is likely to be dependent on their distance from the stop line when the amber light first appeared. While *Distance* is shown to have a direct influence on driver's decision therefore, the significant effects of speed on driver's decision are dependent on their relative distance. For instance, driver's approach speed appears to influence a driver's decision effectively only for *Distance* > 15m in this study. By assuming reaction time of 1s (Chang, et. al., 1985; ITE, 1989), even vehicles travelling at a lower speed, e.g. 30km/hr (or 8.3m/s), will be able to travel more than 15m in 3 seconds of amber duration without any acceleration.

It appears from the data however that the traditionally accepted definition of the upper (maximum distance) boundary of the option zone is incorrect, with a more accurate 'extended' option zone being identified using the observed data (the upper bound of the extended option zone for each speed set by comparing the observed stopping vehicles and red light violators) being included in Figure 3.7(a), (b) and (c) for comparisons. For this approach, the upper bound was observed at a distance within 40 to 45m from the stop line with majority of drivers (i.e. 80% and above) beyond this distance choosing to stop (and those choosing to continue being likely to run a red light when they enter the junction). This shows that the common assumption when modelling option and problem zones (that vehicle speed is constant) is clearly not appropriate as drivers are identifying the situation and increasing their speed to ensure that they can pass safely through the junction before the onset of the red light.

It should also be noted that this appears to be a correctly designed junction as the existence of a problem zone was found only at approach speeds greater than 50km/hr, Figure 3.7(d), i.e. speeds in excess of the maximum speed limit for the road.

3.3.5. Influence of heavy vehicles

About 19% among the observed traffic flow in the study are classified as heavy vehicles, which represents a substantial population on all vehicles travelling through the study site. No significant difference was found between heavy vehicles and passenger cars on their stopping decision when considering vehicle type as a single explanatory variable (recall that *Vehicle type* had a significance level of only 0.737 in Table 3.1); however, the inclusion of *Position_3* in the models suggest the need to explore the potential for a further impact occurring if the preceding vehicle is a heavy vehicle (*After_HV* = 1), i.e. it is possible that drivers may react differently when the vehicle they are following is a heavy vehicle.

Exploring the dataset to identify vehicles which were following a heavy vehicle produces 108 instances (although not necessarily all within 3 second headway). It should be noted that the average speed of vehicles following a heavy vehicle does not seem to differ significantly (*p-value = 0.434 in Mann-Whitney Test of differences in medians*) depending on the headway (average speeds are 9.2m/s and 9.5m/s respectively for close following and non-following vehicles), suggesting that any speed impact is limited to stopping decisions rather than wider driving behaviour. It should be noted that longer headways were typically observed when following heavy vehicles than when following passenger cars, a similar observation to those of Bonneson, et. al. (2002) and Zimmerman and Bonneson (2006). Recalibrating the regression models to allow the intercept to vary for both different types of preceding vehicle and different following headways produces equations for *Logit(p)* as given in Table 3.6, with impact being more clearly visualised for different speeds in Figure 3.8(a)-(d), where for simplicity a following distance of more than 3 seconds behind the preceding vehicle is denoted as ‘not following’.

Table 3.6: Logistic Regression models allowing for preceding vehicle

Preceding vehicle	Following within 3 seconds	Following more than 3 seconds
Passenger car	-3.438+0.176*Distance-0.37*Speed	-1.984+0.176*Distance-0.37*Speed
Heavy vehicle	-2.901+0.176*Distance-0.37*Speed	-1.093+0.176*Distance-0.37*Speed

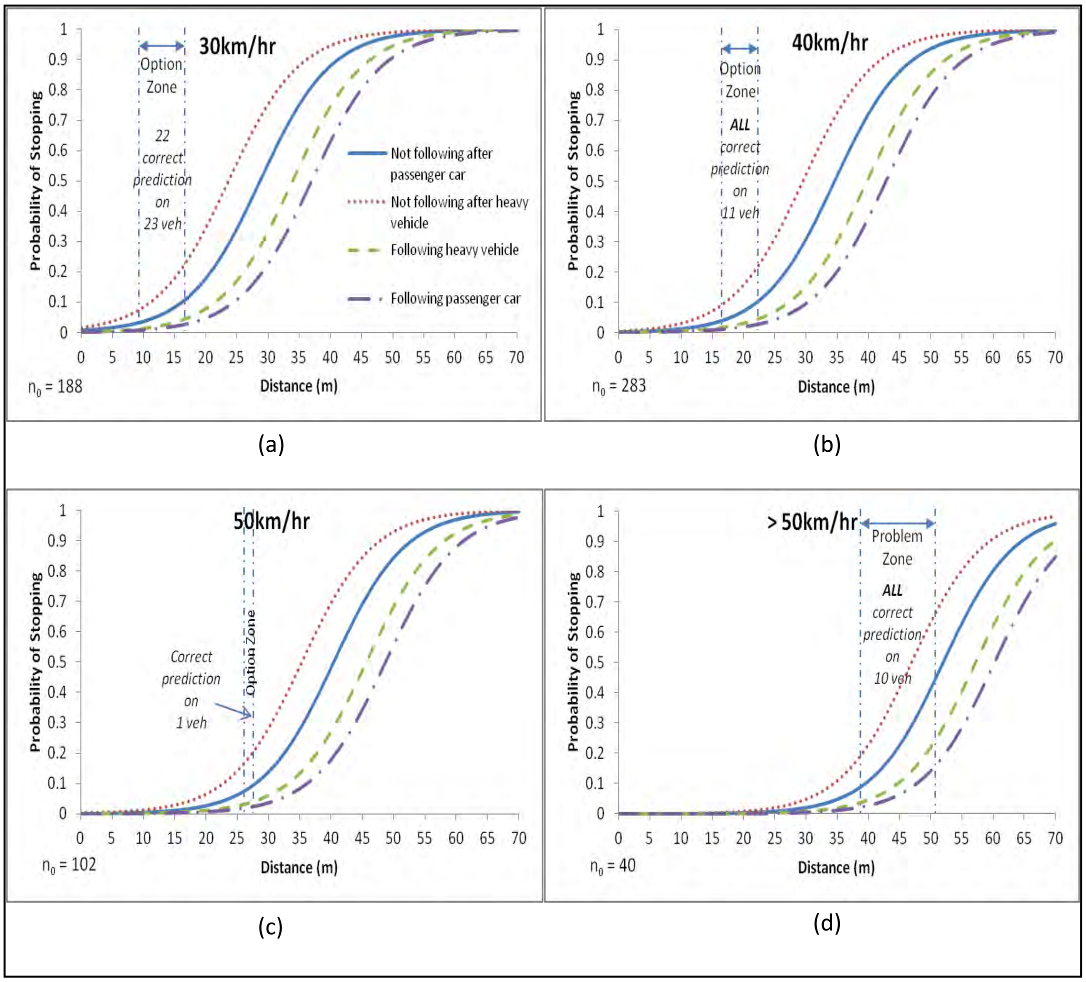


Figure 3.8: Comparative predicted probability of stopping dependent on preceding vehicle type

As shown in Table 3.6, driver's likelihood of stopping at a junction was tested against their following headway behind different vehicle types (the predictors), by setting the coefficient values of the situational variables (Distance and Speed) to remain identical to replicate the context of a problem zone. Given that drivers take no advantage over their speed and distance in the model, different intercept values in the model thus imply different level of effectiveness of the predictors to the model; in particular, the predictor with larger intercept values (in either positive or negative values) may contain data that is highly correlated to the decision of the drivers. For instance, driver's reduced likelihood of stopping can be found among vehicles following within 3 seconds behind a passenger car, with larger coefficient (i.e. -3.438).

While these models have overall predictive accuracies of stopping or continuing decisions for vehicles following behind a heavy vehicle of 90% when the headway is less than 3 seconds and 92% when the headway is more than that value, the overall predictive accuracy for the models only rises to 88% through inclusion of the additional variables as these instances only make up a small portion of the full dataset. It is clear from this analysis though that contextual variables relating to the preceding vehicle (headway and vehicle type) do seem to be having a significant effect on the probability of a driver choosing to stop. It is clear that

- Drivers are less likely to stop if they are following closely behind the preceding vehicle, possibly suggesting a subconscious heard/safety in numbers mentality;
- Drivers are more likely to stop if the preceding vehicle (not closely behind) is larger, possibly suggesting a subconscious assessment of the potential damage an impact with the vehicle in front may cause.

For example a driver travelling at 40km/hr (i.e. 11.1m/s) who is 20m away from the junction at the onset of the amber signal (in the option zone in Figure 3.8(b)) is being predicted to have a probability of stopping of 0.07 if they are more than 3 seconds behind a preceding car, but this is reduced to 0.02 if the following headway is less than 3 seconds, or increased to 0.16 if the preceding vehicle is a heavy vehicle rather than a passenger car.

Under the influence of the preceding vehicle, the risks of driver's decision to the amber onset may be carefully assessed. For instance, travelling behind larger vehicles but not within close proximity may encourage drivers to stop unnecessarily earlier at a junction, and thus increases the risks of rear-end collisions with the succeeding vehicle. See Table 3.7. Figure 3.8 also demonstrates that the complex driver decision behaviour associated with the subconscious assessment of the potential risks may be more accurately modelled than with traditional methods using only the physical variables.

Table 3.7: Risk assessment on driver's crossing behaviour under the influence of preceding vehicle

	Driving context		Possible consequences			
				Rear-end collision		
Likelihood	Within close proximity?	After heavy vehicle?	Red light violation	with preceding vehicle	with succeeding vehicle	Right-angle collision
Most likely to cross in most circumstances	✓	×	☠	☠☠	☠	☠☠☠
Likely to cross frequently	✓	✓	☠	☠☠	☠	☠☠☠
Unlikely to cross but could happen	×	×	☠	☠	☠☠	☠☠
May cross but only in rare circumstances	×	✓	☠	☠	☠☠	☠

☠☠☠ *denotes high hazard severity causing death or serious injury*
☠☠ *denotes moderate hazard severity causing injury and/or damage to automobiles*
☠ *denotes minor or no injury*

3.4. Discussion

Based on the initial position of all vehicles at the onset of amber light, the current study has demonstrated that option zones should be considered dynamic rather than static and the size of the option zones was greater than that previously considered because of the potential for drivers further from the junction to increase speed to enter the junction safely. These 'extended option zones' in the data are defined as the regions where both stopping and safe crossing vehicles were observed (see Figure 3.7 and Appendix A). Further analysis suggests that the extended option zones for vehicles crossing the junction in a straight movement were potentially bounded by a constant maximum distance, irrespective of the speed that the vehicles were originally travelling (suggested by the data to be about 45m, equivalent to vehicles travelling at about 54km/hr (i.e. 15m/s) for the duration of the amber light, slightly faster than the speed limit for the road).

The main purpose of this analysis however was to determine whether it was possible to identify contextual issues in the driving environment that are associated with higher stopping propensity, enabling better understanding of driver's behaviour in option and problem zones and causes of red light running. The results from the current study had provided some insights on the potential impact of contextual factors (turning movements, pedestrians, heavy vehicles and following headways) on driver's stopping decisions. One key result from the analysis is that drivers following closely to their preceding vehicle (within 3 seconds) tend to decide to cross the junction more often, even when their preceding vehicle is a heavy vehicle. The current study also revealed that drivers are more likely to stop when pedestrians are observed crossing or waiting to cross. Both results from the study therefore show that drivers do seem to react to the context of their driving environment and tend to make stop or cross decision based on the environmental factors. The influence of these contextual factors may also be directly related to the flow rate of other road users. For instance, the magnitude and effect of travelling behind heavy vehicles may vary with different proportion of heavy vehicles in the traffic stream. Sensitivity of driver decision behaviours to the effects of the proportion of heavy vehicles in the traffic stream may thus suggest the redesigning of the inter-green interval or display of signal phases based on the proportion of different traffic flows.

To understand the importance of the results in relation to red light running, of the 22 vehicles observed in the data entering the junction with the red light showing 17 vehicles were observed closely following their preceding vehicle whereas only 5 were in a leading position when crossing the junction at a red onset. This suggests that the tendency for vehicles to follow a preceding vehicle into the junction can be a major cause of red light running.

The majority of the red light violators in the current study were found within the extended option zones where both crossing and stopping decisions were possible (rather than being in problem zones as would be expected theoretically), with 17 of the 22 red light violators travelling at lower approach speeds (30km/hr and 40km/hr). The precise reasons for the red light violations in the current study will never be known, but they do seem to be associated with driver's unwillingness to stop, or the influence of the contextual factors such as close following, as many of the red light violations could have been safely avoided if the driver has decided to stop.

The conceptual framework of context-aware driver decision behaviour model is shown in Figure 3.9.

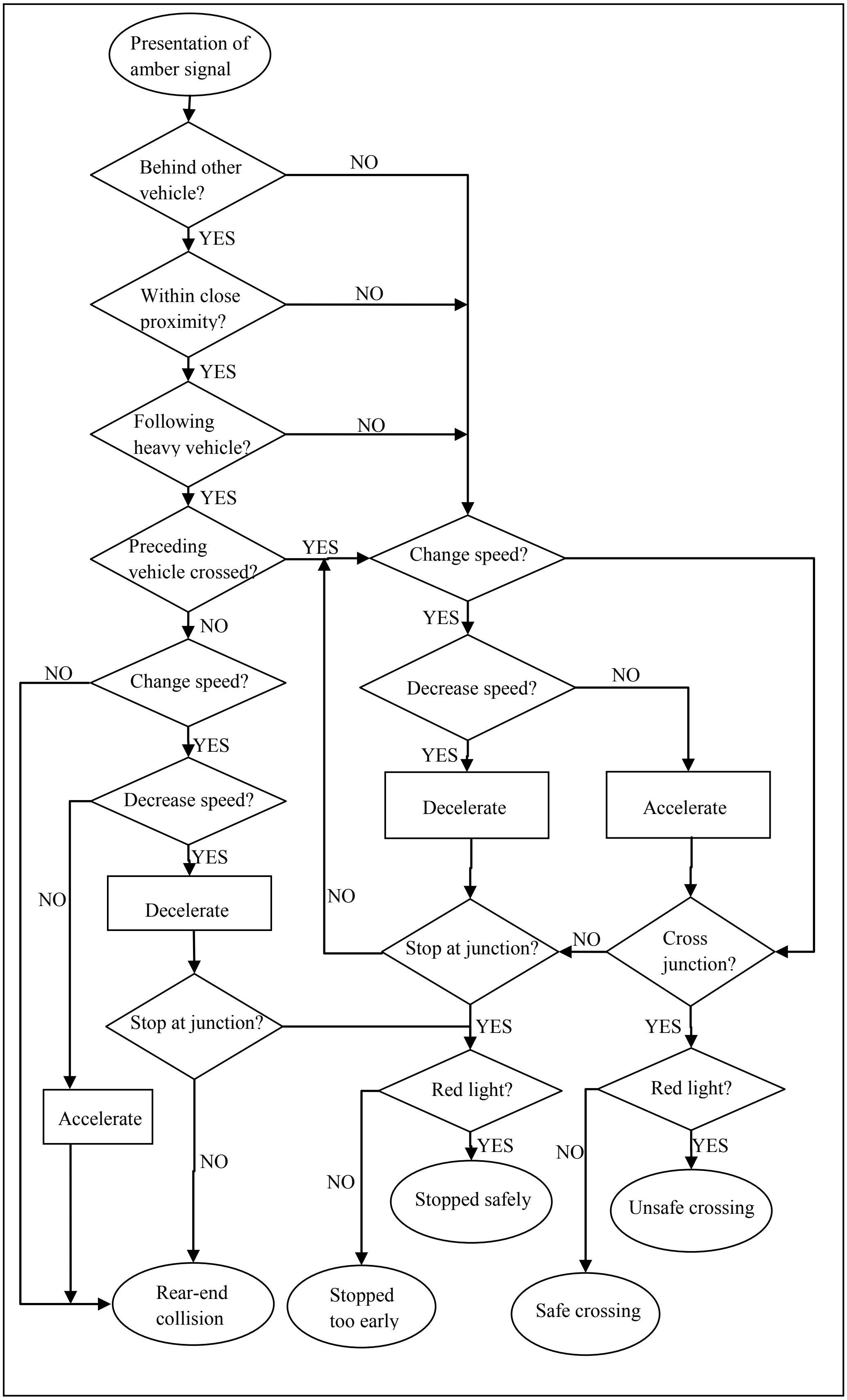


Figure 3.9: Conceptual framework of context-aware driver decision behaviour

3.5. Conclusions

The main aim of the current study was to observe any change in the frequencies of stopping decision under different conditions (for drivers in problem zones and drivers in option zones) with designated range of junction related factors and other road users directly ahead of the drivers, and to reveal any potential indicator of driver's stopping/crossing decision and hence red light running. Four key results have been identified:

- That option zones defined by considering a constant vehicle speed do not reflect the true nature of the decision and that many red light violations occur within an extended option zone rather than a problem zone;
- That drivers following behind a heavy vehicle (more than 3 seconds) are more likely to stop than those at an equivalent speed and distance following a smaller vehicle;
- That the presence of pedestrians at the junction increases the probability of a driver deciding to stop;
- That vehicles following closely (within 3 seconds) of a preceding vehicle are more likely to decide to enter the junction than a vehicle of equivalent speed and distance, but with a larger headway.

Overall, the current study has therefore shown that the traditional 'dilemma zone' models which are based solely on the physical variables of the individual vehicle (speed, distance and vehicle type), neglecting the situational variables identified here do not fully represent the complexity of the decision being made by the driver.

4. Validation study of the driving simulator

This chapter describes a pilot study conducted among a diverse sample of drivers (combinations of younger and older drivers of both genders) to assess the validity of the STISIM driving simulator to replicate a problem zone. Statistical assessment of driving performances between non-overlapping driver groups is presented, which identifies the focus driver group demonstrating potentially unsafe responses to the amber onset.

4.1. Introduction

Driver's decision making at a green to red traffic light transition is, in general, highly dependent on situational variables (Williams, 1977; Sheffi and Mahmassani, 1981; Chang, et. al., 1985; Yong, et. al., 2013). The most common variables have been measured as a combination of their travelling speed and their respective distance from the junction when the amber light was first shown (Gazis, et. al., 1960; May, 1968; Chang, et. al., 1984; Van der Horst, 1988; Elmitiny, et. al., 2010). For instance, shorter distance to the junction results in a more favourable decision to cross (Williams, 1977; Chang, et. al., 1985). Their decisions however, become more difficult when both opportunities of stopping and crossing are highly uncertain (Rakha, et. al., 2007). i.e. when drivers face a problem zone or an option zone. Within a problem zone, the chances of getting exposed to red light are relatively high when a driver chooses to cross the junction; stopping decision on the other hand requires the driver to brake abruptly. Drivers facing an option zone however, would be able to either cross the junction before the amber light ends, or stop safely at the junction.

When comparing between vehicles with similar approach speeds, differences in the magnitudes and boundaries of the problem zone were found among previous findings in the literature (Olson and Rothery, 1972; ITE, 1974; Chang, et. al., 1985; Maxwell and Wood, 2006), thus revealing the dynamic nature of the problem zone. Because drivers vary in performance (Urbanik and Koonce, 2007), driver behaviour remains as the most important factor when the opportunity of stopping or crossing, based solely on their speeds and positions from the junction, appears to be highly uncertain (Rakha, et. al., 2007). In particular, driver population (Liu, 2007) and driver characteristics (Moon and Coleman III, 2003; Rakha, et. al., 2007) have been found to be correlated with the magnitudes of the problem zone; for instance, the boundaries of the problem zone decrease as the driver population age increases (Rakha, et. al., 2007). There have been clear variations in speed and response time between drivers of different ages, with higher speed (Delhomme and Meyer, 1998; Yagil, 1998; Clarke, et. al., 2006; Abdel-Aty, 2009) and higher acceleration rates (McGarva and Steiner, 2000; Shinar and Compton, 2004) found to be associated with younger drivers. In terms of their crossing behaviour in response to the amber light at junctions, younger male drivers are more likely to take risky decision (McDonald, et. al., 1992; Lajunen, et. al., 1998; Golias and Karlaftis, 2002; Oltedal and Rundmo, 2006) to cross regardless of the greater exposure to hazards at the junction during the onset of red signal (Retting and Williams, 1996; Retting, et. al., 1999; Liu, 2007; Rakha, et. al., 2007; Palat and Delhomme, 2012). Decision making by older drivers however, may be constrained by their ability to respond to signal transition (Lu and Pernía, 1999; Retting, et. al., 1999; Dft, 2001; Rakha, et. al., 2007), as a result of their longer reaction time when compared to younger drivers (Demirarslan, et. al., 1998; Green, 2000; Lu and Pernía, 2002).

An understanding of driver characteristics and their ability to respond to the signal transition may provide an insight into predicting driver's decision at junctions more accurately, particularly in a problem zone where the chance of crossing or stopping is close to even. The relationship of driver's decision as a function of driver characteristics could be identified when situational variables remained constant, i.e. to assess how different drivers perform in identical conditions. The assumption of an identical condition for all vehicles is not possible in reality but remains feasible when using a driving simulator. Driving simulators are able to provide a controlled driving environment where each driver meets exactly the same treatment at the same point on the road under the same conditions (Jamson, et. al., 2010). Whether a driving simulator can be a valid research tool is however, assessed by the level of correspondence between performance in the driving simulator and that in the real situation. In the current study, relative validity is necessary (Törnros, 1998) to ensure that the effects of different variations in the driving situation are similar in the same direction (Kaptein, et. al., 1996; Bella, 2005).

Relative validity of driving simulators to reflect driving behaviours (Kaptein, et. al., 1996; Törnros, 1998; Bella, 2005) have been shown in many aspects. For instance, similar levels of workload and psychological environment have been demonstrated between the simulated and real driving environments (Stanton, et. al., 2001). In terms of driver's reactions and decision at junction, measurements from the driving simulators have been shown to be consistent with the real data (Shechtman, et. al., 2007; Abdel-Aty, et. al., 2009; Chan, et. al., 2010; Jamson, et. al., 2010). For instance, rear-end crash propensity measured in the simulator has remained consistent with the crash history analysis data (Yan, et. al., 2008; Abdel-Aty, et. al., 2009); when comparing between two junctions with different approach speeds, the findings revealed a higher probability to face a problem zone at the higher speed junction (Baguley, 1988; Bonneson, et. al., 2002; Papaioannou, 2007). Direct comparisons between individual driver's traffic errors in the simulator and field studies also revealed that similar types of errors have been committed by the same drivers in both studies (Shechtman, et. al., 2009). Using driving speed as a surrogate measure for driver's level of aggressiveness (Mesken, et. al., 2007), variability in driver behaviour to different traffic situations can be reflected in their speed management of the driving simulator (Stephens and Groeger, 2009). For instance, driver's higher level of aggressive behaviour was observed with increasing driving speed (Delhomme and Meyer, 1998; Lajunen, et. al., 1998). Lower speed in simulators was found with more distracted, or more complex environment (Santos, et. al., 2005; Jamson, et. al., 2010) such as roads with difficult manoeuvre (Comte and Jamson, 2000; Bella, 2008).

In general, approach speed in simulators is more likely to be higher (Blaauw, 1982; Riemersma, et. al., 1990; Godley, et. al., 2002; Yan, et. al., 2008) when compared with the real data; this may be due to lower perceived risk in driving simulators (Bella, 2008). The same argument has been used to support for the larger variation in acceleration rates in simulator (Blaauw, 1982). In a similar trend, speed performance between drivers of different ages in the field study were also shown in simulator studies, such as higher speed, and higher acceleration and deceleration rates which have been found more likely to be adopted by younger drivers (Caird, et, al, 2007; Yan, et. al., 2008), particularly among male drivers (Retting and Williams, 1996; Liu, 2007; Yan, et. al., 2008). Although simulator experiments may not be appropriate for all drivers due to possible motion sickness (Shechtman, et. al., 2007), a driving simulator has been useful as a research tool to replicate traffic situations (e.g. potentially risky situations), and predict traffic evolution to improve junction safety (Stephens and Groeger, 2009; Casucci, et. al., 2010). From many aspects, the comparisons between driving performance in field studies and simulator studies have shown the potential of driving simulators to explain the interaction between drivers and roadway surroundings (Yan, et. al., 2008).

Younger male drivers have been found in the literature with greater tendency in speeding (McDonald, et. al., 1992; Lajunen, et. al., 1998; Golias and Karlaftis, 2002; Cestac, et. al., 2011) and running red lights (Retting and Williams, 1996; Retting, et. al., 1999; Liu, 2007; Rakha, et. al., 2007; Palat and Delhomme, 2012) as against drivers of opposite gender (Retting and Williams, 1996; Shinar, 1998; Retting, et. al., 1999; Liu, 2007) and different age group (Delhomme and Meyer, 1998; Yagil, 1998; Yan, et. al., 2008). Whether there exists any difference between drivers of different age groups and/or different gender in terms of their decision behaviour to the amber light could not be determined by the observational study (c.f. Chapter 3). The effect of gender difference and age difference in driving performance could however be measured in this study by dividing the samples into non-overlapping subgroups with similar characteristics. Previous studies have also suggested that cultures between demographic areas constitute a difference in risk taking concept when confronted with an amber signal (Ulleberg and Rundmo, 2003; Chliaoutakis, et. al., 2005; Papaioannou, 2007). In particular, deceleration rates have been observed to be significantly higher in rural areas than urban areas (Bennett and Dunn, 1995). Studying the effect of road types on driver decision behaviour to the amber light requires setting up of a series of observational studies at multiple sites, which can be expensive. The use of simulator could therefore provide a more feasible way to measure driver deceleration rates and other variables to evaluate driving performance between different demographic areas.

The aim of the current study is therefore to explore the potential influence of driver characteristics (i.e. age and gender) and road environments (i.e. demographic regions) on driving performance and their decision in response to the onset of the amber light.

4.2. Methodology

4.2.1. Equipment (Driving Simulator)

The Southampton University Driving Simulator (SUDS), an interactive fixed-base driving simulator, was used in the study as a valid tool for studying straight-road driving behaviour (Blaauw, 1982). The simulator's vehicle cab is based around a Jaguar XJ saloon with fully operational driver controls, see Figure 4.1. The road scenario is projected onto three screens with 135 degree driver field-of-view and the sounds of the engine were reproduced. In the present study, the simulator was set up to run with automatic transmission to avoid the potential differences in driving performance due to driving experience (Shinar, et. al., 1998) and the engagement of gears and clutch control in manual transmission (Warshawsky-Livne and Shinar, 2002; Harley, et. al., 2008).

Figure 4.1: Driving simulator with virtual environment

4.2.2. Driving scenario (Simulated route)

The simulated route was developed using a total of 26 signalised junctions divided across sections of rural, sub-urban and urban roads. The route incorporated no turning manoeuvre; drivers were required to drive only in ahead movement and the route took approximately 20 minutes to complete. A total of 26 signalised junctions were allocated on the route and the inter-green interval was set to be identical to the settings at Burgess Road (c.f. Chapter 3) which comprises an amber signal of 3 seconds and an all-red signal of 2 seconds. Static signs showing the imposed speed limits (50mph (i.e. 22.4m/s) for rural, 40mph (i.e. 17.9m/s) for sub-urban and 30mph (i.e. 13.4m/s) for urban) were set up between road intervals to remind drivers of their speed compliance. 5 junctions (3 in rural, 1 in sub-urban, 1 in urban) were designed to replicate a problem zone where drivers with their individual approach speed would get exposed to the onset of amber light when they were within 3 seconds upstream of the junction. The remaining 21 signalised junctions were assigned with red and green lights. Green to red transition was included across road types to evaluate whether driver's performance would change between rural, sub-urban and urban areas.

Figure 4.2: Screenshots of driving scenario from (a) rural (b) sub-urban (c) urban junction

4.2.3. Participants (Drivers)

80 drivers were recruited from the students and staff from the University of Southampton with 19 female and 25 male drivers whose age ranged between 20 and 30 years, and 12 female and 24 male drivers with age between 50 and 60 years. The drivers had held a valid UK (or equivalent) driving license for at least 24 months.

4.2.4. Procedure

Upon arrival at the laboratory, each driver was briefed on the experimental procedure before reading and signing a consent form. Drivers were then given a practice drive for about 10 minutes to familiarise themselves with the driving simulator controls prior to the actual experimental trial. A colour vision test for colour blindness was also included in the practice drive. In the experimental trial, drivers were required to respond accordingly to the traffic light displayed at each of the 26 signalised junctions on the driving route. On completion of the route, drivers were asked to answer a questionnaire if they had been found to violate the red light at any of the 5 junctions designated with green to red transition. Drivers were then debriefed and paid.

4.2.5. Design of experiments

Both between-subjects and within-subjects design were used in this study to allow comparisons between driving performance as an effect of junction specific factors (i.e. different demographic areas with 2 degrees of freedom) and driver factors (i.e. age and gender groups with 3 degrees of freedom). The independent variables were the combination of gender (male or female) of the drivers and their age group (younger or older), and the type of road in the driving scenario (rural, sub-urban or urban). Dependent variables were the driving performance measures taken (speed, reaction time and force applied on simulator controls, and driver decision).

4.2.6. Data manipulation and analysis

Driving performance data of individual driver was obtained at every 0.1 sec, from the output data of the driving simulator, as continuous measures of the following variables:

Table 4.1: List of variables as the output of the driving simulator

Variables
Elapsed time since beginning of each simulated trial
Driver’s longitudinal acceleration with respect to elapsed time
Driver’s longitudinal velocity with respect to elapsed time
Total longitudinal distance driver has travelled since beginning of the simulated run
Current traffic light status
Running compilation of the crashes that the driver has been involved in
Distance and elapsed time when violation occurs
Driver’s brake force with respect to elapsed time

Based on the distance and traffic light status with respect to the elapsed time from the onset of the trial, driving performance data from the 5 junctions on green to red transition (i.e. Junction A, B, C, D and E) were successfully extracted from the output data. The following measures were derived and used as the new variables to evaluate driving performance between the four driver groups:

(a) Vehicle's speed and distance from the stop line when the amber light was triggered;
(b) Vehicle's estimated time to the stop line assuming constant initial speed at the amber light onset;
(c) Driver's braking response time measured as the elapsed time between the onset of amber signal and driver's application on the brake pedal;
(d) Vehicle's maximum acceleration and deceleration rate throughout the amber duration.

Non-parametric statistical tests (e.g. Mann-Whitney, Friedman, and Wilcoxon tests) were applied to the data.

4.3. Results

4.3.1. Validation of the conditions for a problem zone among crossing and stopping vehicles

When the signal light was triggered from green to amber at the control junctions, individual driver's position on the route was measured as the distance from the stop line with their respective approach speed. All vehicles were observed to stop at Junction D. Using the Mann-Whitney U test for the remaining four junctions found no significant differences between stopping and crossing vehicles in terms of their initial positions to the stop line when the amber light first appeared. See Appendix B. The average estimated times to cross the 5 junctions were shown in Table 4.2. Drivers without accelerating at the onset of the amber phase would require significantly more than 3 seconds ($p < 0.05$) crossing each of the junctions A to D, implying that drivers who crossed these 4 junctions with their constant approach speed were more likely to encounter a red light. On the contrary, the average estimated time to cross Junction E was significantly less than 3 seconds ($p < 0.05$), suggesting that drivers were less likely to get exposed to the red phase.

Table 4.2: Averages and standard deviations of estimated time to stop line

Junction	Estimated time to stop line (secs)	
	Median	Standard deviation
A	3.7428	.10910
B	3.1882	.27246
C	3.7413	.12336
D	3.9600	.03554
E	2.7397	.27494

*Median was used in place of mean because the estimated time was found to be non-parametric in the Shapiro-Wilk normality test

Among the stopping vehicles at the five junctions (i.e. Junctions A to E), their maximum deceleration rates were found to be significantly higher than the suggested deceleration rates to stop safely within the signal change interval (Olson and Rothery, 1972; Maxwell and Wood, 2006; ITE, 2009), hence demonstrating unsafe stopping at junctions.

4.3.2. Influence of regional factor

4.3.2.1. Speed

Using a within subjects design, the factorial effects of different road types were tested using the Friedman test and Wilcoxon Signed Rank test. The results showed that driver's approach speeds were significantly higher among rural junctions ($p < 0.05$). Similar trends were also shown between rural and sub-urban, and between sub-urban and urban areas. As shown in Figure 4.3, drivers reduced their speed gradually as they moved across lower speed regions. When compared between rural junctions, approach speed was found to be significantly higher at Junction A than Junction B. With Junction A having been designed as the first signalised junction on the route, reduced approach speed at Junction B may be more likely to be caused by the learning effect.

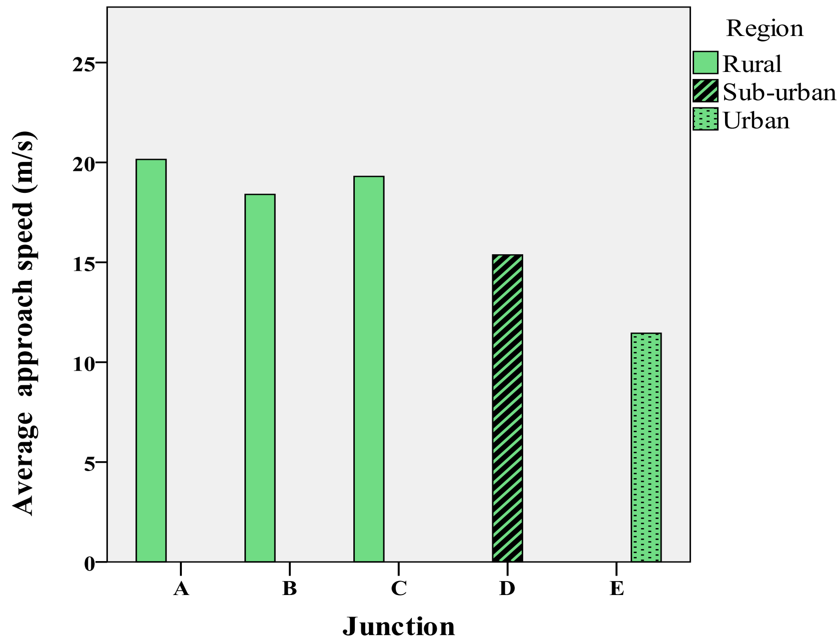


Figure 4.3: Average speed for different junctions

4.3.2.2. Trigger distance

In terms of driver's trigger distances of the amber phase, significant differences were also found between different regions; their respective transition point from green to red signal moved closer towards the junction as they moved from rural to urban areas. Results from the Mann-Whitney test also showed that drivers were more likely to stop only when they were further upstream of the rural junctions at the amber onset. Comparison tests between rural junctions also revealed significant decrement in both driver's approach speed and the trigger distance for Junction B, which was designed with pedestrian crossing. See Figure 4.3 for distribution of speeds and Figure 4.4 for distribution of trigger distances between the five junctions.

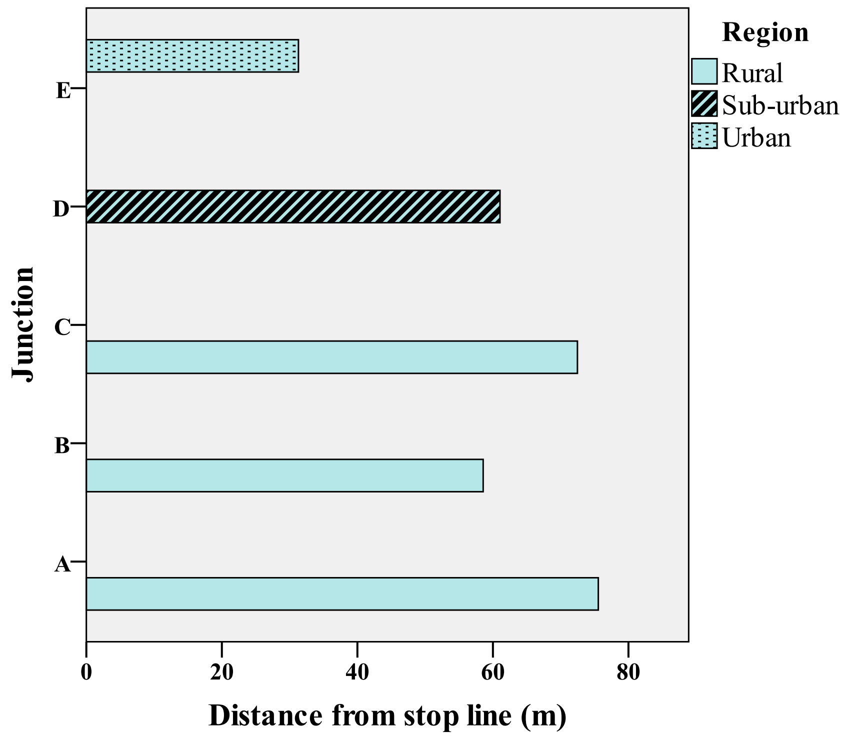


Figure 4.4: Average distances from the stop line at amber onset (between junctions)

4.3.2.3. Deceleration rate

In terms of the deceleration behaviours of independent stopping vehicles, significant variability in deceleration rates were found between the urban and rural junctions. Although driver's deceleration rates at the sub-urban junction appeared to be higher than that at the urban junction, and lower than the rural junctions, the differences were not statistically significant (based on the Mann-Whitney U test). However, significantly higher deceleration rates were found at Junction A in comparison to all other junctions, regardless of the road types, showing consistent learning effects after Junction A. See Table 4.3.

Table 4.3: Significant differences in maximum deceleration rates for stopping vehicles

		Rural		Sub-urban	Urban
	Junction	B	C	D	E
Rural	A	*	*	*	*
	B				*
	C				*
Sub-urban	D				

*indicates significantly higher deceleration rate at Junction i (in row) than Junction j (in column) where i=A to D, j=B to E

In terms of the occurrence rate of red light violations, there seems to be differences between different regions, with rural junctions having the highest violation rates among all three regions. A total of 20 red light violations were found at rural junctions (i.e. Junction A, B and C) compared to the other two regions (i.e. Junction D and E) which had a combined frequency of only 1 violation. Distributions of these violations across the five junctions can be found in Table B.5 in Appendix B.

4.3.3. Influence of driver factor

Driver behaviour has been raised as a critical factor in driver decision at junctions (Williams, 1977; Van der Horst and Wilmink, 1986; Yagil, 1998), particularly when the opportunity of stopping or crossing remains highly uncertain (Rakha, et. al., 2007). Previous studies have shown that driver behaviours vary in different manners between drivers of different age groups and gender (Retting and Williams, 1996; Shinar, 1998; Retting, et. al., 1999a; Liu, 2007), therefore suggesting that gender and age are strong predictors of driver attitudes and behaviour (Nordfjærn, et. al., 2010; Cestac, et. al., 2011). Using age and gender as a between-subjects factor, the subjective assessment of driving performance is described in the following sections, based on the four driver groups: younger female (YF), younger male (YM), older female (OF) and older male (OM). Driver’s approach speed measured at the amber onset was compared across the four driver groups, for five individual junctions. Apart from Junction A, results from the Kruskal Wallis test have shown significant differences among different driver groups. Using the Mann-Whitney U test (post-hoc analysis), significant lower speed in older drivers (of both genders) was identified (see Figure 4.5).

4.3.3.1. Speed

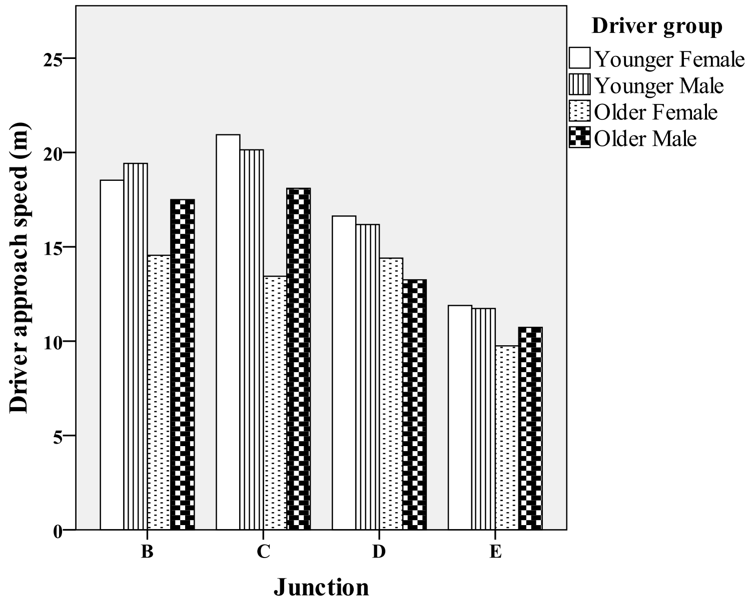


Figure 4.5: Average speed between different driver groups

4.3.3.2. Trigger distance

Significant differences in driver's distance from the junction were also found between younger and older drivers when the amber light first appeared. Results from the Mann-Whitney U test shows that, when the amber light appeared at a distance closer to the junctions, older drivers were more likely than the younger drivers to stop. See Figure 4.6.

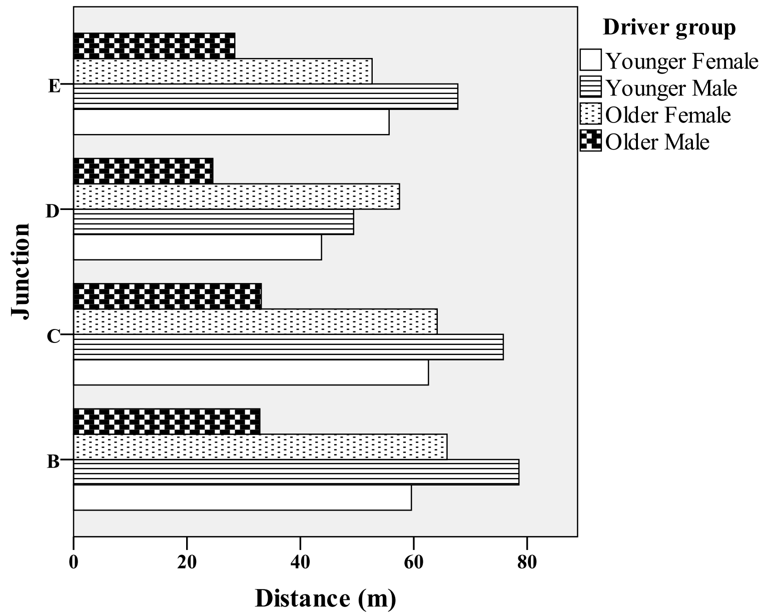


Figure 4.6: Distances from the stop line at amber onset (between different driver groups)

4.3.3.3. Deceleration rate

In terms of deceleration rates, significantly higher deceleration rates ($p > 0.05$) were found among younger female drivers, when compared to the other three driver groups. Their higher tendency to decelerate harder on stopping was however not found at the urban junction (i.e. Junction E). See Table 4.4.

Table 4.4: Significant difference in maximum deceleration rates between driver groups

	Maximum deceleration rates at junction when amber light commences											
	Rural									Sub-urban		
	Junction A			Junction B			Junction C			Junction D		
	YM	OF	OM	YM	OF	OM	YM	OF	OM	YM	OF	OM
YF			*	*		*	*		*	*		*

*indicates significantly higher deceleration rate among younger female drivers (YM) than other driver groups at different junctions

4.3.3.4. Braking response time

Comparisons between different driver groups in terms of their braking response time to the amber phase revealed no significant differences among them. As shown in Table 4.5, the average braking response time in the current study was found to be either less than 1 second or relatively close to 1 second, regardless of their gender or age differences.

Table 4.5: Average braking response times between the four driver groups

	Average braking response times to the amber light (in secs)				
	Junction A	Junction B	Junction C	Junction D	Junction E
YF	0.99	0.97	0.81	0.91	0.92
YM	0.83	0.98	0.97	1.03*	1.01*
OF	0.94	0.86	0.8*	0.84	0.92
OM	0.92	0.94	0.9	1.03	0.88

*Median was used in terms of mean due to the braking response times of the respective samples being non-normal based on the Shapiro-Wilk test

4.3.3.5. Problem and option zones

The sizes of the problem zone and option zone have been demonstrated to be an important indicator in terms of the level of safety at junctions (Gazis, et. al., 1960; May, 1968; Chang, et. al., 1985; Prashker and Mahalel, 1989). In the current study, the sizes of these zones were estimated at all the 5 junctions as a function of approach speed, brake response time and deceleration rate. These three variables were utilised, based on individual driver, to set up three important measures, formulated as equations [4.1], [4.2] and [4.3].

$$\textit{Minimum stopping distance} = \frac{V^2}{2a} \qquad [4.1]$$

$$\textit{Maximum amber passing distance} = V(\tau - t_{brake}) \qquad [4.2]$$

where V denotes the speed in m/s when the amber light first appeared;

t_{brake} denotes the brake response time in seconds, which is assumed to be 1;

a denotes the maximum decelerate rate (in m/s^2) of the vehicle and

τ denotes the amber duration, which is taken as 3 seconds.

Equation [4.1] and [4.2] are the two important measures respectively defined by Gazis, et. al. (1960, pp. 114-116), as 'x_c, *the critical distance to stop safely*' and 'x_0, *the maximum distance to cross without acceleration*'. The difference between these two equations then decides between the formation of either a problem zone or an option zone.

$$\left.\begin{array}{lll} Problem\ Zone = abs\left(V(\tau - t_{brake}) - \frac{V^2}{2a}\right) & \text{if} & V(\tau - t_{brake}) - \frac{V^2}{2a} < 0 \\ \quad\quad\text{(or)} & & \\ Option\ Zone = abs\left(V(\tau - t_{brake}) - \frac{V^2}{2a}\right) & \text{if} & V(\tau - t_{brake}) - \frac{V^2}{2a} > 0 \end{array}\right\} \quad [4.3]$$

The estimated sizes of the problem zones and option zones from equation [4.3] were plotted for the four driver groups. For example, an estimated option zone of approximately 13.5m (as indicated in Figure 4.7(a)) was encountered by a younger female driver from the sample who was travelling at a speed of 21m/s when the amber light first appeared. On applying a higher deceleration rate of 7.2m/s^2 (0.9 second after the amber light appeared), the size of the option zone was estimated as:

$$\left|21(3 - 0.9) - \frac{21^2}{2(7.2)}\right| \approx 13.5m$$

If a driver from the same sample group, with similar travelling speed and reaction time, chose to apply lower deceleration rate to stop, she may be more likely to encounter a problem zone instead of an option zone. For instance, an estimated problem zone of approximately 21m was encountered (see Figure 4.7(a)) when the driver chose to decelerate at 3.6m/s^2, i.e.

$$\left|22(3 - 0.9) - \frac{22^2}{2(3.6)}\right| \approx 21m$$

It seems that the chances of encountering an option zone are significantly higher than that of a problem zone, as illustrated in Figure 4.7. Driver's critical distance to stop (x_c) and their respective maximum distance to cross each junction without accelerating (x_0) were plotted in terms of their distances from the stop line; as shown in Figure 4.8, a shorter critical distance was found among older drivers. Longer critical distances were also found at locations further upstream of the rural junctions (i.e. Junction A, B and C) when average approach speed was high. For all driver groups except the older females, their chances of getting trapped in a problem zone were found only when their approach speed was beyond 12m/s at the amber onset. This lower bound was found to be 10m/s among older female drivers, the driver group that experienced smaller magnitudes of problem zones than the other three groups, and therefore less chance than others to make difficult decision when the traffic signal changes to amber (York and Al-Katib, 2000).

4.3.3.6. Red light violation rate

In terms of the statistics of red light violations in the current study, it is obvious that younger female drivers had committed the highest number of red light violations (i.e. 8 out of 21 violations). See Table 4.6. These violations were again, identified at rural junctions where the approach speeds remain higher.

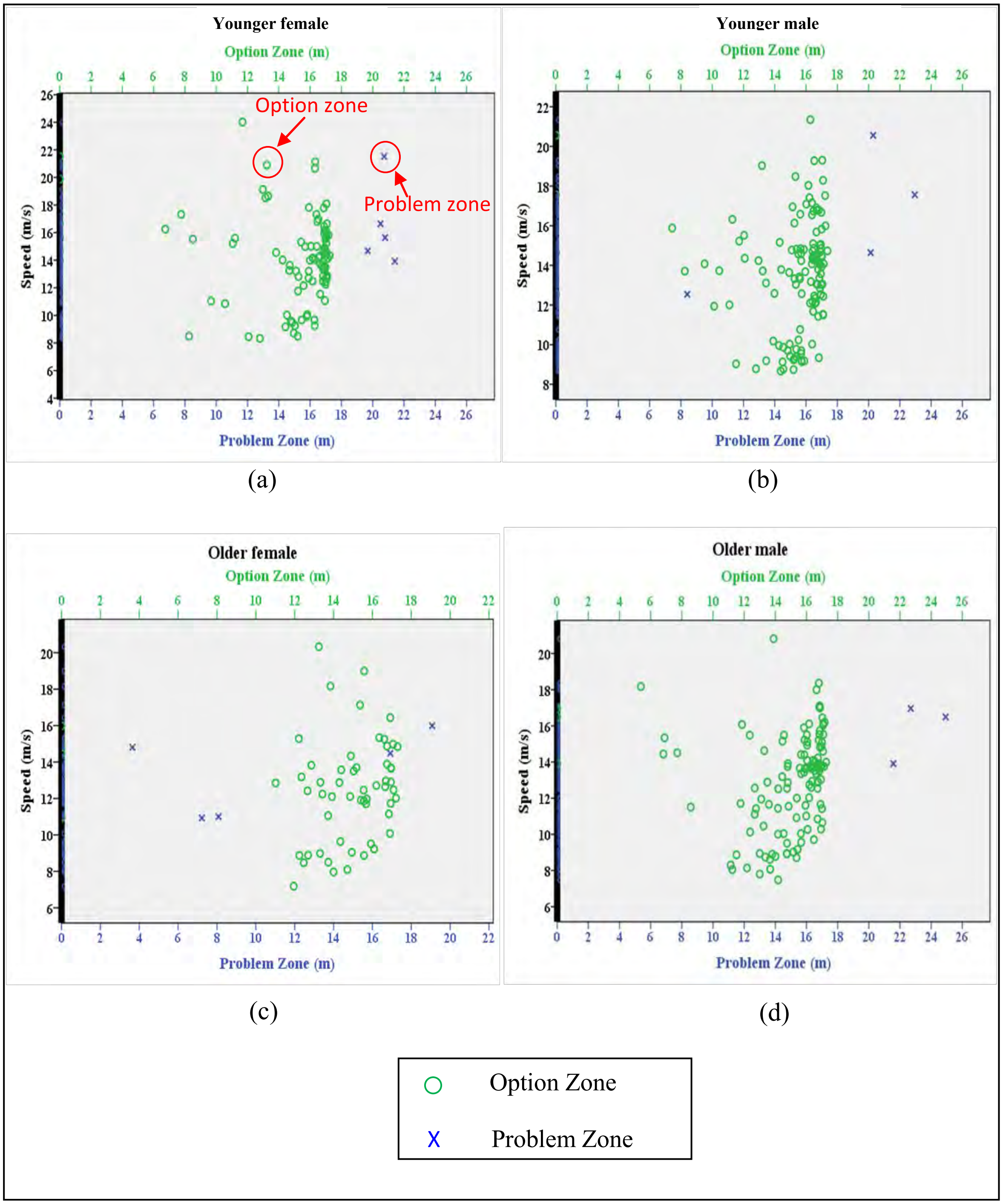


Figure 4.7: Illustration of the magnitudes of the estimated problem zones and option zones with respect to driver's speed (between different driver groups) when amber light appeared.

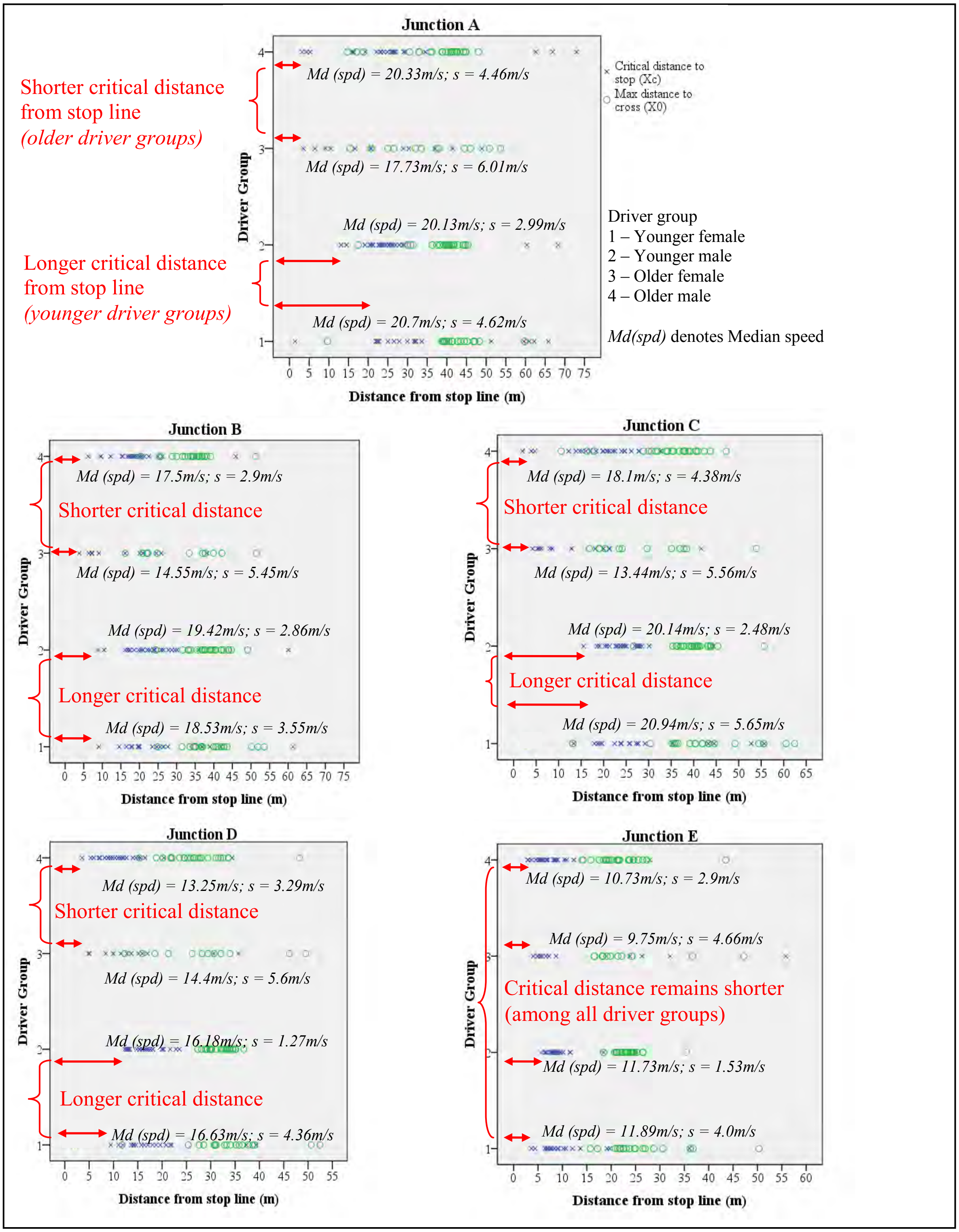


Figure 4.8: Driver's critical distance to stop and maximum possible distance to cross at Junctions A to E (between different driver groups)

Table 4.6: Frequency of red light violations by different driver groups

	Junction					
	A	B	C	D	E	Total
Younger female (YF)	4	4	0	0	0	8
Younger male (YM)	3	1	1	0	0	5
Older female (OF)	1	0	1	0	1	3
Older male (OM)	4	0	1	0	0	5
	12	5	3	0	1	21

4.3.4. Questionnaires

Questionnaires were given out only to the 17 drivers who had violated the red light at least once on the simulated route. Among the red light violators, four of them had run the red light twice. Approximately 50% of the violators, in particular female drivers, reported that they had overestimated their ability to cross the junction before the amber light terminated. In terms of their assessment on the potential red light countermeasures, about half of the total drivers reported that their violations would have been avoided if they were provided with advanced information on the impending signal change. A summary of the questionnaires is shown in Table 4.7 and 4.8.

Table 4.7: Statistics of the reasons of red light violations based on driver's responses from the questionnaires

I did not stop because…	Driver group			
	Younger female	Younger male	Older female	Older male
1. I did not notice the traffic light	1	2	0	1
2. I was confident to be able to cross the junction before the signal turns red	4	1	2	1
3. 'Amber light does not mean stop'	0	1	1	0
4. I want to avoid waiting at the red light	0	1	1	1
5. I thought it was safe to cross	1	2	1	0
6. I was driving too fast	1	1	1	0
7. There was no oncoming traffic from other lanes	0	1	0	0
8. I was distracted	0	1	0	0
9. I don't like to stop unless necessary	0	0	1	0
10. I was close to the junction	3	1	0	0

Table 4.8: Statistics of driver's assessment on the potential countermeasures

I would have stopped if…	Driver group			
	Younger female	Younger male	Older female	Older male
1. There was a red light traffic camera	3	1	1	1
2. There was/were clear stopping sign(s)	2	2	0	1
3. I knew the remaining amber time	2	1	1	0
4. I knew that I would encounter the red signal(s)	3	2	1	2
5. I was instructed when to stop	2	0	1	1

4.4. Discussion

Using a driving simulator, the current study explored the variability in driving performance between different driver groups and different demographic regions when confronted with the amber phase onset. The results from the current study demonstrated the ability of the driving simulator to replicate the conditions for a problem zone. In particular, higher likelihood to commit red light violations on crossing, and higher deceleration rates among stopping vehicles in the current study are the two important indicators of a problem zone (Gazis, et. al., 1960; May, 1968; Mahalel and Prashker, 1987; Urbanik and Koonce, 2007; Puan and Ismail, 2010). The use of the simulator has the benefits towards providing increased experimental control over situational variables to ensure that all vehicles were treated with identical situations on the same route when the amber light appeared. The differences in driver responses to the signal transition would therefore imply the effects of driver factors on their driving performances. Age for instance, was used as a good indicator in the current study to predict driver speed performance. In line with the literature (Parker, et. al., 1992; Yang and Najm, 2007; Caird, et. al., 2007), younger drivers were found to approach the junctions at higher speed than the older drivers and were more likely to increase their speed during the signal change interval (Konečni, et. al., 1976). As speed increases among younger drivers, trigger distances for their problem zone also extend further upstream (Olson and Rothery, 1972; ITE, 1974; Chang, et. al., 1985; Maxwell and Wood, 2006). The nature of the problem zone to enlarge at higher approach speeds (Gazis, et. al., 1960; May, 1968; Urbanik and Koonce, 2007; Hurwitz, et. al., 2011) is illustrated in Figure 4.8, with shorter critical distance among older drivers and therefore less likely to be within a problem zone. The chances of drivers facing a problem zone however are far less than that of an option zone, as shown in Figure 4.7. This finding is consistent to the observational study in Chapter 3, which revealed that drivers commonly do not maintain their constant speed in response to the amber onset (as opposed to the assumption of a problem zone).

In contrast to the previous studies which have shown that higher approach speeds among younger drivers were less pronounced in females (Oltedal and Rundmo, 2006; Cestac, et.

al., 2011), no significant difference was found between younger male and female drivers in the current study in terms of their approach speed. Likewise, the current study also found that younger female drivers were more likely to contribute to higher speed and higher deceleration rates, which is not in line with the literature (Oltedal and Rundmo, 2006; El-Shawarby, et. al., 2007; Cestac, et. al., 2011). The reason for the opposite trend although is not clear, this might be due to the differences in the classification of age groups between the two studies. For instance, the younger driver groups in the current study were sampled from drivers whose age ranged between 20 and 30 years, but the same classification was used for drivers with age below 40 years old in the study by El-Shawarby, et. al. (2007). Perhaps the sample size of female drivers with the age between 20 and 30 years old were too small in their study to make a statistical inference of their high deceleration rates. This minor inflection of the results also raised attention on providing safety measures to female drivers aged between 20 and 30 years.

In line with the literature, driver's braking response time did not seem to change between different age groups (Warshawsky-Livne and Shinar, 2002). In particular, the current study supported the findings that one-second response time is sufficient for all age groups to stop for the amber light (Olson and Rothery, 1961; Chang, et. al., 1985; ITE, 1989, Caird, et. al, 2007). See Table 4.5. Previous findings also explained that if longer reaction times were found among older drivers, it may be due to their delay in recognition of the driving environment (Demirarslan, et. al., 1998).

In terms of driving performance over different demographic regions, the results in the current study were consistent with previous findings, with higher approach speed observed at the rural junctions (May, 1968; Hanna, et. al., 1976; Van der Horst and Wilmink, 1986; Bennett and Dunn, 1995; Jamson, et. al., 2010). The likely events of a problem zone to be located at distances further upstream of the rural junctions were also found (Olson and Rothery, 1972; ITE, 1974; Chang, et. al., 1985; Maxwell and Wood, 2006). See Figure 4.3. Higher frequency of red light violations at the rural junctions (see Table B.5 in Appendix B) may therefore be explained as a consequence of higher approach speed and lower traffic density (Clark and Cushing, 2004; Eiksund, 2009).

The proportion of drivers violating the red light in the current simulator study (i.e. 21 out of 800 vehicles) was found to be similar (i.e. 3%) to that from the observational study on Burgess Road (22 out of 781 observations); the results indicate that driver's intensity to cross a junction on red in response to the amber light are similar in both the simulator and the real situations, which otherwise showed the relative validity of the use of driving simulator to measure driver violation. Based on the feedbacks from the questionnaires, it was revealed that red light violations were in many cases, caused by driver's overestimation of their opportunity to cross the junction before the signal turned red. The error was reported particularly on female drivers. Also, regional effects play an important role on driver's judgment skills; for instance, driver's judgment error on the actual distances (Zegeer and Deen, 1978; Yagil, 1998) has been identified to be more significant in rural areas than in urban areas (Liu and Wu, 2009). Driver's feedback on the potential red light countermeasures also revealed that their violations could be avoided if they had advanced notice of the impending red light.

4.5. Conclusion

The fixed-base simulator has been shown in the current study to effectively replicate the potential problem zones. In similar trends with the literature (Delhomme and Meyer, 1998; Yagil, 1998; Clarke, et. al., 2006), younger drivers of both genders were found to drive significantly faster than the older drivers, thus resulted in their reduced compliance to the red light. Unexpectedly, younger female drivers had demonstrated significantly higher speed on crossing and higher deceleration rates on stopping; both responses were unsafe and require further attention. Red light violations were also found to be more frequent at rural junctions, among younger drivers with significantly higher speed. The likelihood of younger drivers to more risky driving behaviour therefore suggests that attention should be raised on providing safety measures to younger drivers to reduce unsafe responses at junctions.

5. Experiment design and methodology

The objectives of this chapter are to describe the simulation equipment, design of driving simulations, sample of drivers, the general experimental procedure and the parameters used to assess driving performance.

5.1. Equipment (Driving simulator)

The study was performed using the Southampton University Driving Simulator (SUDS). Briefly, the SUDS is a fixed-base driving simulator integrated to the STISIM Drive software, and the simulated environment is projected at 135 degree driver field-of-view (cf. Chapter 4). The displayed roadway is interactive with driver's inputs from the simulator controls. In the current study, the simulator was set up to run with 4-speeds manual transmission.

5.2. Driving scenario (simulated route)

Identical route was repeatedly used in the current study for a series of four driving experiments. The simulated route took approximately 20 minutes to drive and incorporate rural, sub-urban and urban scenarios with no turning manoeuvre, where drivers were required to drive only in ahead movement to avoid the differences in potential delays due to road complexity (Green, 2000; Liu and Wu, 2009). Static signs were displayed alongside the road to inform drivers of the traffic lights ahead and the imposed speed limits of 50mph (i.e. 22.4m/s), 40mph (i.e. 17.9m/s) and 30mph (i.e. 13.4m/s) respectively in rural, sub-urban and urban areas as the drivers drive through the route. Examples of these static signs are shown in Figure 5.1.

(a) (b) (c)

Figure 5.1: Static sign to inform drivers of the (a) signal light ahead; (b) speed limit of 30mph; and (c) speed limit of 50mph

A total of 26 signalised junctions were allocated across the simulated route which incorporated no turning manoeuvre. The inter-green interval was set to be 5 seconds, which comprises an amber signal of 3 seconds and an all-red signal of 2 seconds. Problem zones, where drivers experience exposure to the onset of the amber phase when they are within 3 seconds upstream of the junction, were replicated at 7 junctions (i.e. 4 in rural, 1 in sub-urban, 2 in urban) throughout the route. Red and green signals were allocated at the remaining 19 junctions distributed across different sections on the route. Traffic was present in the opposite lane, and drivers were constrained by vehicles (i.e. heavy vehicles and passenger cars) directly ahead of them approaching three selected junctions when the amber phase appeared. Results from the observational study (c.f. Chapter 3) have indicated a trend of crossing behaviour in relative to their headway when travelling behind a preceding vehicle during the amber onset. This behaviour may be reflected in the current driving simulator study in terms of driver's variation in speed until their final decision.

From the review of the literature (May, 1968; Hanna, et. al., 1976; Van der Horst and Wilmink, 1986; Bennett and Dunn, 1995; Eiksund, 2009), it was believed that higher risk behaviours are found in rural areas than urban areas. Scenarios with preceding vehicles (i.e. contextual factors) were therefore duplicated in rural and urban roads on the route. Inclusion of pedestrian crossing at a selected rural junction also allows comparison of performance between different layouts.

5.3. Participants (Drivers)

Drivers were selected among younger drivers whom have been found more likely to exceed speed limit (e.g. Delhomme and Meyer, 1998; Yagil, 1998; Clarke, et. al., 2006) and get involved in risky driving behaviour at junctions (e.g. McDonald, et. al., 1992; Ulleberg and Rundmo, 2003; Eiksund, 2009) such as violating the red light on crossing and abruptly applying the brake on stopping. The results from the driving simulator study (c.f. Chapter 4) are consistent with the literature, suggesting that younger drivers are more likely to encounter problem zones in response to the amber onset.

32 drivers (17 male and 15 female) between the ages of 20 and 35 years were therefore recruited from the students and staffs of the University of Southampton to participate in the current driving study. The current study required all drivers to have held a full UK (or equivalent) driving license for at least 24 months and be able to operate a manual car.

5.4. Procedure

Upon arrival at the laboratory, each driver was briefed on the experimental procedure before reading and signing a consent form. Drivers then completed a practice drive for about 10 to 15 minutes to familiarise themselves with the driving simulator controls. Following this, each driver drove the simulated route 4 times, once for each of the three interventions and once without any intervention (i.e. control condition). Throughout the entire study, drivers were instructed to maintain their approach speeds below the imposed speed limits wherever possible. Drivers were given a rest of 5 to 10 minutes in between consecutive trials that were pre-arranged in different orders. The orders of the trials in the entire study were counterbalanced among the first 24 drivers, and the remaining 8 drivers were tested in a random order of the 4 trials. On completion of the four trials and a questionnaire, drivers were debriefed and paid £20. The entire driving study took approximately two hours.

5.5. Design of experiments

Both between-subjects and within-subjects design were used in this study to allow comparisons between driving performance as an effect of junction specific factors (i.e. different demographic areas with 2 degrees of freedom), driver factors (i.e. gender with 1 degree of freedom), contextual factors (i.e. existence of preceding vehicle and its vehicle type with 3 degrees of freedom) and the mode of interventions (i.e. types of intervention with 3 degrees of freedom). The independent variables were the gender (male or female) of the drivers, the type of road in the driving scenario (rural, sub-urban or urban), position on road relative to the preceding vehicle and vehicle type (following or not following heavy vehicle/passenger vehicle) and the type of interventions (control, extended-amber, flashing-amber or advanced signal). Dependent variables were the driving performance measures taken (speed, reaction time and force applied on simulator controls, and driver decision).

5.5.1 Interventions design

From the review of the literature on different types of proposed interventions to reduce potential red light violations at signalised junctions, it is suggested that interventions to provide shorter warning time (Van der Horst, 1988) or 'necessary' reaction time (Peterson, 2006) to drivers may be effective in avoiding unsafe decision at junctions; it is believed that 1 second is sufficient reaction time among all drivers (Jourdain, 1986; Caird, et. al, 2007). The question then arises on the best method to provide the extra 1 second to drivers. The empirical method of adding 1 second to the amber phase has been shown to have a consistent reduction in red light violations across rural (May, 1968) and sub-urban roads (Stimpson, et. al, 1980). Impacts on the benefits and drawbacks have been reported in the literature (Retting and Greene, 1997); details of driver decision behaviour during the signal change interval are however missing. In the more recent studies on red light countermeasures, advanced warning aids (Moon, et. al., 2008) such as the use of flashing amber phase (Newton, et. al, 1997) and additional signal pole (Harb, et. al., 2007) to convey warning messages have been shown to be effective in raising driver's awareness to the amber onset; Lum and Halim (2006) also reported that the warning aid should not convey precise quantum of the signal phase to be practically effective. Driver's feedback from the driving simulator validation study (c.f. Chapter 4) on the potential red light countermeasures also revealed that their violations could be avoided if they had advanced notice of the impending red light. Suggestions from the literature and the simulator validation study therefore suggest the designing of the following three interventions.

(i) Extended amber intervention: junctions were treated with amber duration of 4 seconds in replacement of the standard 3-seconds amber phase from the baseline scenario;

(ii) Flashing amber intervention: junctions were treated with installation of a standalone flashing amber light adjacent to the original traffic light, to inform on the impending signal change while keeping the amber duration fixed at 3-seconds;

(iii)Advanced signal intervention: junctions were treated with installation of an advanced signal light at some distances upstream of the original traffic light to display the impending signal status while keeping the amber duration fixed at 3-seconds.

The main aim of the current study was to assess the efficacy of the three different interventions to improve driver's safety decision at signalised junctions. The entire driving simulator study comprises a series of four experiments with the aims to measure and compare between driving performance with and without (i.e. baseline scenario) each of the above three interventions.

5.6. Data extraction and manipulation

For individual driver, their relevant driving performance data were measured, extracted from the STISIM output data file, and re-organised into the following variables:

Table 5.1: List of variables extracted from the output of the driving simulator

Variables
Elapsed time since beginning of each simulated trial
Driver's longitudinal acceleration with respect to elapsed time
Driver's longitudinal velocity with respect to elapsed time
Total longitudinal distance driver has travelled since beginning of the simulated run
Traffic light status with respect to elapsed time
Running compilation of the crashes that the driver has been involved in
Distance and elapsed time when violation occurs
Driver's brake force with respect to elapsed time

Non-parametric statistical tests (e.g. Mann-Whitney, Friedman, Binomial and Wilcoxon tests) were applied to the data due to their driving performance data between drivers being non-normally distributed. Prior to data analysis, driver's speed and distance from the stop line at the amber onset were compared between each other among the three interventions and with the control condition. The comparison tests were carried out for all junctions. Results from the Wilcoxon test revealed that there was no difference in driver's initial positions when they got exposed to the amber onset in the four independent trials. Due to the high frequency of speed violations observed from drivers approaching the first junction (i.e. J1) on the simulated route, J1 was eliminated from the sample data prior to data analysis. The approach speed at the remaining 6 junctions remained consistent throughout the study, showing the learning effect after J1. No driver was found to experience simulator sickness in the experiment, therefore potential differences in driving performance due to the effect of motion sickness (e.g. Caird, et. al., 2007) has been avoided.

5.7. Performance measure

The effect of gender difference in driving performance could be measured in the study by dividing the samples into two non-overlapping subgroups. The assessment of the effectiveness of different interventions was compared with the control condition based on the following measures:

(i) Number of stopping decisions;

This measure indicates the number of safe stopping (stopped with deceleration rate < $4.9 m/s^2$ (c.f. Olson and Rothery, 1961)) and the number of unsafe stopping (stopped with deceleration rate > $4.9 m/s^2$);

(ii) Number of crossing decisions;

This measure indicates the number of safe crossing (on amber without running red light) and the number of unsafe crossing (red light running);

(iii) Direction and magnitude of speed change within the amber onset;

This measure indicates the driver's speed change from the onset of the amber phase with or without acceleration or deceleration;

(iv) Threshold of acceleration and deceleration rates within the signal change interval;

This measure indicates the maximum acceleration rate recorded for a crossing decision and the maximum deceleration rate recorded to stop;

(v) Braking response time;

This measure indicates the elapsed time between the transition of the amber signal and driver's application on the brake pedal;

(vi) Number of transitions between accelerating and decelerating;

This measure indicates the number of times the driver switched between the accelerator and the brake pedal;

(vii) Magnitudes of predefined problem and option zones (assuming that drivers travelled with constant speed as at the amber onset);

This measure indicates the magnitude of either a problem zone or an option zone calculated as

$$\left.\begin{array}{lll} Problem\ Zone = abs\left(V(\tau - t_{brake}) - \frac{V^2}{2a}\right) & \text{if} & V(\tau - t_{brake}) - \frac{V^2}{2a} < 0 \\ \text{(or)} & & \\ Option\ Zone = abs\left(V(\tau - t_{brake}) - \frac{V^2}{2a}\right) & \text{if} & V(\tau - t_{brake}) - \frac{V^2}{2a} > 0 \end{array}\right\} [5.1]$$

where V denotes driver's speed (m/s) when the amber light first appeared;

t_{brake} denotes the braking response time (s);

a denotes the maximum deceleration rate (m/s^2) of the vehicle and

τ denotes the amber duration (s)

6. Does extending the amber light duration increase the option zone or uncertainty?

This chapter describes an analysis of the effects of extending the amber phase duration by 1 second. Specifically, effectiveness of the extended amber intervention can be addressed through an analysis of before-and-after data. Statistical assessment and behavioural interpretation of the results are also presented.

6.1. Introduction

Inappropriate settings of an amber duration have been shown to create problem zone at signalised junctions which in turn increases the frequency of red light violations (Gazis, et. al., 1960). As a consequence, there is an increase in potential conflicts between vehicles (Stimpson, et. al., 1980). Research on evaluating an appropriate amber duration has therefore received much attention; as a result, different recommendations have been made on formulating the optimal length of the amber interval. The length of the amber time has been proposed as a positive linear function of vehicle approach speeds (Bissell and Warren, 1981; ITE, 1985); this was found later to be irrelevant because an increase in the approach speed tends to cause a reduction instead of an increase in the amber interval requirement (Lin, et. al., 1987; Lin and Vijaykumar, 1988). Lin (1986) has further shown that the change interval requirement can be better estimated as a linear function of the time required for the vehicles to clear the junction. Whether or not an amber interval is adequate can thus be evaluated in terms of the percent of vehicles entering the junction after the termination of the amber interval (ITE, 1985).

Although variations in the level of vehicle supply at junctions have been shown to be affected by signal co-ordination (Lin and Vijaykumar, 1988), traffic volume (Zegeer and Deen, 1978; Stimpson, et. al., 1980; Mohamedshah, et. al., 2000), and type of signal control implemented at the respective junctions (Van der Horst and Wilmink, 1986; Van der Horst, 1988; Mohamedshah, et. al., 2000), setting dynamic amber intervals to satisfy a high level of demand was found to be impractical and could adversely affect the efficiency of signal control (Lin and Vijaykumar, 1988). Instead, the amber interval demands were demonstrated to be based on some normative values, regardless of different approach speed (May, 1968; Chang, et. al., 1985; Mahalel and Prashker, 1987; Lin and Vijaykumar, 1988). The configuration of 3-seconds amber light for instance, has been recommended as the minimum amber duration for safety reasons (Williams, 1977; Butler, 1983), but has also been claimed to be insufficient in many studies (Gazis, et. al., 1960; Williams, 1977; Bissell and Warren, 1981; Butler, 1983; Zador, et. al., 1985). Amber interval shorter than 3 seconds however, is not recommended (Retting and Greene, 1997) because they may cause some drivers to apply excessively high decelerations in order to avoid entering the junction on red (Lin, et. al., 1987). There is in general no consensus on the global settings of the amber duration. The appropriate amber duration suggested in the literature ranges from 3 to 5.5 seconds (Olson and Rothery, 1961, 1972; Chang, et. al., 1985; Wortman and Fox, 1986; Lin, et. al., 1987; Lin and Vijaykumar, 1988; Bonneson and Zimmerman, 2004), as determined by different measures of effectiveness. Examples of these studies are illustrated in Table 6.1.

Table 6.1: Some recommended settings for amber light duration

Author(s)	Country	Amber duration (s)	Approach speed	Measure of effectiveness
Olson and Rothery (1961; 1972)	U.S.	5.5	30mph≤spd≤50mph (13.4m/s≤spd≤22.4m/s)	95^{th} percentile time for stopping vehicles
Chang, et. al (1985)	U.S.	4.5	25mph≤spd≤50mph (11.2m/s≤spd≤22.4m/s)	95^{th} percentile time for crossing vehicles
Wortman and Fox (1986)	U.S.	4	30mph≤spd≤50mph (13.4m/s≤spd≤22.4m/s)	
Lin, et. al. (1987)	U.S.	3 – 5	20mph≤spd≤35mph (8.9m/s≤spd≤15.6m/s)	
Lin and Vijaykumar (1988)	U.S.	4 and above	25mph≤spd≤55mph (11.2m/s≤spd≤22.4m/s)	
Van der Horst and Wilmink (1986)	Netherlands	4 – 5	30mph≤spd≤50mph (13.4m/s≤spd≤22.4m/s)	85^{th} percentile time for stopping vehicles
Jourdain (1986)	U.K.	3	spd≤30mph (spd≤13.4m/s)	

It has been common practice to use the frequency of red light violations to measure the effectiveness of the amber duration (Stimpson, et. al., 1980; Hulscher, 1984; Zador, et. al., 1985; Van der Horst and Wilmink, 1986). Based on the statistics of vehicles encountering the amber light at junctions, improvement had been shown at majority sites with reduced red light violations after extending the amber duration by at least one second (Stimpson, et. al., 1980; Van der Horst and Wilmink, 1986; Lin and Vijaykumar, 1988; Van der Horst, 1988; Bonneson and Zimmerman, 2004). The positive effect of the extended duration was however, found to be inconsistent at some sites, showing little or no significant improvement (Liu, et. al., 2007), and some sites with positive effects that erode over time (Hulscher, 1984; Retting and Greene, 1997; Bonneson and Zimmerman, 2004). It seems that the variation in effects was due to regional differences in driving behaviour (Clark and Cushing, 2004; Eiksund, 2009; Liu and Wu, 2009; Nordfjærn, et. al., 2010). With longer amber time, reduction in the frequency of red light violations was consistently found across rural junctions (May, 1968; Van der Horst and Wilmink, 1986; Bonneson and Zimmerman, 2004) and sub-urban junctions (Stimpson, et. al., 1980). Similar trend although was found among urban junctions, the improvement was however shown only as short-term effects (Retting and Greene, 1997). Drivers at urban junctions tend to adjust their stopping behaviour to offset the effect of longer amber duration (Retting and Greene, 1997); this adaptation over time is more likely to increase the percentage of unsafe crossing (May, 1968). This finding also suggests that driver behaviour may not change as a function of amber duration (Olson and Rothery, 1961; Hulscher, 1984).

Driver's response time to different amber duration has been widely studied based on the time elapsed from the amber light onset until the brake is applied (Gates, et. al., 2007; Rakha, et. al., 2007). Without any warning advices, most drivers use approximately 1 second to react to the termination of a green light (Jourdain, 1986). While response time of 1 second has been found to be sufficient for stopping vehicles in many studies (Olson and Rothery, 1961; Chang, et. al., 1985; ITE, 1989, Caird, et. al, 2007), there is lack of information on the reactions of crossing vehicles. Kikuchi, et. al. (1993) in particular, has suggested that inclusion of the responses from crossing vehicles should be adopted for a better estimation of the problem zone and option zone; the authors proposed a theoretical model which revealed different levels of uncertainty between different drivers. In contrast to the existence of a problem zone that was caused by insufficient amber time, the size of the option zone is found to increase with longer amber duration (May, 1968; Prashker and Mahalel, 1989), which therefore provides greater flexibility for drivers to execute either stopping or crossing manoeuvre successfully (Mahalel and Prashker, 1987; Urbanik and Koonce, 2007); as a result, the problem zone was transformed into an option zone (May, 1968). Whether the transformation improves the safety level at junctions is however unclear. Previous findings have emphasised on the likely effects of a larger option zone to contribute to other unexpected junction errors (May, 1968), such as rear-end accidents (Mahalel and Prashker, 1987).

The main aim of the current study is therefore to examine the effects of the extended amber intervention using measurable metrics and to determine if an extended option zone caused by an extended amber phase would provide any safety benefits to drivers.

6.2. Intervention design

The extended amber intervention uses a 4-seconds amber phase in replacement of the standard 3-seconds amber phase for the control condition (i.e. baseline scenario).

6.3. Results

18 drivers drove the simulator with baseline condition before the extended amber intervention, and the remaining 14 in the opposite order. Comparisons between performance of drivers from the baseline condition (i.e. control condition) and the extended amber intervention are presented in the following sections. No significant differences were found when comparing driving performances between male and female drivers to the amber onset.

6.3.1. Frequency of stopping decisions

By increasing the amber duration by 1 second in the current study, reduction in crossing vehicles during the signal change interval was found at all 6 junctions. Although lower number of stop line crossings during the amber light onset has been shown as a good indicator of higher level of safety at signalised junctions (Köll, et. al., 2004), the safety benefit was however, not convinced in the current study. As shown in Table 6.2, both safe and unsafe stopping rates have increased for the extended amber intervention. Although the Binomial test statistics showed that the overall stopping rates with the extended amber intervention was significantly higher than that from the control condition ($p < 0.05$), the reduction in unsafe stopping rates was however not significant (p =0.304).

Table 6.2: Frequency of stopping vehicles

		Control			Extended amber		
	Junction	safe stopping	unsafe stopping	Total (/192)	safe stopping	unsafe stopping	Total (/192)
Rural	2	0	14	14	5	17	22
	3	0	17	17	5	18	23
	4	0	15	15	8	15	23
Sub-urban	5	2	17	19	8	17	25
Urban	6	0	10	10	5	15	20
	7	0	9	9	9	10	19
		2	**82**	**84**	**40**	**92**	**132**

6.3.2. Frequency of red light violation

The occurrence rate of red light running had increased at 4 junctions (i.e. J2, J4, J6, J7) after increasing the amber duration from 3 to 4 seconds. See Table 6.3. The red light running behaviour seemed to deteriorate with longer amber phase. Drivers tend not to use the extended amber phase to perform more uniform stopping decisions.

Table 6.3: Frequency of red light violations

	Junction	Control	Extended amber
	2	1	3
	3	1	1
	4	0	2
Sub-urban	5	1	0
Urban	6	0	2
	7	0	1
		3	9

6.3.3. Magnitudes of driver’s speed and acceleration

Based on the acceleration and deceleration rates of each vehicle measured per 0.1 second throughout the simulated route, acceleration profiles during the signal change interval were created for all drivers, at individual junctions of interest (i.e. J2 to J7). Range of acceleration rates were compared between the control condition and the extended amber interventions for all the junctions. Variance in acceleration rates was not significant between crossing vehicles from the comparative groups. Apart from J3, significantly lower range of acceleration rates was found among the vehicles which stopped at the rural junctions with extended amber duration: J2 (p = 0.011); J4 (p = 0.041).

The opposite trend was shown at the urban junction J7 (p = 0.046), with higher range of acceleration rates, when the amber duration was set to be longer. Driver’s acceleration profiles for the control condition and extended amber intervention were illustrated in Figure 6.1, and in Appendix C. With extended amber phase, drivers tend to be more stable with their acceleration and deceleration rates at rural junctions, thus revealing the beneficial effects of longer amber duration particularly at rural junctions (May, 1968; Van der Horst, 1988). No significant difference was found between the control condition and the extended amber intervention for junctions J3, J5 and J6. The reason although was not clear, might be as a result of the differences in geometry and road layout in sub-urban region (i.e. J5), or the presence of other vehicle ahead of the drivers (i.e. J3 and J6).

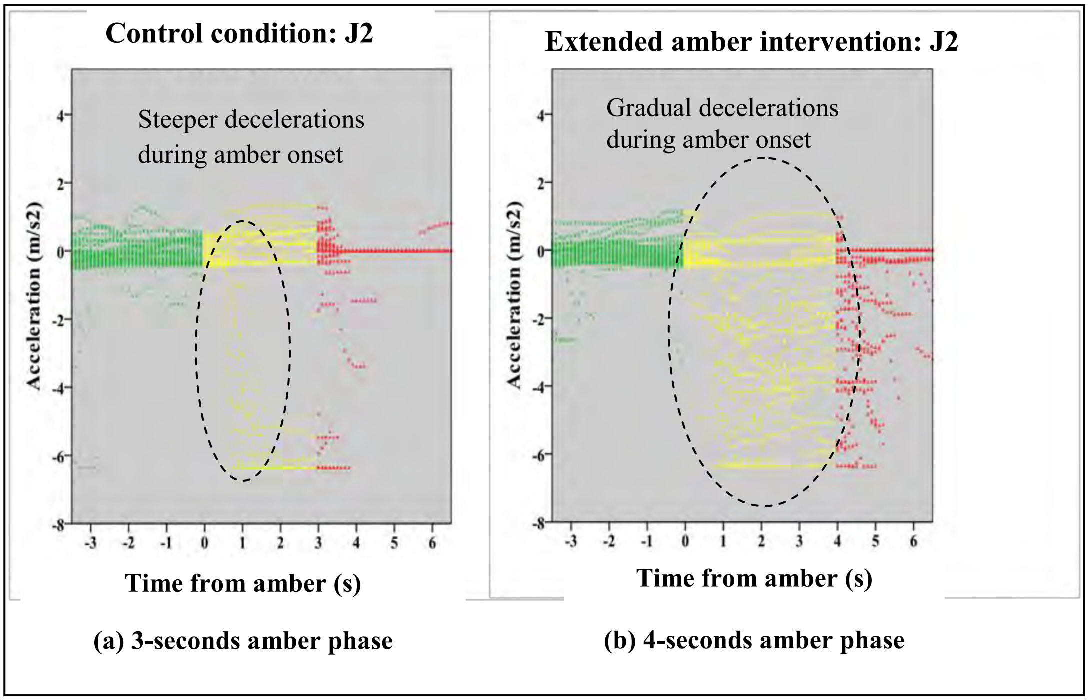


Figure 6. 1: Acceleration profiles for junction J2 with the control condition and the extended amber intervention

Improvement was observed at all other junctions implemented with the extended amber intervention in terms of driver's maximum deceleration rates within the amber duration. Drivers were found to execute significantly lower deceleration rates to stop, when faced with a 4-seconds amber light.

6.3.4. Braking performance among stopping vehicles

Driver's braking performance to the amber onset was estimated in the current study based on their individual braking response time, and their respective maximum deceleration rates to stop for the amber light. Braking response time was measured among the stopping vehicles as the elapsed time from the onset of amber light until the driver pressed the brake pedal. Using a between-subjects design in the current study, driver's braking response time to the amber onset was compared between the control condition and the extended amber intervention. As a result, significantly longer response time was found at J3 ($p = 0.007$), J5 ($p = 0.028$) and J6 ($p = 0.035$) when the amber light duration was set to be 4-seconds; no significant difference was found at other junctions.

6.3.5. Driver's level of uncertainty

Highest degree of uncertainty at junctions, which has no physical meaning (Rakha, et. al., 2007), has been used to describe the event when the possibility of the two conflicting decisions, crossing and stopping, are equally likely (Kikuchi and Riegner, 1992; Kikuchi, et. al., 1993; Rakha, et. al., 1997). In the current study, number of transitions between acceleration and deceleration, measured as the number of times a driver triggers between the accelerator pedal and the brake pedal within the amber interval, was introduced as a surrogate measure of the degree of uncertainty in drivers. Based on the analytical model of driver's uncertainty (Kikuchi, et. al., 1993), degree of uncertainty has been identified to be lowest when a driver either accelerates or decelerates monotonically along the approach (Kikuchi, et. al., 1993, Rakha, et. al, 2007). For example, consistent deceleration to stop or consistent acceleration to cross a junction would be demonstrated in the current study by only one transition. Higher level of uncertainty in other words, could be identified by increased number of transitions.

The number of transitions between acceleration and deceleration were measured and compared between the control condition and the extended amber intervention for the junctions; significantly higher number of transitions was found at all 6 junctions implemented with extended amber intervention, which reflect a higher level of uncertainty to be found at junctions with longer amber time. The results also showed consistency across all urban, sub-urban and rural areas, as illustrated in Figure 6.2.

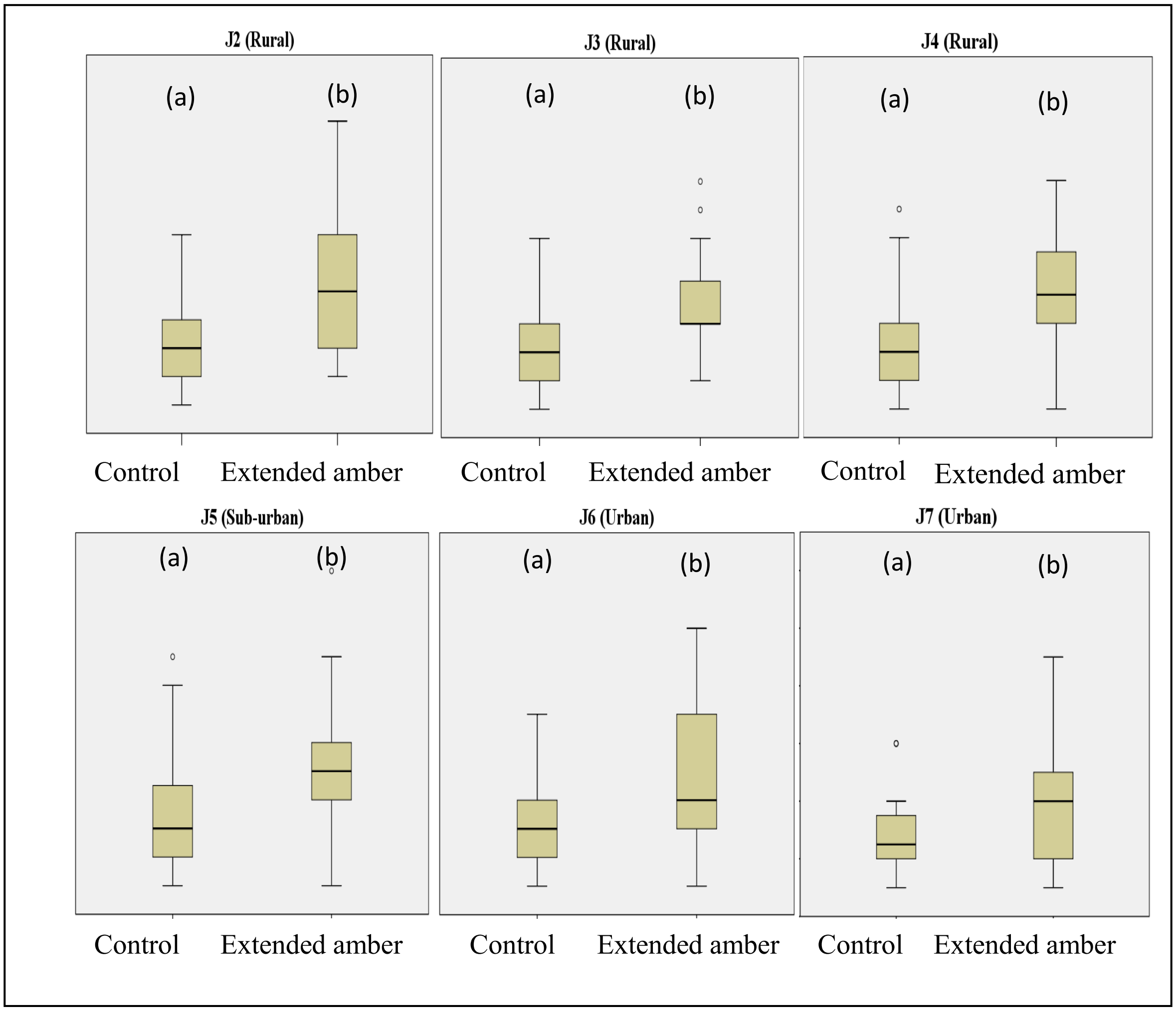


Figure 6.2: Driver's uncertainty levels at 6 pairs of junctions with (a) the control condition and (b) the extended amber intervention

6.3.6. Estimated magnitudes of problem zone and option zone

Problem zones and option zones were estimated in the current study, based on individual driver's approach speed, their braking response time to the amber onset, and their respective maximum deceleration rate within the amber duration. The magnitude of these two zones in particular, has been shown to be an important indicator in terms of the level of safety at junctions, with lower safety to be demonstrated with greater magnitude (Gazis, et. al., 1960; May, 1968; Chang, et. al., 1985; Prashker and Mahalel, 1989). These two zones however, do not exist at the same time. The formation of either a problem zone or an option zone, and its magnitude, was determined by Equation [5.1] in Chapter 5.

The estimated sizes of the problem zones and option zones from Equation [5.1], when compared between the control condition and the extended amber intervention, revealed a significant decrement in the magnitude of the potential problem zones at junctions with longer amber duration. In line with the literature (May, 1968; Prashker and Mahalel, 1989; Allos and Al-Hadithi, 1992), the potential problem zones at the control junctions were replaced by option zones at the junctions with extended amber intervention. The option zones at the control junctions were also found to enlarge with the extended amber intervention. This trend was shown at all junctions across different regions. See Figure 6.3 and Appendix D.

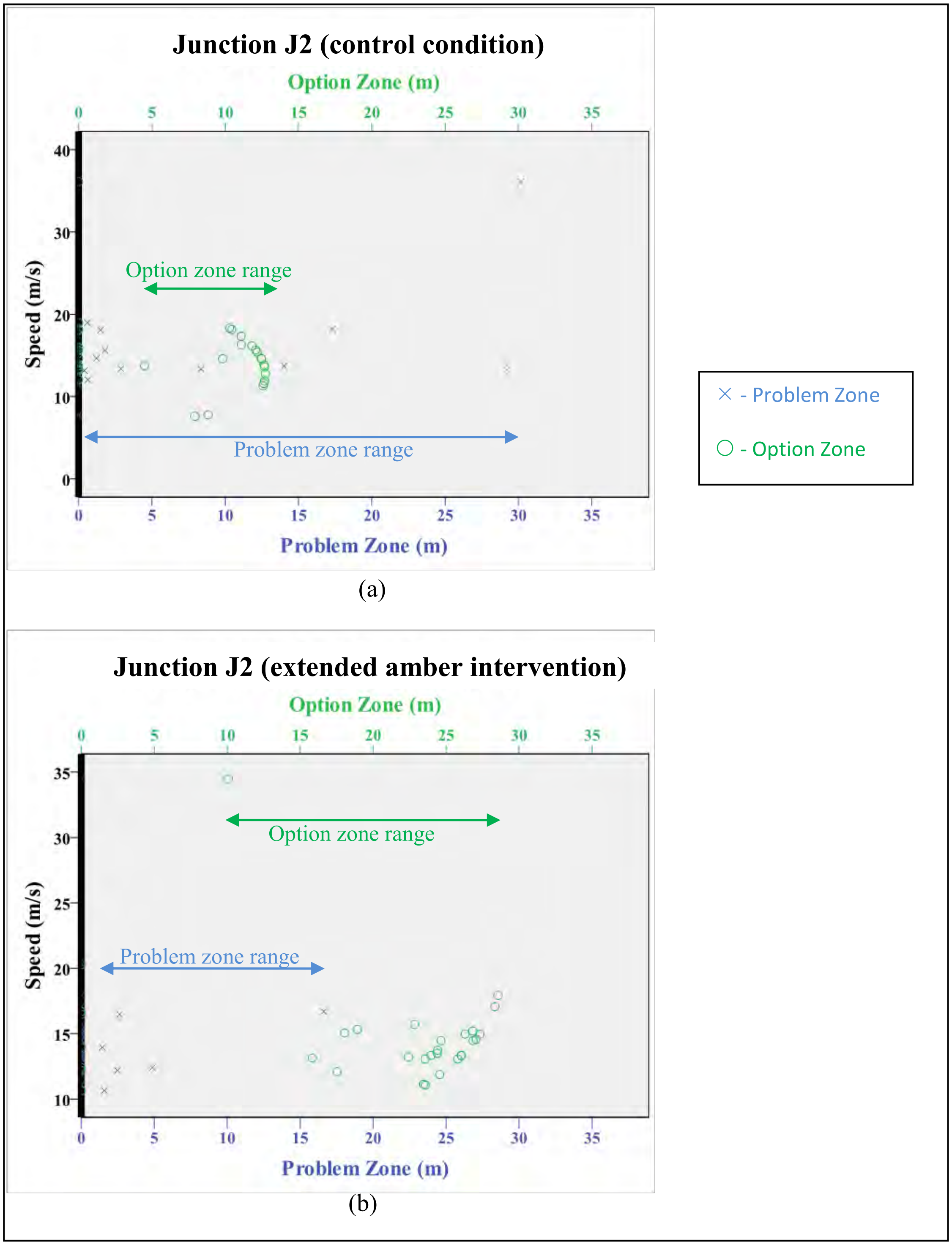


Figure 6.3: Magnitudes of problem zones and option zones at Junction J2 for (a) the control condition and (b) the extended amber intervention.

6.4. Discussion

Results of the current study demonstrate that driver's compliance to stop at amber light had increased at all 6 junctions associated with a 4-second amber phase, but the safety benefits of longer amber time to reduce conflicts at junctions (Stimpson, et. al., 1981, Retting and Greene, 1997) were not convincing in this study. In particular, the reduction in unsafe stopping decisions was not significant. On the contrary, the occurrence rate of red light violations has increased at 4 junctions (i.e. J2, J4, J6 and J7). Consistent with reports in the literature (May, 1968; Hulscher, 1984), longer amber duration in the current study was not effective in reducing red light violations, particularly for urban junctions which have been found with increased violations. The positive effects of longer amber duration to reduce the frequency of potential conflicts at junctions (Stimpson, et. al., 1980; Van der Horst and Wilmink, 1986) seem to be negated by the increased number of drivers accelerate through the amber light interval (Puan and Ismail, 2010).

Significantly smaller range of acceleration rates were found in vehicles stopping at rural junctions associated with longer amber phase (see section 6.3.3), which revealed increased stability between driver's acceleration and deceleration rate during the longer amber interval. Drivers were also found to execute lower deceleration rates when stopping in response to the 4-seconds amber phase but they did not apply the brake earlier. On the contrary, significant longer braking response times were found at some junctions implemented with longer amber phase (see section 6.3.4), implying that drivers were unlikely to prepare to stop earlier with the extra time allocated (Olson and Rothery, 1961), particularly when travelling behind other vehicles (Harbluk, et. al., 2007), i.e. at J3 and J6, or within a sub-urban region (i.e. J5). Without shorter braking response times to be observed among the stopping vehicles however, the decrement in the deceleration rates was argued to be independent of the length of the amber duration (Olson and Rothery, 1972; Gates, et. al., 2007). There has been no evidence to show that changes in driver behaviour occur from lengthening the duration of the amber light (Mahalel and Prashker, 1987).

The benefit of longer amber time was apparent to eliminate problem zone at junctions (May, 1968; Urbanik and Koonce, 2007) but at the same time increases the range of option zone (May, 1968; Prashker and Mahalel, 1989) and consequently, higher chance of rear-end accidents (Mahalel and Prashker, 1987). As an example, the mitigation from problem zone to option zone as a result of extended amber duration was shown in Figure 6.3. Longer amber duration on the other hand, has been found more likely to generate a period of uncertainty to drivers (Olson and Rothery, 1961; May, 1968). It has particularly been argued that there is a trade off between the length of amber interval and driver's degree of uncertainty at junctions (Mahalel and Prashker, 1987; Rakha, 2007). Whilst the level of uncertainty is commonly used to explain between the uncertainty and uniformity among the behaviour of drivers (Kikuchi, et. al., 1993), there has been no precise way to quantify the level of uncertainty. In the current study, the number of transitions triggered between the acceleration and deceleration modes was introduced as a surrogate measure to driver's level of uncertainty. Compared to the control condition, larger number of triggered transitions was found at the junctions with extended amber intervention, across all demographic regions (see Figure 6.2). The findings from the current study were consistent to the literature (May, 1968; Prashker and Mahalel, 1989), showing a tendency for larger option zones during a longer amber light (see Figure 6.3) and therefore increases driver uncertainty at junctions (Köll, et. al., 2004; Rakha, et. al., 2007). Apart from the higher level of uncertainty in drivers, longer amber phase was also raised as undesirable because of the delay it causes to the traffic waiting along the cross-street (Liu, et. al., 1996). Although amber interval demand has been found to vary significantly from one junction to another (Lin and Vijaykumar, 1988), longer amber phases, unless critically required, were not recommended at signalised junctions to avoid higher variability among driver performance (Young, et. al., 2008).

6.5. Conclusion

In the present study, the implementation of the extended amber intervention was shown to have both positive and negative impacts. On the positive side, the extended amber duration encourages stopping at signalised junctions. The findings in the current study were consistent with the literature (Gazis, et. al., 1960; May, 1968) that longer amber duration can effectively eliminate the potential problem zone but at the same time, elicit an option zone. As the amber time increases, the magnitude of the option zone also increases, thus resulting in higher uncertainty in drivers, which has been known to be associated with higher chance of rear-end accidents (May, 1968; Hakkert and Mahalel, 1978; Mahalel and Zaidel, 1985). For safety benefits, extended amber duration should be avoided wherever possible. Moreover, the findings also suggested that the frequency of stopping vehicles alone may not potentially be a good measure for driving performance. Consequently, results from the current study imply the direction of future work to seek for interventions that can effectively reduce the size of option zone and the degree of driver uncertainty. Particularly in hazardous situations, delivery of clear information to drivers, associated with well-defined criteria to make decision, might encourage improved safety at signalised junctions.

7. Evaluation of flashing amber intervention to improve driver decision at signalised junctions

This chapter describes an analysis of the performance of a standalone flashing amber intervention to inform drivers of the impending signal change at 1s prior to the amber onset. Driver performances to the intervention were compared to the control condition. Statistical assessment and behavioural interpretation of the results are also presented.

7.1. Introduction

The issue of the design of traffic signal change interval has long been a problem at junctions, particularly in terms of its effectiveness to reduce road hazards. For instance, occurrence of right-angle collisions may reflect a lack in design of the inter-green interval (Gazis, et. al., 1960; May, 1968; Mahalel, et. al., 1985). Time reference aids, such as advanced warning signs (Eck and Sabra, 1985; Pant and Huang, 1992; Pant and Xie, 1995; Bonneson, et. al., 2002) and flashing signals (Hakkert and Mahalel, 1978; Mahalel and Prashker, 1987; Van Houten and Malenfant, 1992), have been used to inform drivers of the impending signal change, thereby enabling drivers to anticipate the amber light onset.

Flashing lights are in general use to convey warning messages (such as to raise caution) in different environments. The use of flashing signals at junctions has been limited, and in general is not recognised at universal level. Austria and Israel, for instance, are among the countries that include flashing green signal before an amber signal to indicate the end of green time (Hakkert and Mahalel, 1978; Mahalel, et. al., 1985; Köll, et. al., 2004). The flashing green signal is itself part of the green phase, showing drivers their right to proceed whilst indicating them to prepare to make decisions soon. The duration of the flashing green time is 2 seconds and 3 seconds respectively in Austria and Israel, during which alternate sequence between dark and illuminated green phases are shown. Engineers in Israel in particular, argue that providing drivers with early warning information would lead to more appropriate decisions (Mahalel, et. al., 1985). Despite the increased visibility aid of the flashing green signals to driver's response to hazards at junctions (Hakkert and Mahalel, 1978; Van Houten and Malenfant, 1992), they have been shown to be incapable to replace the normal traffic signals (Demetsky and Moreno, 1985; Mahalel, et. al., 1985). Evaluation of the flashing green signals has led to different conclusions, depending on the type of performance measures. For instance, implementation of flashing green signals at junctions has been shown to reduce the number of drivers in the problem zone (Hakkert and Mahalel, 1978), and hence decreasing potential right-angle collisions (Mahalel and Zaidel, 1985). In terms of driver's stopping behaviour at junctions however, abrupt brakings were observed with significant increment in their deceleration rates (Hakkert and Mahalel, 1978; Mahalel and Prashker, 1987). Range of stopping behaviours in drivers is much greater with the presence of the flashing green signals (Köll, et. al., 2004), creating a larger option zone for drivers where both stopping and crossing decisions are possible (May, 1968; Mahalel and Prashker, 1987), and thus contributing to the increment of potential rear-end accidents (Mahalel and Zaidel, 1985; Mahalel and Prashker, 1987; Retting, et. al., 2003; Köll, et. al., 2004). The enlarged option zone in particular, may trigger an increase in driver's earlier responses to stop before the green light actually ends, thus resulting in unnecessary stops at junctions and potential conflicts between successive drivers (Mahalel and Zaidel, 1985; Mahalel and Prashker, 1987; Köll, et. al., 2004). Longer response times for crossing decisions in the option zone on the other hand, can also sometimes lead to right-angle collisions (Mahalel and Zaidel, 1985; Mahalel, et. al., 1985). Effectiveness of adaptive traffic control, as expected, was shown to decrease with the flashing green signals, as it increases the duration of the phase transitions (Hubacher and Allenbach, 2004; Köll, et. al., 2004).

The number of right-angle accidents although has been reduced, the addition of a flashing green light prior to the amber light have been shown to have negative effects in providing junction safety to drivers because the number of rear-end accidents increased (Hakkert and Mahalel, 1978). Due to their unlikely effect to restrain drivers from junction accidents, particularly at low approach speed, implementation of flashing green signals has not been recommended as a solution to improve driver's compliance to red light at junctions; removal of the flashing green signals at urban junctions however, has been encouraged (Mahalel and Zaidel, 1985). Alternatively, replacement of flashing green phrase with similar indicators prior to an amber light has been suggested (Mahalel, et. al., 1985; Mahalel and Zaidel, 1985); a more visible signal indication has also been recommended (Bonneson, et. al., 2002), for instance, the use of the flashing amber signal which creates less confusion to drivers than the flashing green (Mussa, et. al., 1996).

Using a driving simulator, modifications have been made to the normal traffic lights to include flashing amber signal which overlaps with the green signal shortly before the onset of the solid amber signal (Mussa, et. al., 1996; Newton, et. al., 1997). In their experiments, duration of the flashing amber signal has been designed to be dynamic and speed-dependent, with 1 second of flashing amber light to be allocated to each 10mph (i.e. 4.5m/s) of approach speed. For instance, vehicles with approach speed of 25mph (i.e. 11.2m/s) and 45mph (i.e. 20.1m/s) were allocated respectively a flashing amber signal phase of 2.5 and 4.5 seconds to appear before the onset of the solid amber signal, triggered at a predetermined distance with respect to the driver's approach speed. With an extra signal phase, drivers were more likely to stop during the solid amber indication, compared to the traffic lights with normal settings of three signal phases, i.e. green, amber and red in sequence (Mussa, et. al., 1996).

The flashing amber phase, when tested for its effectiveness to provide warning aid to drivers, was shown to have the potentials in reducing red light violations and the severity of maximum decelerations at junctions (Newton, et. al., 1997), particularly when approach speed is high and traffic density is low (Mussa, et. al., 1996). As a result, no problem zone was found. Implementation of flashing amber signal was expected to improve driver anticipation of the onset of the solid amber, but would not increase junction safety (Mussa, et. al., 1996, Newton, et. al., 1997). Similar to the deleterious effects of the flashing green signal (Mahalel, et. al., 1985, Köll, et. al., 2004), the trend of reduced red light violations and enlarged option zones were found to be associated with greater variability in driver's decision (Mussa, et. al., 1996; Newton, et. al., 1997).

The length of the warning period has been demonstrated in the literature (Olson and Rothery, 1961; Prashker and Mahalel, 1989) to have a direct implication on the size of the option zone; drivers, on perceiving the flashing amber signal as an extension to the normal amber time, may contribute to a less predictable behaviour. For instance, higher variability in driver's responses (Mahalel, et. al., 1985; Mussa, et. al., 1996; Newton, et. al., 1997) has been demonstrated with the empirical flashing green signal (i.e. 3 seconds duration) and flashing amber signal (i.e. 2.5 to 4.5 seconds duration), revealing that drivers might have been given excessive time to make a crossing or stopping decision. A warning period beyond 5 seconds in particular, has been shown to increase the frequency of red light violation (Van der Horst and Wilmink, 1986), implying that the deficiency of the flashing green signals as an effective warning tool might be due to the flashing green duration being set too long. These findings therefore suggest the advanced signal duration to be adjusted so that drivers are not provided with more than necessary time to safely clear a junction (Peterson, 2006). When additional signal pole was used to alert drivers of the impending signal transition, decrement in red light violations was observed (Harb, et. al., 2007); the design of a separate amber signal, combined with a much shorter warning time was therefore recommended (Van der Horst, 1988).

As a consequence of fundamental work in the design of advanced warnings with flashing green or flashing amber signals, there is now a better understanding of the problem of the aggregated option zones caused by longer duration of the amber time and warning signals (May, 1968; Mahalel, et. al., 1985; Mussa, et. al., 1996; Newton, et. al., 1997; Köll, et. al., 2004). In particular, previous findings have suggested that a longer warning phase is likely to increase driver uncertainty and therefore increases rear-end accidents. The main aim of the current study is therefore to examine if there is any significant changes in driver performance between a shorter (i.e. 1s) and longer (i.e. 3 to 5s) warning phase.

7.2. Intervention design

The primary input to the intervention is the installation of the flashing amber light on a separate pole, adjacent to the original traffic light at each junction, to indicate drivers of the impending signal at 1 second before the end of green time, and continue flashing till the end of the solid amber signal. The empirical design of the four-phase signal that includes flashing amber as an additional signal phase to the normal traffic lights (Mussa, et. al., 1996; Newton, et. al., 1997) was not used in this experiment due to the limited design features of the STISIM software. Alternatively, the flashing amber signal was designed to stand explicitly from the original traffic light, displaying either flashing amber light to inform the impending green to amber signal transition, or no light otherwise. The flashing signal is aimed to compensate for the 1-second reaction time lost in making crossing or stopping decision when drivers encounter an amber light (Chang, et. al., 1985; ITE, 1989). See Figure 7.1 for a conceptual framework of the flashing amber system and Figure 7.2 a screenshot of the intervention.

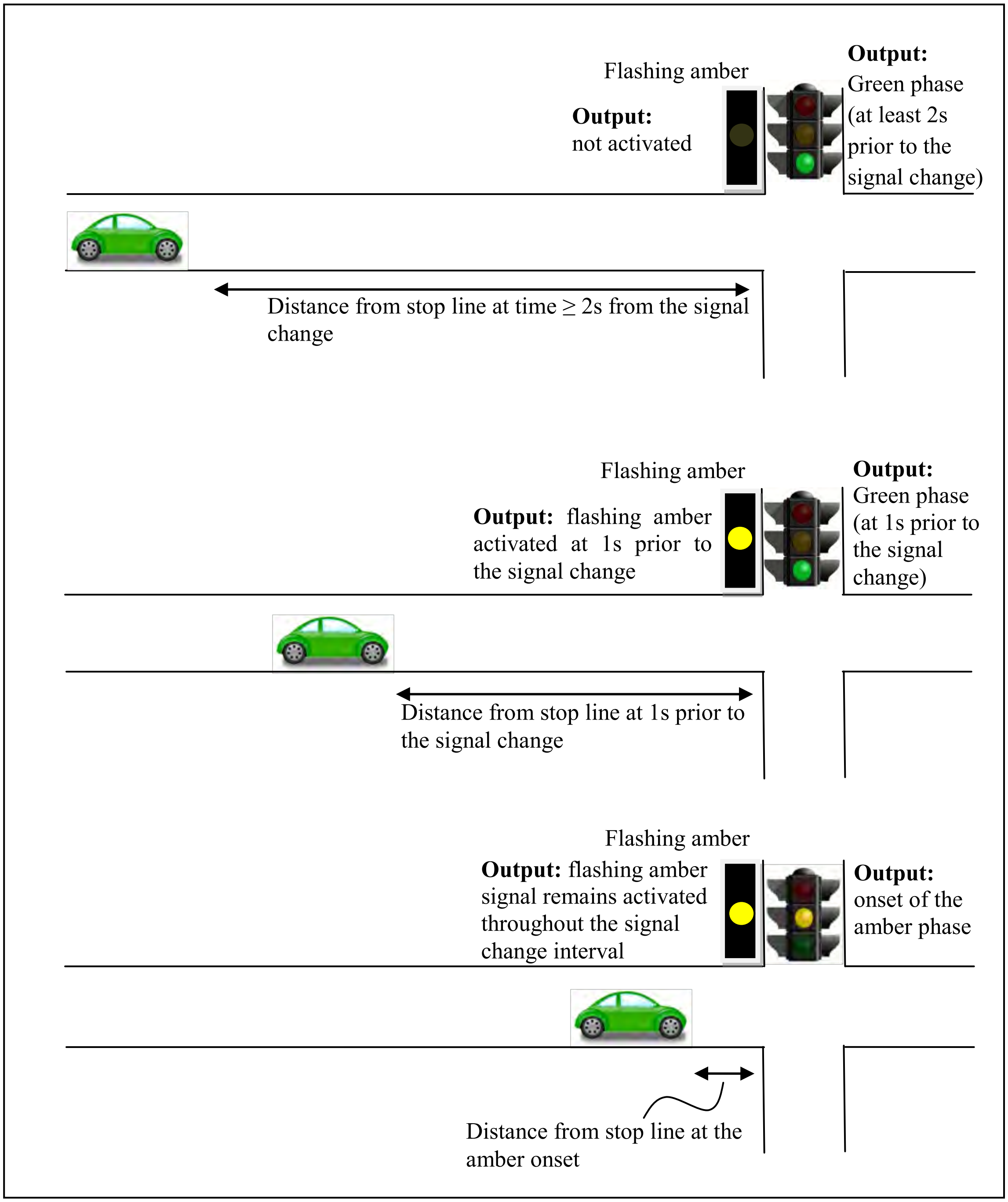
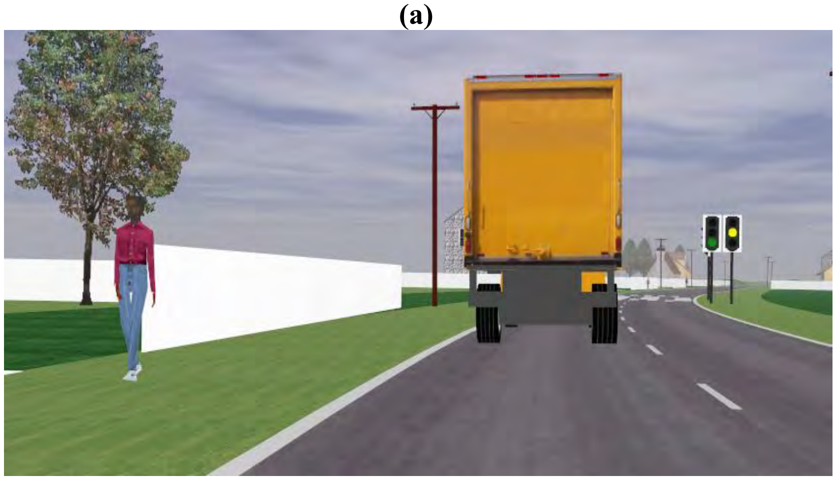
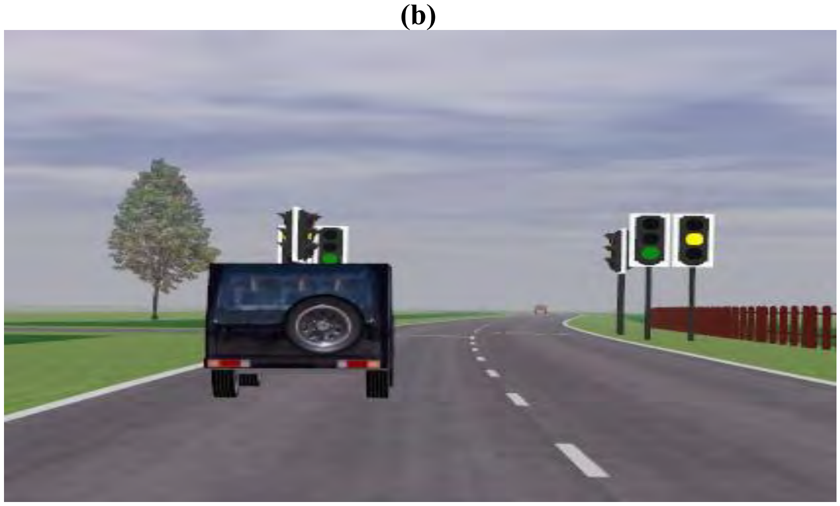


Figure 7.1: Conceptual framework of the extended amber system

(a)



(b)



(c)

Figure 7.2 A screenshot of the flashing amber light in adjacent to the original traffic light, showing 1 second of countdown time to the impending signal change (a) on sub-urban road (b) following behind a heavy vehicle on rural road (c) following behind a passenger vehicle on rural road

7.3. Results

20 drivers drove the simulator with baseline condition before the flashing amber intervention, and the remaining 12 in the opposite order. Comparisons between performance of drivers from the baseline condition (i.e. control condition) and the flashing amber intervention are presented in the following sections. No significant difference was found when comparing between male and female drivers in terms of their driving performance to the amber onset.

7.3.1. Frequency of stopping decisions

Based on the frequency of stopping and crossing vehicles at the 6 pairs of junctions with control condition and flashing amber intervention, the latter was shown to successfully reduce the frequency of vehicles crossing after termination of green light. The overall stopping decisions at the junctions with flashing amber intervention has increased significantly from the control condition (p = 0.001). Among these stopping decisions however, there was also a significant increase in unsafe stopping decisions (p = 0.01). The statistics of the stopping decisions are shown in Table 7.1.

Table 7.1: Frequency of stopping vehicles

		Control			**Flashing amber**		
	Junction	safe stopping	unsafe stopping	Total (/192)	safe stopping	unsafe stopping	Total (/192)
	2	0	14	14	2	17	19
	3	0	17	17	1	21	22
	4	0	15	15	2	20	22
Sub-urban	5	2	17	19	4	19	23
Urban	6	0	10	10	0	13	13
	7	0	9	9	0	14	14
		2	**82**	**84**	**9**	**104**	**113**

7.3.2. Frequency of red light violation

In the current study, the number of red light violations was found to increase particularly at the urban junctions with the flashing amber intervention. See Table 7.2.

Table 7.2: Frequency of red light violations

	Junction	Control	Flashing amber
	2	1	1
	3	1	0
	4	0	0
Sub-urban	5	1	1
Urban	6	0	2
	7	0	2
		3	6

7.3.3. Magnitudes of driver's speed and acceleration

By inspecting the speed and acceleration profiles of drivers continuously over the amber interval, significant changes were observed between the control condition and the flashing amber intervention in terms of the way the drivers controlled their speed. A change in driver's accelerating and decelerating pattern was demonstrated, with drivers gradually decelerating to stop for the flashing amber intervention; steeper accelerations and decelerations were observed at the control junctions. See Figure 7.3 and 7.4 as examples of the speed and acceleration profiles.

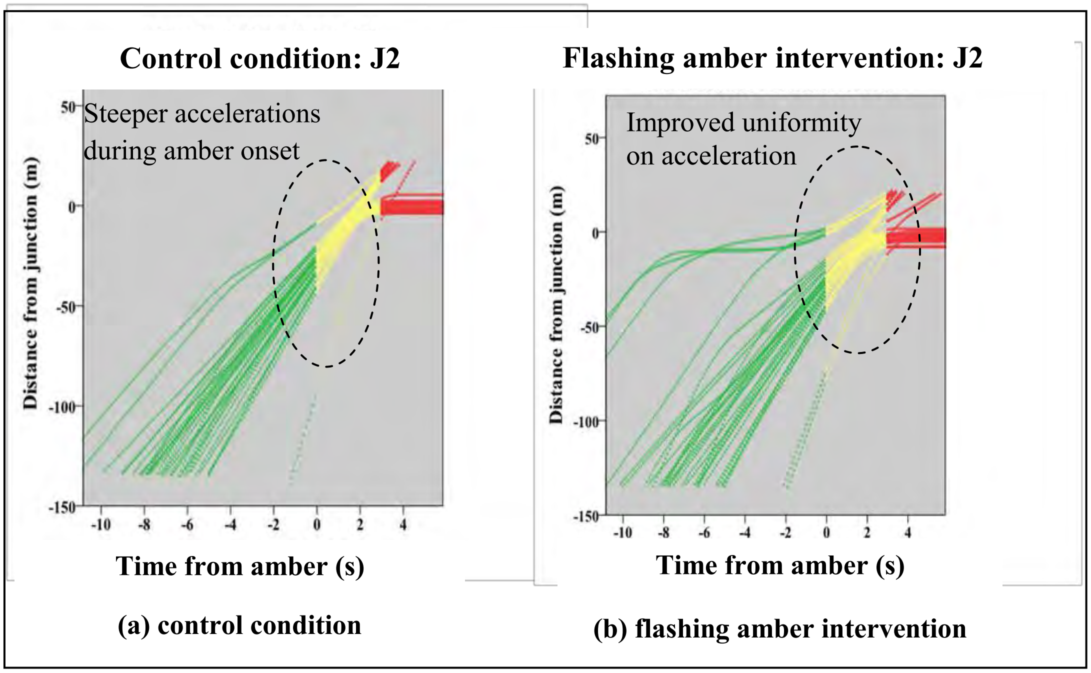


Figure 7.3: Speed profiles of vehicles approaching junction J2 with (a) the control condition and (b) the flashing amber intervention

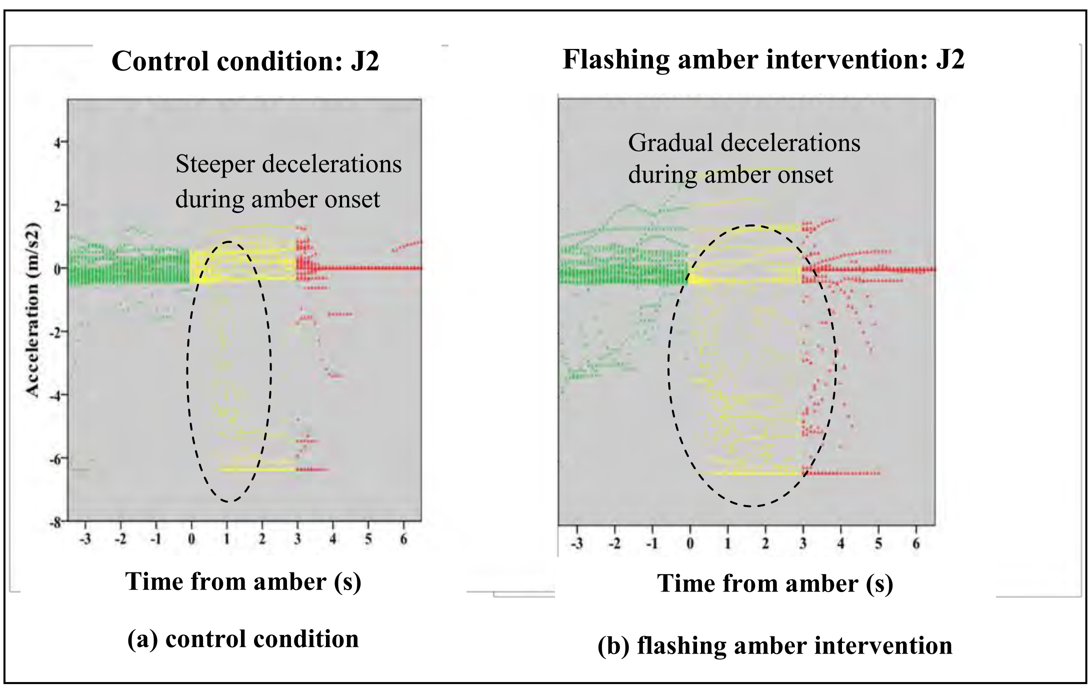


Figure 7.4: Acceleration profile of vehicles stopping at junction J2 with (a) the control condition and (b) the flashing amber intervention

One of the remarkable changes that occurred in drivers at junctions with the flashing amber intervention is their variation in speed during the amber time being more stable, when compared to the control condition. As shown in Tables 7.3, 7.4 and 7.5, drivers were found to exhibit significantly lower maximum acceleration rates on crossing and significantly lower maximum deceleration rates to stop at the junctions implemented with flashing amber intervention. Compared to the control condition in the current study, safety benefits were demonstrated with a lower magnitude in driver's acceleration and deceleration rates at the junctions with flashing amber intervention, across all demographic regions (see Table 7.5).

Table 7.3: Test Statistics for percentage increase in speed between the control condition and the flashing amber intervention

	Percentage increase in speed after amber ($J2_{FA}$) - Percentage increase in speed after amber ($J2_{C}$)	Percentage increase in speed after amber ($J3_{FA}$) - Percentage increase in speed after amber ($J3_{C}$)	Percentage increase in speed after amber ($J4_{FA}$) - Percentage increase in speed after amber ($J4_{C}$)	Percentage increase in speed after amber ($J5_{FA}$) - Percentage increase in speed after amber ($J5_{C}$)	Percentage increase in speed after amber ($J6_{FA}$) - Percentage increase in speed after amber ($J6_{C}$)	Percentage increase in speed after amber ($J7_{FA}$) - Percentage increase in speed after amber ($J7_{C}$)
Z	-2.685[a]	-3.684[a]	-4.637[a]	-4.170[a]	-3.347[a]	-3.833[a]
Asym. Sig. (2-tailed)	.007*	<.0001*	<.0001*	<.0001*	.001*	<.0001*

a. Based on the hypothesis: Percentage increase in speed at junction with the flashing amber intervention (FA) > Percentage increase in speed at the control condition (C).
*Hypothesis is rejected at p-value < 0.05.

Table 7.4: Test Statistics for maximum acceleration rates between the control condition and the flashing amber intervention

	Max acc during amber time ($J2_{FA}$) – Max acc during amber time ($J2_{C}$)	Max acc during amber time ($J3_{FA}$) – Max acc during amber time ($J3_{C}$)	Max acc during amber time ($J4_{FA}$) - Max acc during amber time ($J4_{C}$)	Max acc during amber time ($J5_{FA}$) - Max acc during amber time ($J5_{C}$)	Max acc during amber time ($J6_{FA}$) - Max acc during amber time ($J6_{C}$)	Max acc during amber time ($J7_{FA}$) - Max acc during amber time ($J7_{C}$)
Z	-4.394[a]	-4.189[a]	-4.460[a]	-4.694[a]	-3.684[a]	-3.170[a]
Asymp. Sig. (2-tailed)	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	.002*

a. Based on the hypothesis: Maximum acceleration with the flashing amber intervention (FA) > Maximum acceleration with the control condition (C).
*Hypothesis is rejected at p-value < 0.05.

Table 7.5: Test Statistics for range of acceleration of stopping vehicles between the control condition and the flashing amber intervention

	Range acc ($J2_{FA}$) - Range acc ($J2_C$)	Range acc ($J3_{FA}$) - Range acc ($J3_C$)	Range acc ($J4_{FA}$) - Range acc ($J4_C$)	Range acc ($J5_{FA}$) - Range acc ($J5_C$)	Range acc ($J6_{FA}$) - Range acc ($J6_C$)	Range acc ($J7_{FA}$) - Range acc ($J7_C$)
Z	-2.521[a]	-3.296[a]	-3.296[a]	-3.517[a]	-2.366[a]	-2.201[a]
Asymp. Sig. (2-tailed)	.012*	.001*	.001*	<.0001*	.018*	.028*

a. Based on the hypothesis: Range of acceleration with the flashing amber intervention (FA) > Range of acceleration with the control condition (C).

*Hypothesis is rejected at p-value < 0.05.

7.3.4. Braking performance among stopping vehicles

Using the Mann-Whitney test, braking response times from independent drivers were compared between the junctions with the control condition and the flashing amber intervention, revealing driver's shorter braking times at 5 junctions (excluding J6) implemented with the standalone flashing amber light. See Table 7.6.

Table 7.6: Test statistics for braking time between the control condition and the flashing amber intervention

	J2	J3	J4	J5	J6	J7
Mann-Whitney U	57.500	109.000	82.000	97.500	72.000	26.000
Wilcoxon W	288.500	409.000	313.000	422.500	177.000	146.000
Z	-3.244	-2.531	-2.851	-3.809	-1.225	-2.523
Asymp. Sig. (2-tailed)	.001*	.011*	.004*	<.0001*	.221	.012*

*p-value < 0.05 (last row) indicates a significant shorter braking time for the flashing amber intervention than the control condition.

7.3.5. Driver's level of uncertainty

When drivers trigger the accelerator and brake pedal in response to the amber onset, their frequency of transitions were measured and used as a surrogate measure to describe driver's uncertainty level, which is commonly used to explain between the uncertainty and uniformity among the behaviour of drivers (Kikuchi, et. al., 1993). Highest level of uncertainty for instance, has been identified in the literature as the most hazardous situation; where the probability of stopping and probability of crossing are literally equal (Mahalel and Prashker, 1987; Köll, et. al., 2004; Zimmerman and Bonneson, 2004; Papaioannou, 2007). In the current study, higher level of uncertainty was demonstrated by higher frequency of transitions between acceleration and deceleration. With implementation of the flashing amber light across the simulated route, higher number of transitions was found only at 1 urban junction (i.e. J3), showing that drivers might be more uncertain to respond to the flashing amber light when they were following another passenger car. There was however no difference in their level of uncertainty at the remaining 6 junctions.

7.3.6. Estimated magnitudes of problem zone and option zone

Using Equation [5.1], the estimated sizes of the problem zones and option zones were measured and compared between the junctions with control condition and flashing amber intervention. The standalone flashing amber intervention was shown in the current study to effectively eliminate the potential problem zones from the control condition, accompanied by a substantial increase in the occurrence of the option zones. See Figure 7.5 and Appendix D. Driver's option zones were, as expected, enlarged at all the junctions with flashing amber intervention, when compared to the control condition.

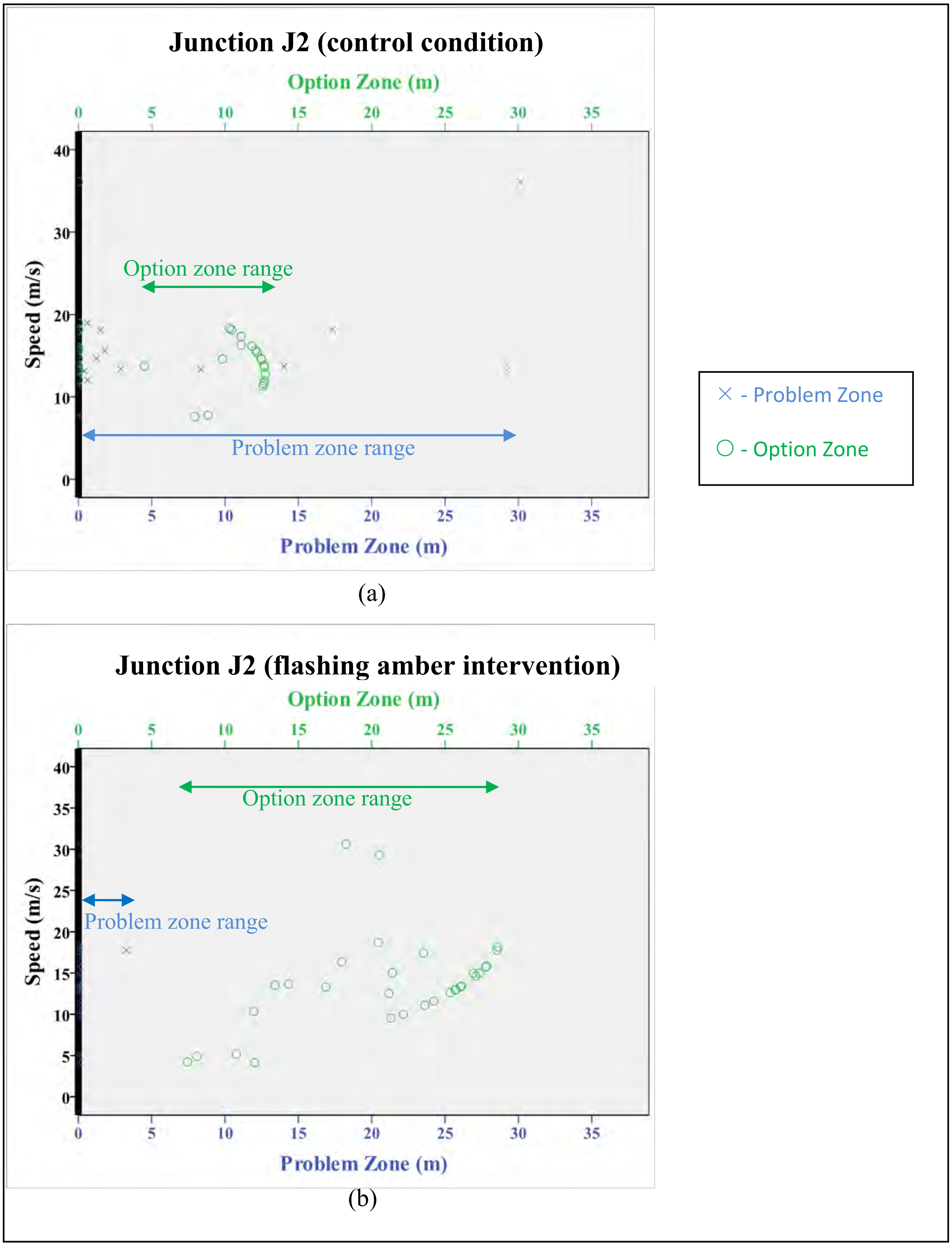


Figure 7.5: estimated magnitudes of problem zones and option zones at Junction J2 with (a) the control condition and (b) the flashing amber intervention.

7.4. Discussion

The results showed that the use of the proposed flashing amber light in this study was being advantageous in several ways, one of which is the increasing of stopping propensity at all junctions. See Table 7.1. Similar to the effects of displaying a flashing green signal (Mahalel, et. al., 1985) or flashing amber signal (Mussa, et.al., 1996; McCoy and Pesti, 2003) before the onset of a solid amber light, a marked increase in the frequency of stopping decisions has been found at all junctions. The effects of advanced flashing lights on red light compliance however, were not evident. Previous findings have shown the effects in two opposite trends. For instance, Burnett and Sharma (2011) claimed that advanced flashing lights can potentially increase risks in red light violations, although a significant reduction in the occurrence rates of red-light violation has been found at the junctions after implementing the flashing green signal (Köll, et. al., 2004) or flashing amber signal (Mussa, et. al., 1996). In the current study however, red light violation rates have increased with the flashing amber intervention, particularly at the urban junctions which were free from red light violation for the control condition.

Based on the analysis of driver performance on speed control, the concept of providing advanced warning signals to improve driver's decision (Mahalel, et. al., 1985) and driver anticipation of the onset of amber light (Mussa, et. al., 1996) seems to be encouraging. In particular, drivers tend to pay more attention on the warning of the impending onset of the amber and preparing earlier to stop when flashers were used (McCoy and Pesti, 2003). The implementation of the empirical flashing green and flashing amber signals however, have been shown to encourage unnecessary early stops, and therefore increased the chances of rear-end accidents at the junctions (Hakkert and Mahalel, 1978; Mahalel and Zaidel, 1985; Mussa, et. al., 1996; Köll, et. al., 2004). Advanced warning flashers, installed upstream of the junction to deliver warning signs or messages to drivers of the impending signal change, were found to have similar side effects as the flashing green signal hereby increasing the risk of red light violations and/or severe decelerations (Burnett and Sharma, 2011). In the current study, significantly shorter braking times were also observed at 6 of the junctions with flashing amber intervention, which suggested that drivers were using the flashing phase as request for immediate action and not simply an advance warning (Mussa, et. al., 1996; Newton, et. al., 1997). By setting the standalone amber warning signal to flash at 1 second prior to the onset of the solid amber light, reduction in potential conflicts at junctions was shown with higher stability in driver's performance on the simulator controls. As shown in Table 7.3 to 7.5, variability in driver's approach speed and acceleration rates within the amber interval has remained low at junctions implemented with the flashing amber intervention. The results were consistent with both genders, revealing no significant difference between male and female drivers in terms of their performance in the driving simulator controls in response to the amber light.

Similar to the effects of the flashing green light to warn drivers of the impending signal change, the flashing amber indication in the current study was found to trigger an earlier response to stop, compared to the normal amber light (Mahalel and Zaidel, 1985; Mahalel, et. al., 1985). See Table 7.6. No difference in braking time was found, however, when drivers were following a heavy vehicle at low approach speed (i.e. J6), implying that the flashing amber signal might be less effective at urban junctions or when drivers were within close proximity behind other vehicles (Harbluk, et. al., 2007). This finding suggested that heavy vehicles may have an effect on their succeeding vehicles; the reason of such an effect although has remained obscure, might be partially due to drivers being more cognizant of the vehicle immediately ahead of them (Harbuk, et. al., 2007). The red light violations at J6, in particular, might be committed under the influence of a non-stopping preceding vehicle (Van der Horst and Wilmink, 1986; Bonneson, et. al., 2002; Elmitiny, et. al., 2010), showing the lack of driver's compliance to stop for the flashing amber signal when following behind a heavy vehicle at urban junction.

Level of uncertainty in drivers, when compared between the control condition and the flashing amber intervention, revealed a higher level of uncertainty in drivers only at J3 (i.e. rural junction), where drivers were travelling behind another vehicle in response to the flashing amber signal. No significant difference was found at the remaining 6 junctions.

Under the influence of the vehicle directly ahead of the drivers, the current intervention again, showed its lack of effectiveness in providing the drivers with more safety decisions.

Significant increase in the magnitude of option zones, which has been found to be responsible for increased rear-end accidents (Hakkert and Mahalel, 1978; Mahalel and Zaidel, 1985; Mussa, et. al., 1996; Köll, et. al., 2004), have led the authors to argue that the empirical flashing signals may not be effective. Drivers tend to interpret the additional phase as a longer amber warning (May, 1968; Mahalel and Zaidel, 1985). Flashing green signals in Austria, in particular, has resulted in a substantial increase of early stops, thus generating a period of uncertainty for drivers (Köll, et. al., 2004). In the current study however, higher level of uncertainty was only found at J3 upon implementation of the standalone flashing amber light at junctions; driver's level of uncertainty did not seem to increase with larger magnitude of option zones at the remaining junctions with flashing amber intervention.

Similar to the effects of the empirical flashing amber light (McCoy and Pesti, 2003), the standalone flashing amber light is also shown to be effective in raising driver's attention on the impending signal change.

7.5. Conclusion

This study demonstrated that the proposed flashing amber light has the potential to encourage driver's stopping decisions at signalised junction, when used as a standalone device adjacent to the normal traffic light. Unlike the empirical flashing lights that create larger indecision zone with higher level of uncertainty, the flashing amber intervention seems to increase earlier stopping without elevating driver's uncertainty at junctions. The higher level of uncertainty with the empirical flashing lights might be due to the duration of the warning phase being set too long (May, 1968). Alternatively, driver's attention and attitudes towards the position of the flashing lights might be an issue.

8. Real-time traffic signal status to improve uniformity in driving behaviour at signalised junctions

This chapter describes the analysis of the effects of the advanced signal intervention. The performance of the advanced signal intervention is compared with the control condition. Statistical assessment and behavioural interpretation of the results are also presented.

8.1. Introduction

With the existence of problem zones being identified at high speed signalised junctions (Gazis, et. al., 1960) and option zones at lower speed junctions (May, 1968), many experiments have been performed to search for the optimal solution to reduce the magnitude of these two zones, and to eliminate the problem zone where possible. Both enforcement and engineering countermeasures have been tried (May, 1968; Zegeer and Deen, 1978; Chin, 1989); engineering countermeasures in particular, have been designed to tackle unintentional red light violations among drivers with reduced awareness of potential hazards at signalised junctions (Mahalel and Zaidel, 1985; Retting, et. al., 1998; Bonneson, et. al., 2002; Bonneson and Zimmerman, 2004; Köll, et. al., 2004). Past studies have suggested that time reference aids, such as advanced warning systems, could improve driver's anticipation of the amber onset (Hakkert and Mahalel, 1978; Mahalel and Zaidel, 1985; Mussa, et. al., 1996; Newton, et. al., 1997).

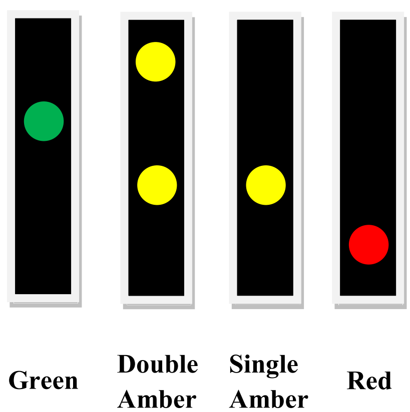
Using symbols and messages, static advanced warning signs are installed upstream of the signalised junctions to forewarn drivers that they are approaching a signalised junction, particularly when there are sight limitations due to road alignment and geometry (Pant and Huang, 1992; Martin and Kalyani, 2003; Lum and Halim, 2006). Reduced red light violations were shown (Bonneson, et. al., 2002; Moon, et. al., 2003) when dynamic advanced warning signs, accompanied by flashing beacons, were used in place of the static signs to ensure that drivers would detect the warning message and thus their greater tendency to stop (McCoy and Pesti, 2003; Sunkari, et. al., 2005). Comparative studies of different advanced warning signs are reported elsewhere (Eck and Sabra, 1985; Pant and Huang, 1992; Pant and Xie, 1995). Dynamic advanced warning systems in general, are operated without influencing the traffic signal controller operation to predict in advance the termination of the green signal and activate the amber beacons (Sunkari, et. al., 2005); the activation time of the amber beacons may differ between different junctions. The use of dynamic advanced warning signs at signalised junctions was not recommended in the literature due to their increased likelihood to encourage higher speed and abrupt stopping (Eck and Sabra, 1985; Pant and Huang, 1992; Pant and Xie, 1995). In particular, the condition has been found to deteriorate when the flasher was inactive and the signal indication was either green or amber (Pant and Huang, 1992). Driver's approach speed has been found to vary between different statuses of the dynamic advanced warning sign (Pant and Huang, 1992); drivers tend to decelerate on amber onset when the advanced sign was active, and accelerate to cross if it was not (Pant and Huang, 1992; Pant and Xie, 1995).

Using countdown devices at junctions, drivers are informed of the remaining time before the onset of the solid amber phase, displayed in digital numbers. Similar to the dynamic advanced warning signs, countdown devices not only warn drivers of the impending phase change, but also notify drivers of the exact instance when the onset will occur (Huey and Ragland, 2007; Limanond, et. al., 2009). Green signal countdown devices in particular, have been shown to be practically effective in encouraging red stopping actions, but not curbing red light violations (Lum and Halim, 2006). Drivers tend to experience a longer option zone, causing significant deviations in driver decision (Chiou and Chang, 2010); for instance, some drivers may use the countdown information to accelerate and cross the junction (Lum and Halim, 2004; Ibrahim, et. al., 2008; Chiou and Chang, 2010) whilst the others may use the information to make a timely stop (Kidwai, et. al., 2005; Chiou and Chang, 2010). The green signal countdown device did not seem to improve junction safety; its effect to reduce red light violations appeared to have dissipated over time with the frequency of violations gradually rebounded to the level before installation of the countdown device (Lum and Halim, 2006). On the contrary, junction safety could be adversely affected if drivers overestimate their ability to cross the junction and use the information from the countdown signals to speed through, potentially causing an increase in red light running (Mussa, et. al., 1996; Huey and Ragland, 2007) and rear-end collisions (Lum and Halim, 2004). Drivers may also be too focused on the countdown signal that they find it more difficult to respond quickly to road hazards (Huey and Ragland, 2007). The green signal countdown device has been shown to be somewhat effective under low traffic volumes, but not effective at all under high traffic volumes in the longer term (Lum and Halim, 2006); a practical approach has been suggested to apply a device that warns drivers of the impending termination of the green signal but does not convey the precise quantum of the remaining green time (Lum and Halim, 2006).

Previous findings (Pant and Huang, 1992; McCoy and Pesti, 2003) have suggested that providing warning signals to drivers could raise their attention towards the signal change and thus improve their decision (Mahalel, et. al., 1985) and their anticipation of the onset of amber light (Mussa, et. al., 1996, Moon, et. al., 2003). In particular, the warning initiation time at which the signal controller sends the information on changing signal phase prior to the onset of amber (Moon, et. al., 2008) may be crucial to the effectiveness of an advanced warning system. The main aim of the current study is therefore to examine if there is any significant improvement in driving performance with advanced information on the signal status.

8.2. Intervention design

The function of the advanced signal is to provide information of the traffic light status to drivers before they are getting too close to the junction; the idea was adapted from the four-aspect railway signal system which provides progressive warnings to drivers as they approach the railway junctions (Railway Technical Web Pages, 1998; Stanton and Walker, 2011). See Figure 8.1. Based on the similar concept, modifications were made in the current study to provide advanced signal to drivers at some distances upstream of the original traffic light, dependent on the speed limits. The conceptual framework of the current intervention is illustrated in Figure 8.2, where the location of the advanced signal was measured as the distance a vehicle can travel in 1 second from the traffic light at the approach speed equivalent to the imposed speed limit. For instance, an advanced signal was installed at 22m upstream of the traffic light on an approach with speed limit of 50mph (i.e. 22.4m/s). A screenshot of the intervention is illustrated as in Figure 8.3.



Definition

Green: Proceed

Double Amber: Proceed (but either start slowing down or expect to have to start slowing down at the next signal)

Single Amber: Proceed (but start slowing down in anticipation of having to stop at the next signal)

Red: Stop

Figure 8.1: Signal aspects for a four aspect colour light signal shown at the railway junctions (Adapted from Stanton and Walker, 2011, pp. 1121)

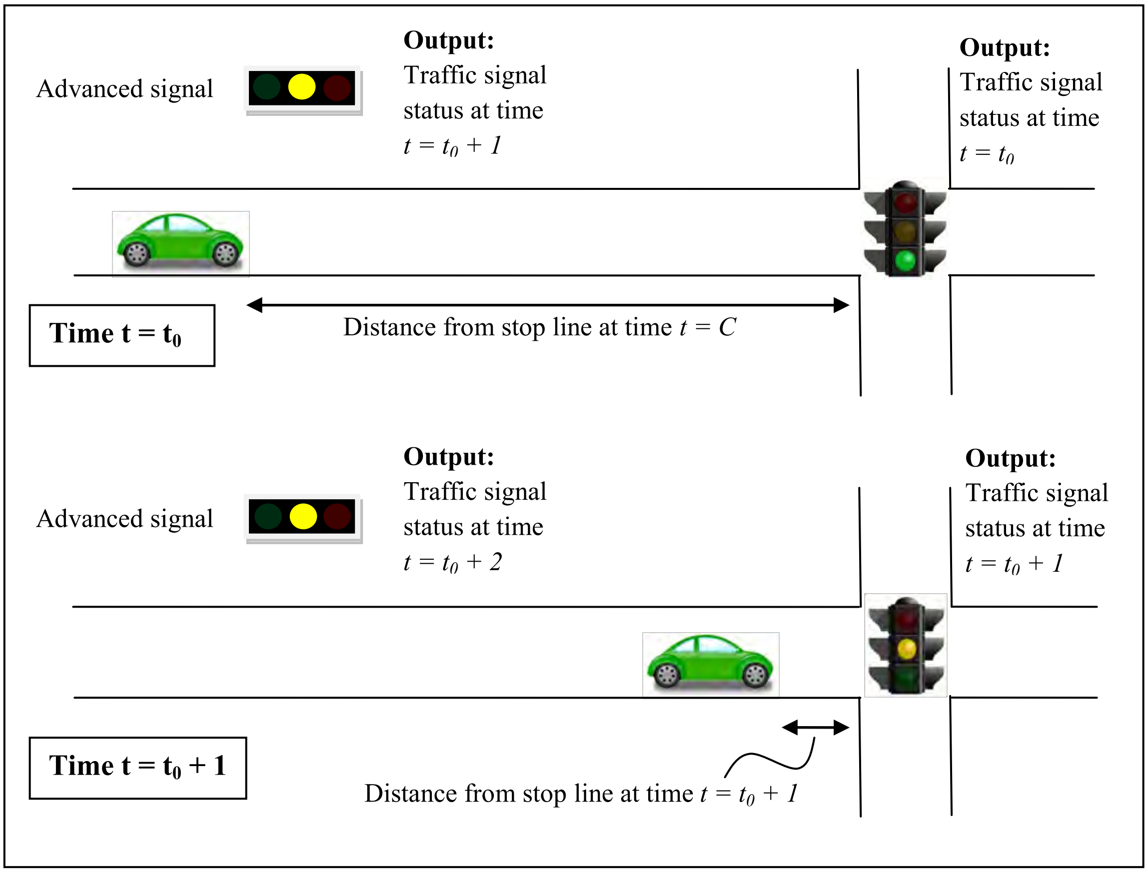


Figure 8.2: Conceptual framework of the advanced signal system

(a)

(b)

Figure 8.3: A screenshot of the advanced signal light upstream of the original traffic light on rural road, showing (a) 1 second of countdown time to the impending signal change (while driving behind another passenger vehicle) (b) the signal to remain green in the next second

8.3. Results

20 drivers drove the simulator with baseline settings before the advanced signal intervention and 12 drivers drove the simulator in opposite order. The 6 pairs of junctions implemented with the control condition and the advanced signal intervention, i.e. J2 to J7, were compared on their performances.

8.3.1. Frequency of stopping decisions

As shown in Table 8.1, the overall stopping rates have increased for the advanced amber intervention. In particular, the intervention has significantly reduced unsafe stopping decisions ($p < 0.001$ in Binomial test) and increased safe stopping decisions.

Table 8.1: Frequency of stopping vehicles

		Control			**Advanced signal**		
	Junction	safe stopping	unsafe stopping	Total (/192)	safe stopping	unsafe stopping	Total (/192)
Rural	2	0	14	14	7	10	17
	3	0	17	17	12	7	19
	4	0	15	15	8	8	16
Sub-urban	5	2	17	19	8	11	19
Urban	6	0	10	10	5	3	8
	7	0	9	9	10	7	17
		2	**82**	**84**	**50**	**46**	**96**

8.3.2. Frequency of red light violation

Red light violation was found to decrease at J2 (rural), but increase at J6 (urban); the difference in both directions was however relatively small. No improvement was found at the remaining junctions.

Table 8.2: Frequency of red light violation

	Junction	Control	Advanced signal
Rural	2	1	0
	3	1	1
	4	0	0
Sub-urban	5	1	1
Urban	6	0	1
	7	0	0
		3	3

8.3.3. Magnitudes of driver's speed and acceleration

Comparisons between the control condition and the advanced signal intervention on driver's speed and accelerating/decelerating behaviour revealed that lower variation in speed was found at junctions implemented with the advanced signal intervention. Driver's maximum acceleration rates and their speed increase during the amber onset were, as expected, significantly higher with the control condition. See Table 8.3 to 8.5. Drivers were also found to apply significantly less steeper deceleration rates to stop, as illustrated in Figure 8.4, suggesting a more uniform decelerating behaviour with the advanced signal intervention.

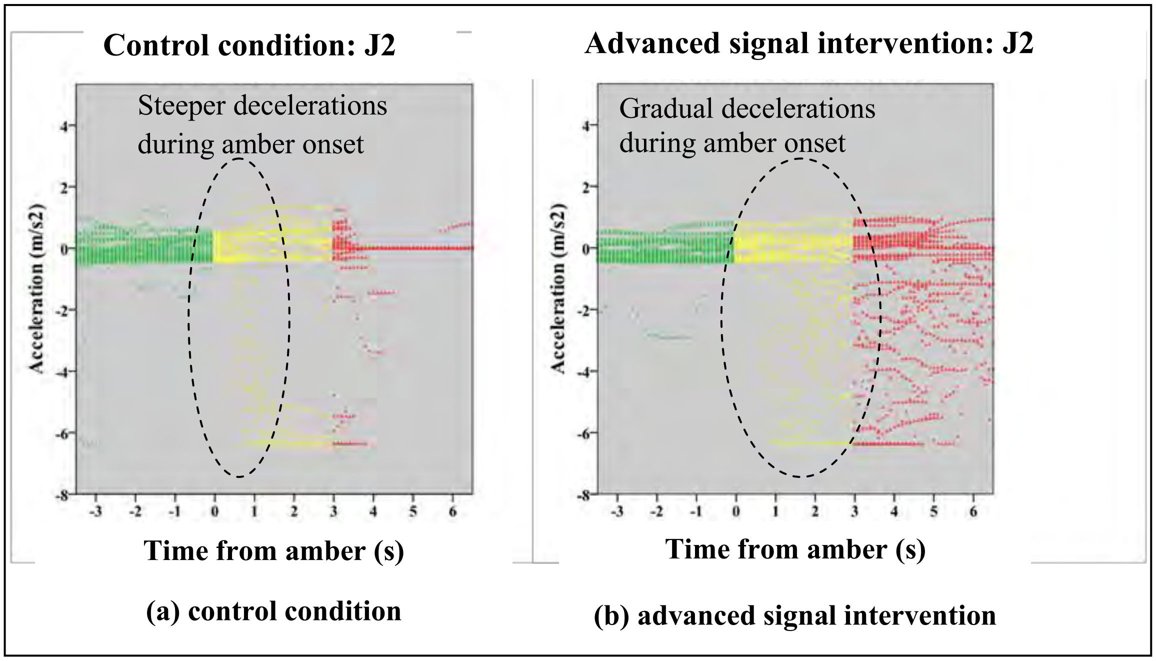


Figure 8.4: Drivers' acceleration profile at Junction J2 with (a) the control condition and (b) the advanced signal intervention.

Table 8.3: Test statistics on percentage increase in speed between the control condition and the advanced signal intervention

	Percentage increase in speed ($J2_{AS}$) - Percentage increase in speed ($J2_C$)	Percentage increase in speed ($J3_{AS}$) - Percentage increase in speed ($J3_C$)	Percentage increase in speed ($J4_{AS}$) - Percentage increase in speed ($J4_C$)	Percentage increase in speed ($J5_{AS}$) - Percentage increase in speed ($J5_C$)	Percentage increase in speed ($J6_{AS}$) - Percentage increase in speed ($J6_C$)	Percentage increase in speed ($J7_{AS}$) - Percentage increase in speed ($J7_C$)
Z	-4.207[a]	-4.189[a]	-4.370[a]	-4.787[a]	-4.189[a]	-4.937[a]
Asymp. Sig. (2-tailed)	<.0001**	<.0001**	<.0001**	<.0001**	<.0001**	<.0001**

a. Based on the hypothesis: Percentage increase in speed with the advanced signal intervention (AS) > Percentage increase in speed with the control condition (C)
** Significance of less than 0.05 found, resulted in the hypothesis to be rejected.

Table 8.4: Test statistics on the maximum acceleration rates between the control condition and the advanced signal intervention

	Max acceleration on amber ($J2_{AS}$) - Max acceleration on amber ($J2_C$)	Max acceleration on amber ($J3_{AS}$) - Max acceleration on amber ($J3_C$)	Max acceleration on amber ($J4_{AS}$) - Max acceleration on amber ($J4_C$)	Max acceleration on amber ($J5_{AS}$) - Max acceleration on amber ($J5_C$)	Max acceleration on amber ($J6_{AS}$) - Max acceleration on amber ($J6_C$)	Max acceleration on amber ($J7_{AS}$) - Max acceleration on amber ($J7_C$)
Z	-4.058[a]	-4.843[a]	-4.450[a]	-4.712[a]	-3.946[a]	-4.507[a]
Asymp. Sig. (2-tailed)	<.0001**	<.0001**	<.0001**	<.0001**	<.0001**	<.0001**

a. Based on the hypothesis: Maximum acceleration rates with the advanced signal intervention (AS) > Maximum acceleration rates with the control condition (C)

** Significance of less than 0.05 found, resulted in the hypothesis to be rejected.

Table 8.5: Test statistics on the range of acceleration/deceleration rates between the control condition and the advanced signal intervention

	Range of acc on amber (J2)	Range of acc on amber (J3)	Range of acc on amber (J4)	Range of acc on amber (J5)	Range of acc on amber (J6)	Range of acc on amber (J7)
Mann-Whitney U	2.000	.000	.000	6.000	.000	.000
Wilcoxon W	155.000	190.000	136.000	196.000	36.000	153.000
Z	-4.645	-5.118	-4.744	-5.095	-3.554	-4.123
Asymp. Sig. (2-tailed)	<.0001**	<.0001**	<.0001**	<.0001**	<.0001**	<.0001**

a. Based on the hypothesis: Variations in speed with the advanced signal intervention (AS) > Variations in speed with the control condition (C)

** Significance of less than 0.05 found, resulted in the hypothesis to be rejected.

8.3.4. Braking performance among stopping vehicles

As shown in Table 8.6, drivers tend to apply brake significantly earlier at junctions implemented with advanced signal intervention, knowing that the change of light is going to happen. Although their braking response time to the advanced signal intervention were significantly shorter among all junctions, J3 has yielded a *p*-value of 0.046 (which is marginally lower than 0.05), thus suggesting that the statistical significance of reduced braking response time was slightly weaker with the presence of other passenger vehicle directly ahead of them.

Table 8.6: Test Statistics of braking response time of stopping vehicles between the control condition and the advanced signal intervention (between-subjects)

	J2	J3	J4	J5	J6	J7
Mann-Whitney U	56.500	135.000	34.500	81.000	28.500	17.500
Wilcoxon W	176.500	288.000	187.500	334.000	133.500	62.500
Z	-3.017	-1.992	-3.804	-3.663	-2.206	-3.192
Asymp. Sig. (2-tailed)	.003**	.046**	<.0001**	<.0001**	.027**	.001**

** indicates braking response time with the control condition (C) > braking response time with the advanced signal intervention (AS)

8.3.5. Driver's level of uncertainty

In the current study, driver's consistency in making a crossing or stopping decision in response to the amber onset was measured by their frequency of alternate contacts with the accelerator and the brake pedal. For instance, higher trigger rates of contact between the accelerator and brake pedal would indicate inconsistent decisions among drivers approaching a signalised junction, and hence demonstrated potentially negative impacts of the engineering treatment towards junction safety (Chiou and Chang, 2010). Using the within-subjects design, driver's levels of uncertainty were compared between the junctions implemented with control condition and advanced signal intervention, across all regions; no significant difference was found, revealing that the implementation of the advanced signal might be beneficial in enhancing driver's decision at the amber onset without increasing driver's anxiety.

8.3.6. Estimated magnitudes of problem zone and option zone

In the current study, the ability of individual driver to stop or to cross the junctions was based respectively on their performance in the driving simulator controls, and on simple motion equations. Using Equation [5.1], the problem and option zones were identified and compared between the control condition and the advanced signal intervention. As shown in Figure 8.5 and Appendix D, problem zones tend to diminish at junctions implemented with the advanced signals, and transform into larger option zones.

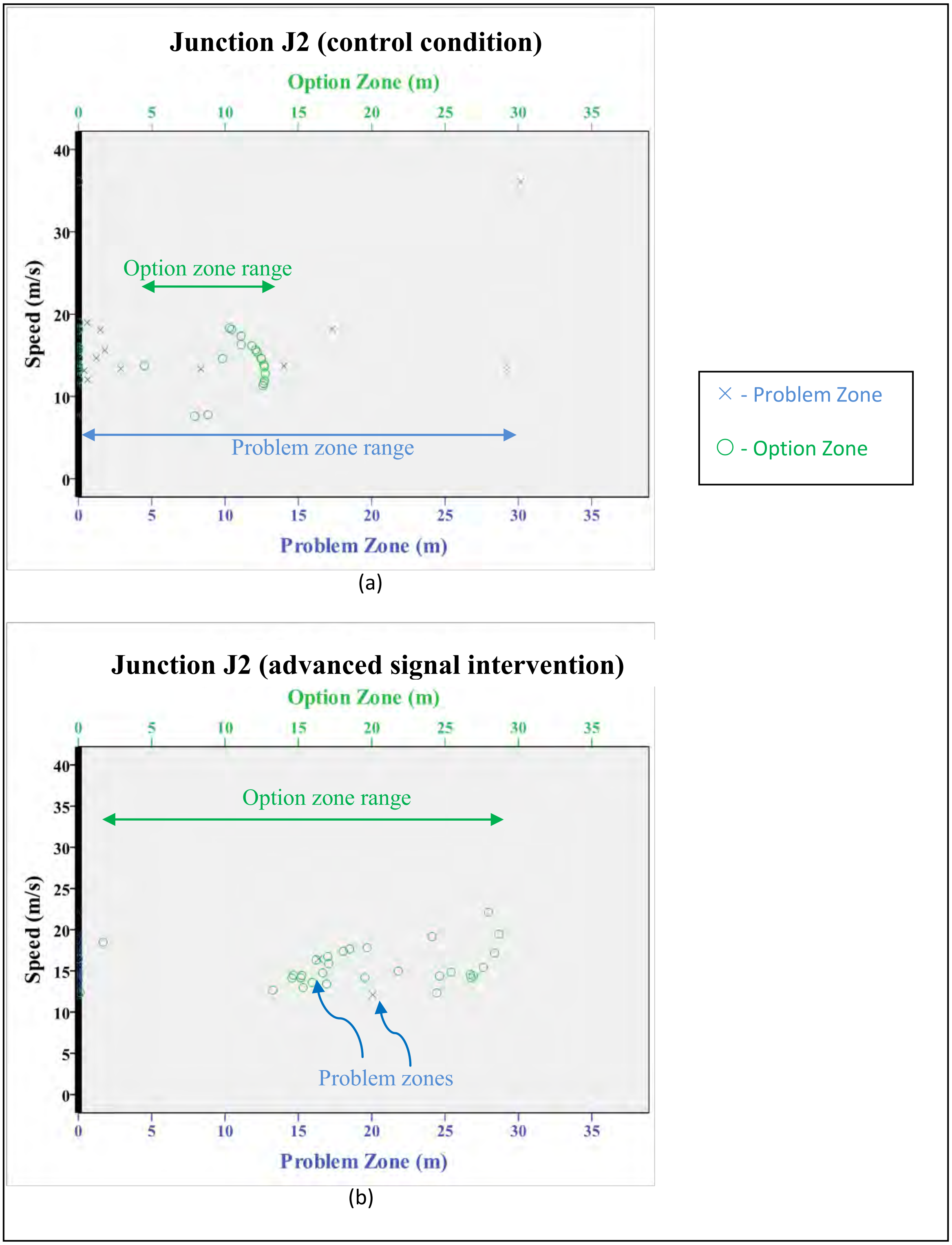


Figure 8.5: Estimated magnitudes of problem zones and option zones with (a) the control condition and (b) the advanced signal intervention.

8.4. Discussion

With the use of the driving simulator, the present study explored the possible effects of delivering advanced information to drivers at 1 second prior to the signal change. In terms of driver's compliance to stop on commencement of the amber onset, the advanced signal intervention has shown substantial increase in the stopping frequency. See Table 8.1. Past studies have suggested that advanced warnings should not be installed at urban junction due to their likely effects to increase the number of unnecessary stopping (Mahalel, et. al., 1985; Sunkari, et. al., 2005).

In the current study, drivers had demonstrated potentially safer stopping with less variability in their speed and acceleration controls (Retting, et. al., 1995, Mussa, et. al., 1996). In contrast to the effect of the empirical advanced warnings to encourage drivers to cross on amber light onset (Pant and Huang, 1992; Pant and Xie, 1995), drivers in the current study were found to exhibit more uniform behaviour with significantly smaller variation in acceleration/deceleration rates compared to the control condition, thus showing improved safety at the signalised junctions. Improved uniformity in driver's speed and acceleration controls were found to be associated with the enlarged option zones when compared with the control condition. It seems that the advanced signal has provided the drivers with a more relaxed decision situation where they can decide and are able to either stop or cross the junctions within the legal amber period (Prashker and Mahalel, 1989).

The display of the traffic light status-to-be at some specific distances upstream of the junctions had been shown to assist drivers in making better decisions. As suggested by Kikuchi and Riegner (1992), differences among individual drivers in their driving behaviour tend to be narrowed as more accurate information became available to the drivers (Kikuchi and Riegner, 1992).

By knowing the traffic light status of the next second, drivers were more likely to escape from the potential problem zones; as a consequence, larger option zones were identified without increasing driver's uncertainty at junctions. Unlike other alerting mechanisms which allow drivers to predict the onset of the amber signal (Mahalel and Prashker, 1989; McCoy and Pesti, 2003; Sunkari, et. al., 2005; Burnett and Sharma, 2011), the advanced signal in the current study provided accurate information of the impending traffic light status in real time, allowing driver's behaviour to be more uniform on making their crossing or stopping decisions.

The effectiveness of the warning system in the current study has indicated the sensitivity of the advanced information to the system reliability (Kikuchi and Riegner, 1992; Maltz and Shinar, 2007). When the advanced warning systems are not quite perfect to convey accurate information to drivers, drivers may fail to take appropriate actions within the allowable period of time (Kikuchi and Riegner, 1992); for instance, on occurrences when the system malfunctions and drivers relaxed their alertness (Pant and Huang, 1992; Maltz and Shinar, 2007), or when drivers were being confused of the information supplied to them and hence their misinterpretation of the information (Stanton and Walker, 2011).

In line with the literature (Mahalel and Zaidel, 1985; Mussa, et. al., 1996; Newton, et. al., 1997), drivers in the current study tend to apply their brake pedal earlier to the advanced signal intervention, showing the effectiveness of the advanced signal in raising driver's attention towards the impending signal change (Taoka, 1989; Demirarslan, et. al., 1998; McCoy and Pesti, 2003; Akçelik, 2008). Associated with driver's reduced variations in speed on stopping, their immediate braking action in response to the amber onset have implied their increased certainty in stopping (Mussa, et. al., 1996; Newton, et. al., 1997). The braking response times between different rural junctions although had not been found to be significantly different, the effect of the advanced signal to encourage earlier braking time might slightly be reduced when drivers were in close proximity behind other vehicle. At urban junctions however, the potential benefits of providing advanced signal to drivers had remained ambiguous in the current study. Driver's compliance to stop for the red light was reduced at one junction, but remained unchanged at the other.

Based on the overall performance of drivers in the current study, it seems beneficial to consider using the advanced signal before the actual traffic light. The reliability of the advanced signal to improve driver's decision over time would be subject to experiments with larger samples.

8.5. Conclusion

Based on the analyses and results from the current study, the use of advanced signal should be seen as encouraging in many aspects. In particular, when advanced signal was provided at the junctions, drivers tend to be more alert of the impending signal change. Drivers in the current study were informed of the signal status in real time; as a result, more accurate decisions were demonstrated in terms of improved uniformity in driver's speed and acceleration controls, associated with enlarged option zones. The improvement was shown without elevating driver's level of uncertainty. By setting the information on the traffic light status to be delivered to drivers at 1 second prior to the impending signal change, the benefits of shorter signal change intervals (May, 1968; Jourdain, 1986; Kikuchi and Riegner, 1992) were verified in the current study. New intervention, such as the advanced signal introduced in the current study however, requires a long period of familiarisation before any operational benefit becomes apparent (Pant and Xie, 1995). Future work on the implementation and validation of the advanced signal is encouraged; in particular, the current design of locating and timing the advanced warning signal at junctions should be reviewed.

9. Simulator evaluation of innovative interventions to enhance driver's safety responses at signalised junctions

This chapter summarises an evaluation study between different engineering interventions. Outcomes of extended amber, flashing amber and advanced signal interventions are compared to the control condition. The chapter concludes with the identification of the most effective engineering intervention to improve driver safer decisions at signalised junctions.

9.1. Background

Red light violations can be generally categorised into intentional and unintentional violations; the latter was found as a likely consequence of the problem zone (Gazis, et. al., 1960; Zegeer and Deen, 1978; Sheffi and Mahmassani, 1981). Many studies have identified that driver non-compliance to red light at junctions during the signal change were caused by driver's inattention to the road (e.g. Bonneson, et. al., 2002; Harbluk, et. al., 2007) and their poor cognitive skills (e.g. Delhomme and Meyer, 1998; Stanton and Walker, 2011); the latter was found more likely to contribute to accidents among younger drivers (Stanton, et. al., 2007). The findings thus suggest practical interventions to raise driver's attention to the impending signal change, in order to avoid delayed reaction to the amber and red signals. Using different mechanisms (such as modification of signal operation, alerting devices, signage etc), a number of engineering interventions have been developed with varying levels of success (e.g. Newton, et. al., 1997; Bonneson, et. al., 2002; Köll, et. al., 2004; Sunkari, et. al., 2005). However, due to the independent design and set up of these experiments, it was not possible to compare the studies in a meta-analysis. There has been particularly limited work to systematically compare between different types of traffic interventions, mainly due to the difficulty in getting field data. Using a driving simulator however, evaluation of different interventions is possible; and direct comparisons between different interventions have become feasible.

Although it has been a common practice to assess the effectiveness of an engineering intervention using the red light violation rates (Zegeer and Deen,1978; Hulscher, 1984; Van der Horst and Wilmink, 1986; Mohamedshah, et. al., 2000; Bonneson and Zimmerman, 2004; Maxwell and Wood, 2006), more recent studies have also shown that evaluation of interventions based on the changes in red light violation rates alone may be misleading (Giuffrè and Rinelli, 2006) and may minimise the impact of other safety factors (Taylor, et. al., 2000; Yeh, et. al., 2012). A reduction in non-compliance to red lights, associated with a reduction in the mean speed (Taylor, et. al., 2000) and improved vehicle control (Stanton, et. al., 2007) should also be considered for the measures of effectiveness of any proposed intervention under investigation.

The main aim of the current investigation is therefore to evaluate the effectiveness of different engineering interventions. Using identical metrics, changes in driver responses to three different engineering interventions (i.e. extended amber, flashing amber and advanced signal interventions) were measured and compared to the baseline condition (i.e. control condition). The data were subjected to a series of analyses to identify the most effective intervention to improve driver safety decisions at signalised junction, and to reveal any potential impact of regional factors on the interventions.

9.2. Summary of the evaluation study

This section summarises an analysis of the simulator study which was divided into four driving sessions for each of the 32 drivers who took part in the study. Detailed description of the study can be found in Chapter 5. Screenshots of the simulated road scenarios modelled with different interventions are illustrated as in Figure 9.1. The orders of the trials in the study were counterbalanced among the first 24 drivers, and the remaining 8 drivers were tested in a random order of the four trials. Table 9.1 shows the before-and-after order among the four experiments. The evaluation study was carried out on driver responses to 6 independent junctions on the route (i.e. J2 to J7).

Table 9.1: The sequences of the experiments

		After			
		Control	Extended amber	Flashing amber	Advanced signal
Before	Control		12	20	20
	Extended amber	14		17	17
	Flashing amber	12	15		16
	Advanced signal	12	15	16	

(a) Extended amber	(b) Flashing amber	(c) Advanced signal

Figure 9.1: Example of junctions with (a) extended amber intervention, (b) flashing amber intervention and (c) advanced signal intervention

9.3. Results

9.3.1. Frequency of safe and unsafe stopping vehicles

An increment in the frequency of stopping decision was observed for all the interventions, when compared with the regular traffic signal settings (i.e. control condition). See Table 8.1. A comparison of stopping propensity across different interventions, using the binomial test (at significance level of 0.05), indicated that increase in stopping propensity with the extended amber intervention was significantly larger than the control condition and advanced signal intervention. However, the advanced signal intervention was found to be better when driver's stopping responses were treated explicitly as either safe or unsafe. In particular, the advanced signal intervention was found to significantly reduce unsafe stopping; the intervention also demonstrated the highest number of safe stopping responses.

Table 9.2: Frequency of stopping vehicles

Intervention	Frequency of safe stopping	Frequency of unsafe stopping	Total stopping frequency at 160 junctions
Control	2	82	84
Extended amber	40	92	**132********
Flashing amber	9	104	113
Advanced signal	**50********	**46***	96

* denotes the lowest frequency

**** denotes the highest frequency

9.3.2. Frequency of red light violations

As a common practice, driver's compliance to stop for red light has been used to assess the level of safety at junctions (Mahalel, et. al., 1985; Mussa, et. al., 1996; Kidwai, et. al., 2005; Sunkari, et. al., 2005). Red light violations in particular, have been found more likely to contribute to junction accidents (Retting, et. al., 1999), regardless of the nature of the violations, being intentional or unintentional. The results in the current investigation showed that the advanced signal intervention, associated with lower red light violation rates, was better than the other two interventions. See Table 9.3. Redundant effects were however found among all the three interventions at urban junctions, with an increment respectively in the red light violation rates. When implemented without any intervention (i.e. control condition), no driver was observed to cross the urban junctions on red light onset, which suggested that red light countermeasures may not be necessary at urban junctions.

Table 9.3: Frequency of red light violation

Intervention	Region			Total frequency of red light violations
	Rural	Suburban	Urban	
Control	2	1	0*	3*
Extended amber	6	0*	3	9
Flashing amber	1*	1	4	6
Advanced signal	1*	1	1	3*

* denotes the lowest number of red light violations

9.3.3. Speed increment during amber onset

The analyses of driver's speed measured continuously over the times shortly (i.e. 3 seconds) before and after the amber light onset revealed that driver's speed differences were statistically significant between different interventions. Driver's speed management behaviour was measured in terms of their maximum speed recorded during the amber onset and their speed increment within the amber duration. As shown in Table 9.4, drivers were found to execute the lowest percentage increase in speed at junctions implemented with the advanced signal intervention. Maximum speeds at these junctions were also found to be significantly lower across different demographical regions. See Table 9.5. Extended amber intervention was however the least effective among all the interventions in improving driver's speed compliance at the signalised junctions.

Table 9.4: Increment in speed during amber interval

Intervention	Region		
	Rural	Suburban	Urban
Control	**	**	***
Extended Amber	**	**	***
Flashing Amber	*	*	**
Advanced Signal	*	*	*

* denotes significantly smallest increment in speed among all interventions
*** denotes significantly largest increment in speed among all interventions

Table 9.5: Maximum speed during amber interval

Intervention	Region		
	Rural	Suburban	Urban
Control	***	**	**
Extended Amber	****	**	**
Flashing Amber	*	*	*
Advanced Signal	*	*	*

* denotes significantly lowest maximum speed among all interventions
**** denotes significantly highest maximum speed among all interventions

9.3.4. Variation in acceleration/deceleration rates

Variation in deceleration rates creates a better picture of driving behaviour for stopping vehicles, and their levels of safety at junctions (Wortman and Matthias, 1983; Papaioannou, 2007). For instance, a measure of the spread of traffic speeds is directly related to the likelihood of junction accidents; the broader the spread, the more accidents (Taylor, et. al., 2000). As shown in Table 9.6, the advanced signal intervention outperformed other interventions, demonstrating the smallest variation in driver's speed among the stopping vehicles, hence implying improved safety at signalised junctions.

Table 9.6: Range of speed variation among stopping vehicles

Intervention	Region		
	Rural	Suburban	Urban
Control	****	**	***
Extended Amber	***	**	***
Flashing Amber	**	*	**
Advanced Signal	*	*	*

* denotes significantly smallest speed variation among all interventions
**** denotes significantly largest speed variation among all interventions

9.3.5. Braking response time

Driver's response time to the brake pedal has been used as a sensitive measure to their respective crash avoidance behaviours (Casucci, et. al., 2010). In the current investigation, braking response times in all trials were measured from the onset of the continuous amber light, until the moment drivers applied force on their brake pedal. As a result, the flashing amber intervention was successful in encouraging significantly earlier braking actions at signalised junctions across different demographic regions.

Table 9.7: Braking response time

Intervention	Region		
	Rural	Suburban	Urban
Control	**	**	**
Extended Amber	***	**	**
Flashing Amber	*	*	*
Advanced Signal	****	***	***

* denotes significantly shortest braking response time among all interventions
*** denotes significantly longest braking response time among all interventions

9.3.6. Driver's level of uncertainty

In the rural and sub-urban scenarios, extended amber intervention was shown to have a negative impact on driver's level of uncertainty; drivers were being indecisive about their ability to cross or to stop at the onset of the amber light, and hence demonstrating lower level of safety at signalised junctions. Although driver's level of uncertainty was not significantly reduced with the flashing amber and advanced signal interventions, neither did these interventions increase their level of uncertainty at junctions when compared to the control condition. In the urban scenarios however, no significant difference was found between all interventions and the control condition in terms of their level of uncertainty.

Table 9.8: Driver level of uncertainty

Intervention	Region		
	Rural	Suburban	Urban
Control	*	*	
Extended Amber	**	**	
Flashing Amber	*		
Advanced Signal	*		

* denotes significantly lower uncertainty
** denotes significantly higher uncertainty

9.3.7. Decision sensitivity of drivers

Signal detection theory (c.f. Raslear, 1996) was applied in the analysis to describe driver's response whether to stop or to cross the junction on commencement of the amber light. In the current investigation, the traffic light status plays the *signal*, and the driving context at the signalised junctions creates *noise* that competes with the signal. When drivers are approaching a signalised junction on amber onset, they must make one of the two choices: stop or cross. Driver's response to the amber onset can then be described by the 2×2 signal response matrix in Table 9.9. A safe stopping is the action to stop on red light onset and a safe crossing the action to cross on amber light onset. Their responses to cross on red light onset, and stopped too early or abruptly at amber onset were described as unsafe actions.

Table 9.9: Stimulus and response matrix for drivers at a signalised junction at the amber onset

Driver's response	Traffic light status: Amber	Traffic light status: Red
Crossed	Safe crossing	Unsafe crossing (RLR)
Stopped	Unsafe stopping	Safe stopping

(Adapted from Yeh, et. al., 2012, pp. 2226)

The sensitivity of each intervention was measured and compared between each other and the control condition to identify the most effective intervention to increase safe decisions at junctions. The sensitivity measure indicates the sensitivity of each intervention to their overall correct rates (safe stopping and safe crossing decisions) and overall error rates (unsafe stopping and unsafe crossing decisions). Using signal detection theory, sensitivity was estimated using *d'* and calculated as the standard score (Z) of the difference between probability of safe and unsafe stopping decisions, i.e.

$$d = Z[P(safe\ stopping)] - Z[P(unsafe\ stopping)] \quad [9.1]$$

where P abbreviates probability. Driver's tendency towards safe responses was estimated using β and calculated as

$$\beta = \frac{e^{-\frac{1}{2}Z[P(safe\ stopping)]^2}}{e^{-\frac{1}{2}Z[P(unsafe\ stopping)]^2}} \quad [9.2]$$

Device effectiveness (c.f. Raslear, 1996) was calculated as the ratio between the probability of unsafe stopping and the observed probability of unsafe crossing (i.e. red light violations), i.e.

$$Device\ Effectiveness = \frac{P(unsafe\ stopping)}{P(unsafe\ crossing)} \quad [9.3]$$

Each intervention was examined for its effectiveness to increase safe decisions. As shown in Table 9.10, junctions without intervention (i.e. control condition) have a negative *d'* rate, which implies an increase in driver's overall error rate (i.e. unsafe stopping and unsafe crossing rates). Driver's inclination to proceed through the junction at the amber onset was also shown with $\beta > 1$ and effectiveness ratio less than 1. Values of β less than 1 indicate a bias toward the *safe responses*, and values greater than 1 indicate a bias toward the *unsafe* responses. *Effectiveness ratio* of each intervention was measured as the proportion of the unsafe stopping decisions to the observed red light violations (Raslear, 1996; Yeh, et. al., 2009); the higher the ratio is above 1, the greater the effectiveness of the intervention. See Figure 9.2. A ratio less than or equal to 1 (e.g. control condition with effectiveness ratio of 0.73) indicates that the intervention is not effective because the accident rate is higher than the accident risk. The measures from Table 9.10 also revealed that advanced signal intervention was consistently more effective than other interventions in terms of driver's ability to detect the amber light onset (*d' = 2*) and their willingness to stop at the junction in response to the amber light (i.e. . *β < 1, effectiveness ratio = 5.85).*

A visual comparison of the performance between different interventions was also shown in Figure 9.3 using internal response probability density functions with and without each of the three interventions. The probability of safe stopping and unsafe stopping are illustrated in terms of the (overlapping) areas under the probability density function. For instance, wider *d'* value in Figure 9.3(c) illustrates higher probability on safe stopping with the advanced signal intervention.

Table 9.10: Sensitivity of all interventions

Intervention	*d'*	β	*Effectiveness ratio*
Control	-0.09858	1.064468	0.730838
Extended amber	0.534009	0.723443	3.50272
Flashing amber	0.032047	0.980323	1.468927
Advanced signal	2.021271****	0.292936*	5.846523****

- *d'* was measured as the sensitivity of the intervention to driver's safe responses; a higher *d'* indicates that the signal can be more readily detected.
- β was measured as the bias of the intervention to driver's responses;
* denotes lowest rate among all interventions
**** denotes highest rate among all interventions

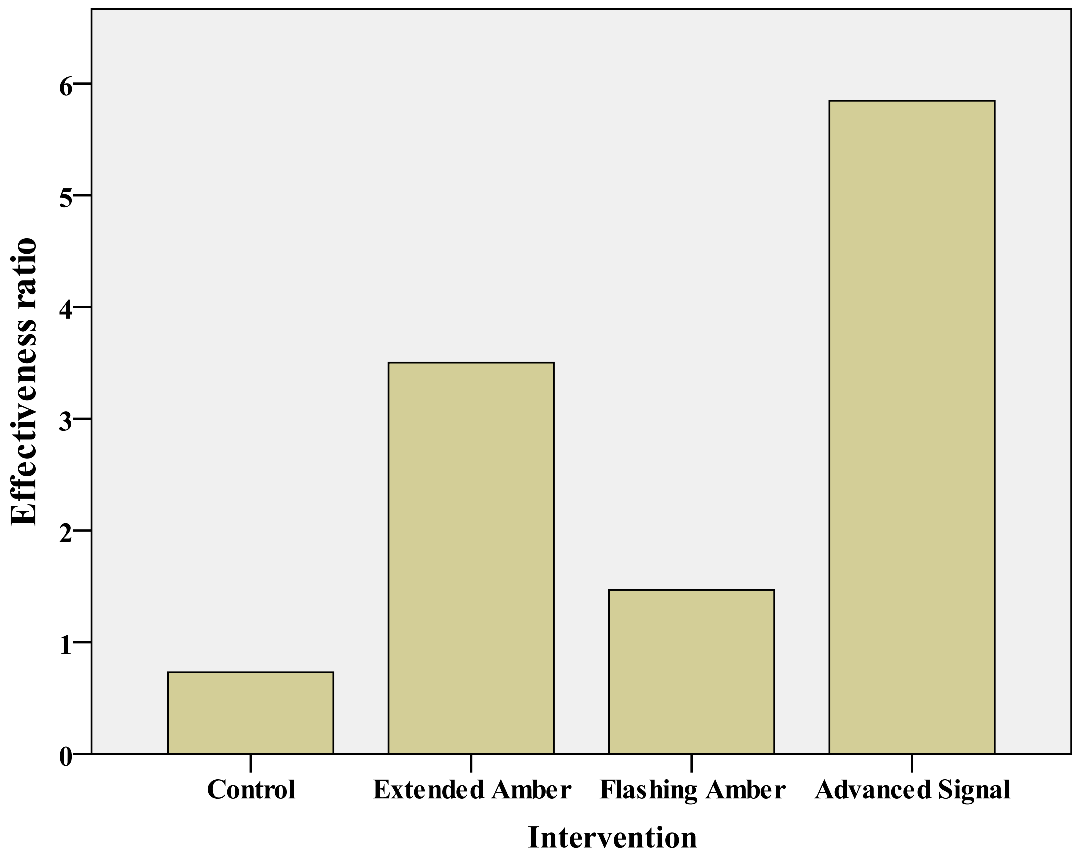


Figure 9.2: Effectiveness ratio of different interventions

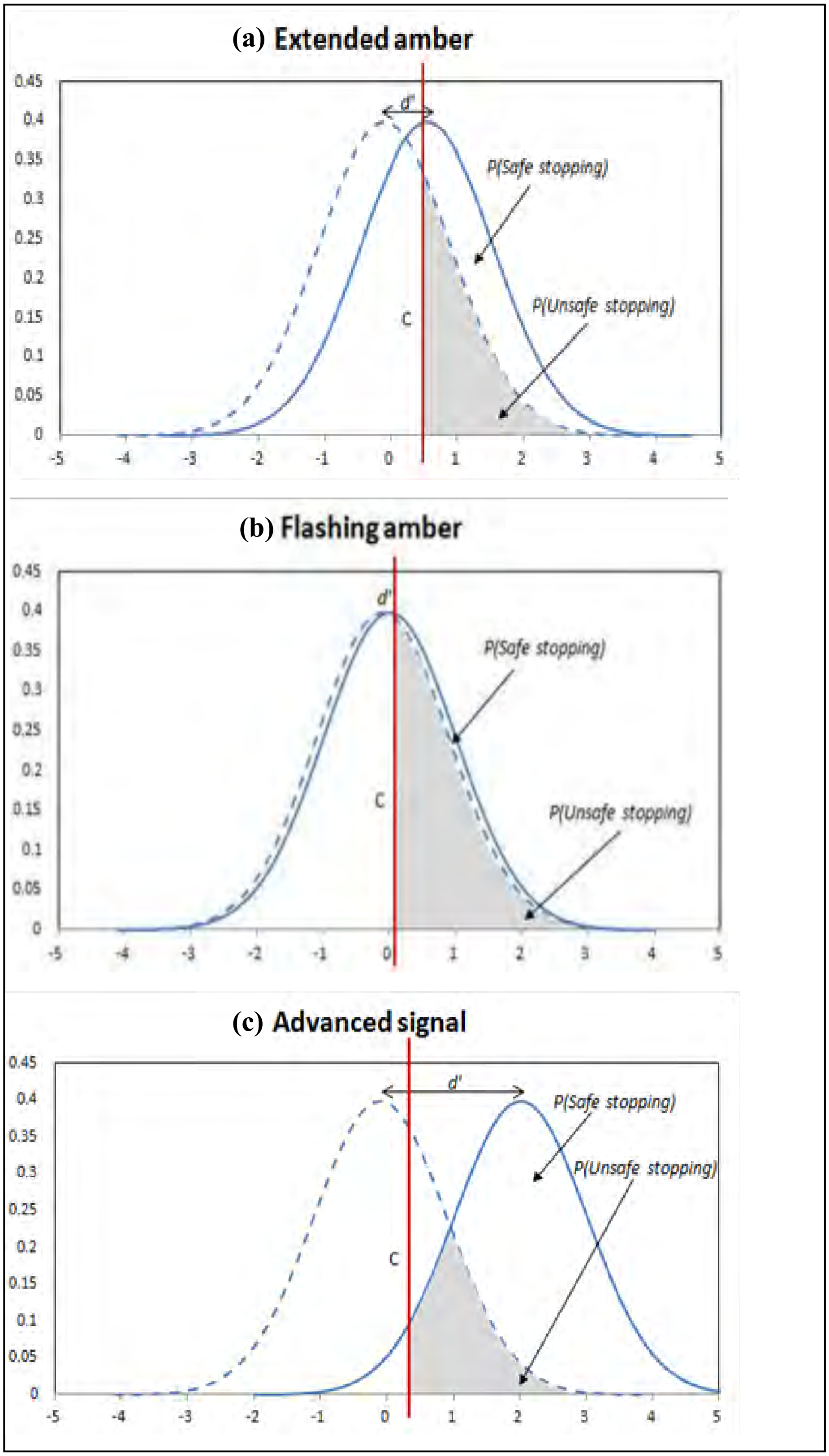


Figure 9.3: Internal response probability density functions: *d'* values for (a) extended amber (b) flashing amber (c) advanced signal intervention in comparison to the control condition

9.3.8. Feedbacks from questionnaires

On completion of the simulator study, all drivers were required to rank the interventions based on their understanding of the interventions, and the effect of different interventions to driver's stopping compliance to the onset of amber light at junctions. Using a score from 1 to 3, drivers rated their understanding of the interventions as 1 – less easily understood, 2 – easily understood and 3- most easily understood. Likewise, drivers reported their likelihood to stop for individual interventions as 1 – least likely to stop, 2 – less likely to stop, 3 – more likely to stop and 4 – most likely to stop. No repeated rank number was allowed for more than one intervention. The feedback from the questionnaires are summarised in Table 9.11 and 9.12. It seems that driver's likelihood of stopping was not directly dependent on how well they understood about the meaning of the interventions; for instance, drivers were least likely to stop for the extended amber intervention which has been reported as the most easily understood intervention.

Table 9.11: Driver's score on their understanding of the meaning of each intervention

Definition	Intervention		
	Extended amber	Flashing amber	Advanced signal
Least easily understood	7	19***	6
Easily understood	6	8	18***
Most easily understood	19***	5	8

***denotes the highest frequency (i.e. sample mode)

Table 9.12: Driver's score on their likelihood to stop at the junctions treated with each intervention

Definition	Intervention			
	Control	Extended amber	Flashing amber	Advanced signal
Least likely to stop	18****	5	6	3
Less likely to stop	5	15****	10	2
More likely to stop	6	4	10****	12
Most likely to stop	3	8	6	15****

****denotes the highest frequency (i.e. sample mode)

9.3.9. Summary of evaluations of different interventions

The results summarised in Table 9.13 show that the advanced signal intervention performed better than other interventions in the current investigation. When implemented with the advanced signal intervention, there was an improved uniformity in driver's speed performance and stopping behaviour in response to the amber onset. Extended amber intervention however, tends to encourage higher approach speed on amber; drivers were also found to experience higher level of uncertainty with longer amber light.

Table 9.13: Evaluation of driving performance between different interventions and the control condition

	Intervention			
	Control	Extended amber	Flashing amber	Advanced signal
Maximum no. of safe stopping				(✓)
Minimum no. of unsafe stopping				✓
Minimum no. of red light violation	(✓)			(✓)
Minimum speed increment				✓
Minimum variation in speed				✓
Minimum braking time			✓	
Maximum speed		×		
Highest uncertainty		×		
Higher decision sensitivity				(✓)
Driver's reported higher likelihood to stop				(✓)

(✓) denotes positive effect at junctions
✓ denotes significant positive effect at junctions
× denotes significant negative effect at junctions

9.4. Discussion

Using a driving simulator in the current investigation allowed direct comparisons of different interventions with the control condition; each of the 32 drivers faced all the interventions in identical situations. For instance, repeated measures from identical drivers avoided potential differences in driving skills among different drivers (Liu and Özgüner, 2007). In terms of driver's stopping propensity, the findings in the current investigation were consistent with the literature, with higher probability of stopping measured at junctions implemented with longer amber duration (Chang, et. al., 1985; Van der Horst and Wilmink, 1986; Bonneson, et. al., 2002) and different warning aids (Mahalel, et. al., 1985; Van Houten and Malenfant, 1992; Newton, et. al., 1997; Bonneson, et. al., 2002; Köll, et. al., 2004). The results also showed that a combination of different measures is required to make comparisons across different interventions, in order to identify the most effective intervention with the least negative impacts. For instance, extended amber intervention was shown to be effective in increasing stopping decisions at signalised junctions (see section 9.3.1), but the intervention also seems to increase the intensity of crossing on amber (May, 1968; Chang, et. al., 1985), and thus the potentials to increase red light violations. Likewise, potential drawbacks were also found for the flashing amber intervention; more drivers were observed to brake significantly earlier to stop (Mahalel and Zaidel, 1985; Köll, et. al., 2004), hence demonstrating inadequate early stopping or unsafe stopping actions which potentially increase rear-end accidents among inattentive drivers (Mahalel and Prashker, 1987; Retting, et. al., 2003; Köll, et. al., 2004).

Unlike the other two countermeasures (i.e. extended amber and flashing amber interventions), the advanced signal intervention was found to promote safe stopping whilst reducing the frequencies of unsafe stopping and red light violations; the increased inclination of safe decisions in response to the amber light onset is supported by the information in Table 9.2 and 9.10. Application of the signal detection theory to driver's responses also indicated that drivers were more able to detect the amber onset and to perform correct responses (i.e. safe stopping and safe crossing) when the advanced amber intervention was present. This could be due to the advanced information was particularly helpful to the drivers; for instance, previous studies (Mahalel, et. al., 1985; McCoy and Pesti, 2003; Moon, et. al., 2008) have reported the use of advanced warning devices to help drivers to stay focused on the road and perform safer stopping action at junctions.

Previous studies have shown that an effective intervention is expected to reduce driver speed on the approach (Comte and Jamson, 2000; Taylor, et. al., 2000; Bonneson, et. al., 2002). The investigation hence suggests that, through the use of extended amber intervention, significant speed increment (see Table 9.4 and 9.5) during the amber onset may have a negative impact on junction safety. An increase in speed at junctions is not desirable for safe movements of vehicles (Pant and Huang, 1992). Additionally, elimination of problem zone is usually not possible for speeds over the speed limit (Papaioannou, 2007). In terms of driver's speed recorded continuously during the desired duration, the results indicate that driver speed remained more uniform when alerting mechanisms were used (i.e. flashing amber and advanced signal interventions). The advanced signal intervention, associated with significantly lower accelerations, appears to be the best intervention. However, the results also showed redundant effects of applying the intervention to urban junctions; there was an increase in red light violations compared to the control condition, suggesting that it may be more difficult to alert drivers in urban environment (May, 1968). Application of extended amber and flashing amber interventions to the urban junctions revealed even more red light violations, implying that countermeasures at urban junctions may be unnecessary.

The current investigation demonstrated that the level of safety at junctions may not be fully captured using the frequency of driver responses alone. For instance, the extended amber intervention which has yielded the maximum number of stopping responses did not seem to perform better than the other interventions; 70% of the overall stopping responses were observed with abrupt braking, which are more likely to contribute to rear-end accidents (May, 1968; Hakkert and Mahalel, 1978; Mahalel and Zaidel, 1985; Retting and Greene, 1997). Unsafe driver responses to the extended amber intervention were also revealed in their significantly higher uncertainty (see Table 9.8). The flashing amber intervention was also shown to be less effective in improving overall safety at junctions; the intervention did not increase driver uncertainty but most drivers tend to apply the brake significantly earlier, which has been known to create unnecessary stopping (Mahalel, et. al., 1985; Mahalel and Prashker, 1987; Köll, et. al., 2004).

The current investigation evaluated the effectiveness of multiple interventions in a systematic way; in many aspects, the results showed that the advanced signal intervention was more effective than other interventions. In particular, uniformity in driving behaviour was achieved, with driver's higher tendency to stop for the amber light; feedback from the questionnaires also reported driver's higher responses to the intervention. Overall, the results suggest that the advanced signal intervention which provides more accurate information to drivers (i.e. real time information on the signal change) may help to narrow the differences between driver behaviour (Kikuchi and Riegner, 1992).

9.5. Conclusion

The current investigation illustrates the usefulness of the advanced signal intervention to inform drivers of the impending signal status for the next second; the intervention provides drivers with sufficient time (i.e. 1 second) to make required speed change on their responses, particularly for drivers who are inattentive or incapable to stop. Comparisons of the intervention performance among different demographic regions revealed that interventions at urban junctions were not required, probably due to the unlikely event of problem zones at urban junctions (May, 1968). The findings from the current investigation imply that more accurate information (i.e. from the advanced signal intervention) may be the key element to improve driver attitudes for speed choice; therefore efforts to change driver attitudes through information may be encouraged to improve driver safety. In addition, the current investigation demonstrated the negative effects of the extended amber intervention, suggesting that the use of extended amber intervention should be avoided at junctions.

10. Conclusion

This chapter summarises the research efforts, findings and major contributions for this thesis while also highlighting areas for possible future research.

10.1. Research summary

A review of the literature revealed that red light violation when making crossing decisions and abrupt braking when making stopping decisions are particularly unsafe responses to the onset of amber signal. Reduced likelihood of the unsafe responses was however found in drivers' awareness of the traffic situations and higher visibility of the driving environment, which however encourages traffic interventions through junction design and driver training. This research work addresses the issue of identifying wider driving context, supported by data from field observations, which can be used to predict more accurately, crossing behaviour with high levels of heavy vehicles and/or pedestrians, including the conditions that would have been theoretically found as problem zones. In particular, the significant effect of the position of the vehicle directly ahead of them has demonstrated the impact of contextual variables on driving behaviour. The finding also identifies an extended option zone rather than a problem zone among drivers who drove slightly faster than the speed limit for the road. A pilot study conducted among a diverse sample of drivers (using a driving simulator) has led to the identification of younger drivers as the focus driver group with reduced compliance to the speed limit. Different speed behaviours have also been found to be dependent on the road type; rural, sub-urban and urban.

In this research work, three interventions have been assessed: *extended amber, flashing amber* and *advanced signal* interventions were compared between each other and the control condition. Driving performance was measured among 32 younger drivers through a series of four simulated drives on the STISIM driving simulator; the details of these tests are provided in Chapters 5 to 9. No significant differences were however found between male and female drivers in terms of their driving performances. When compared with the control condition, an extended option zone has been demonstrated respectively for each of the three interventions. However, an extended option zone did not necessarily imply safer responses from drivers. Extended amber intervention in particular has found to increase driver's speed and uncertainty at the junctions, and therefore should not be suggested at junctions. In contrast, advanced signal intervention being the most effective intervention, has successfully reduced significant number of unsafe stopping without elevating driver's uncertainty; drivers appear to retain more uniform speed during the signal change. Similarly, the flashing amber intervention did not increase driver's uncertainty at junctions; but the intervention did encourage significantly earlier stopping at junctions, which were otherwise categorised as unsafe decisions in this research. Although the advanced signal intervention seems promising, their effects were negated at the urban junctions. Significantly slower braking responses were also found when drivers were within close proximity behind another vehicle; which therefore validates the contextual effect of the preceding vehicle (from the field observations) in the driving simulator study. A summary of the variation between magnitudes of the problem and option zones for the three interventions and the control condition over different road types is shown in Figure 10.1.

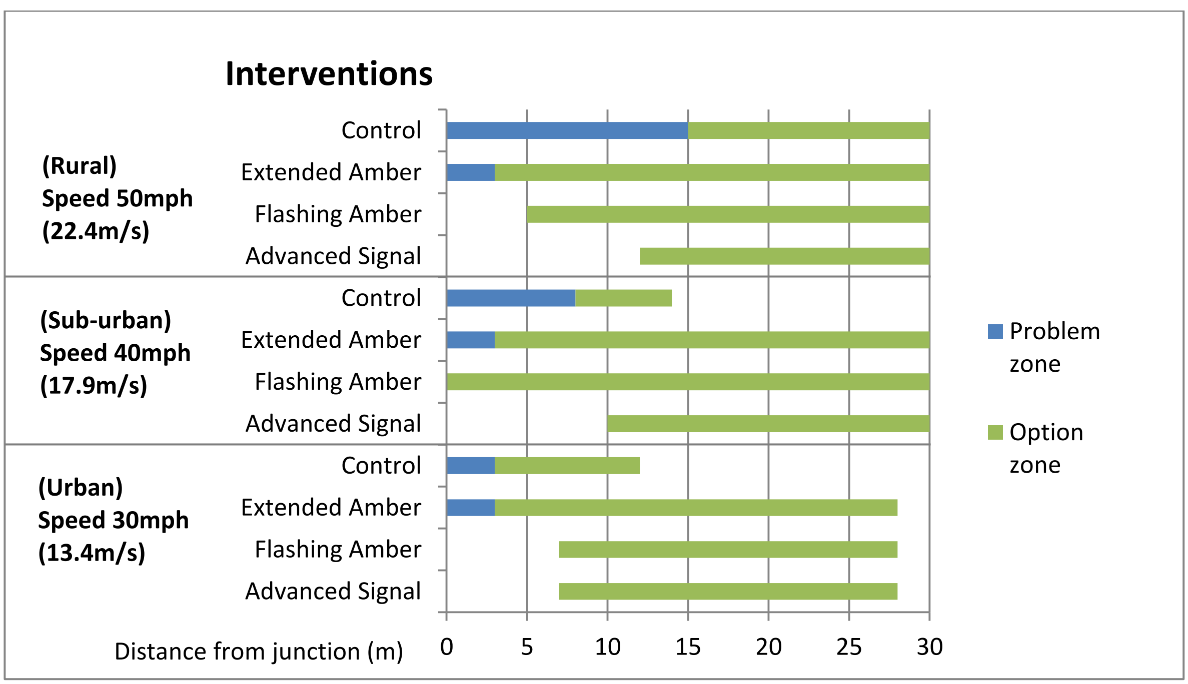


Figure 10.1: Magnitudes of option and problem zones for different interventions

10.2. Research contributions

There has been no standard (reliable) testing protocol to assess the effectiveness of different traffic interventions to improve driver decisions in response to the amber onset. Reduction in red light violation rates or the elimination of a problem zone alone may not be sufficient to explain whether or not the drivers are demonstrating safer actions (e.g. Taylor, et. al., 2000; Giuffrè and Rinelli, 2006). The objective of this research is therefore to improve the modelling of driving decision behaviour in response to the onset of the amber signal. A major contribution by this research has been the development of a framework of modelling driving decision behaviour under the influence of contextual factors. Drivers are not limited to make instantaneous decisions based on their position at the amber onset, but also on anticipated conditions and subconscious risk assessment on the driving context. This decision behaviour framework captures continuously driver's speed and acceleration performance from the amber onset until their final decision. Based on the context-aware framework, a logistic regression model is developed, that considers other road users, turning manoeuvre, and the effect of close following vehicles. The model identifies the significant impact of contextual variables to improved accuracy in predicting driver decision at signalised junction. The model also demonstrates that red light violations are more likely to occur within an extended option zone rather than a problem zone, which has been defined by considering a constant vehicle speed. Based on the driver behaviour decision framework (c.f. Chapter 3), a methodology has been deployed to categorise driver decisions between safe and unsafe decisions. The categorisation is based on driving performance skills by considering multiple performance parameters, including an index which can be used to discriminate between different uncertainty levels in drivers. Higher uncertainty in drivers is identified by an increased number of traversing actions between the accelerator and the brake pedals during the amber onset. Driver's decision, speed and acceleration behaviour, and their uncertainty level as a whole enable prediction of general driving skills in laboratory-based experiments. The methodology has been extended to be used as an assessment tool to examine the effectiveness of different interventions. Negative effects of an extended amber phase to increase driver uncertainty were ascertained in this research.

The finding from this research identifies a potentially effective intervention (i.e. advanced signal intervention) to significantly reduce driver unsafe responses without elevating driver uncertainty approaching the junctions. A conceptual framework of driver decision behaviour model in response to the advanced signal intervention is shown in Figure 10.2. It seems that an advanced signal intervention may improve safer decision behaviour at rural and sub-urban junctions; the benefits however may be apparent when the average rate of flow of heavy vehicles remains considerable higher in the traffic stream.

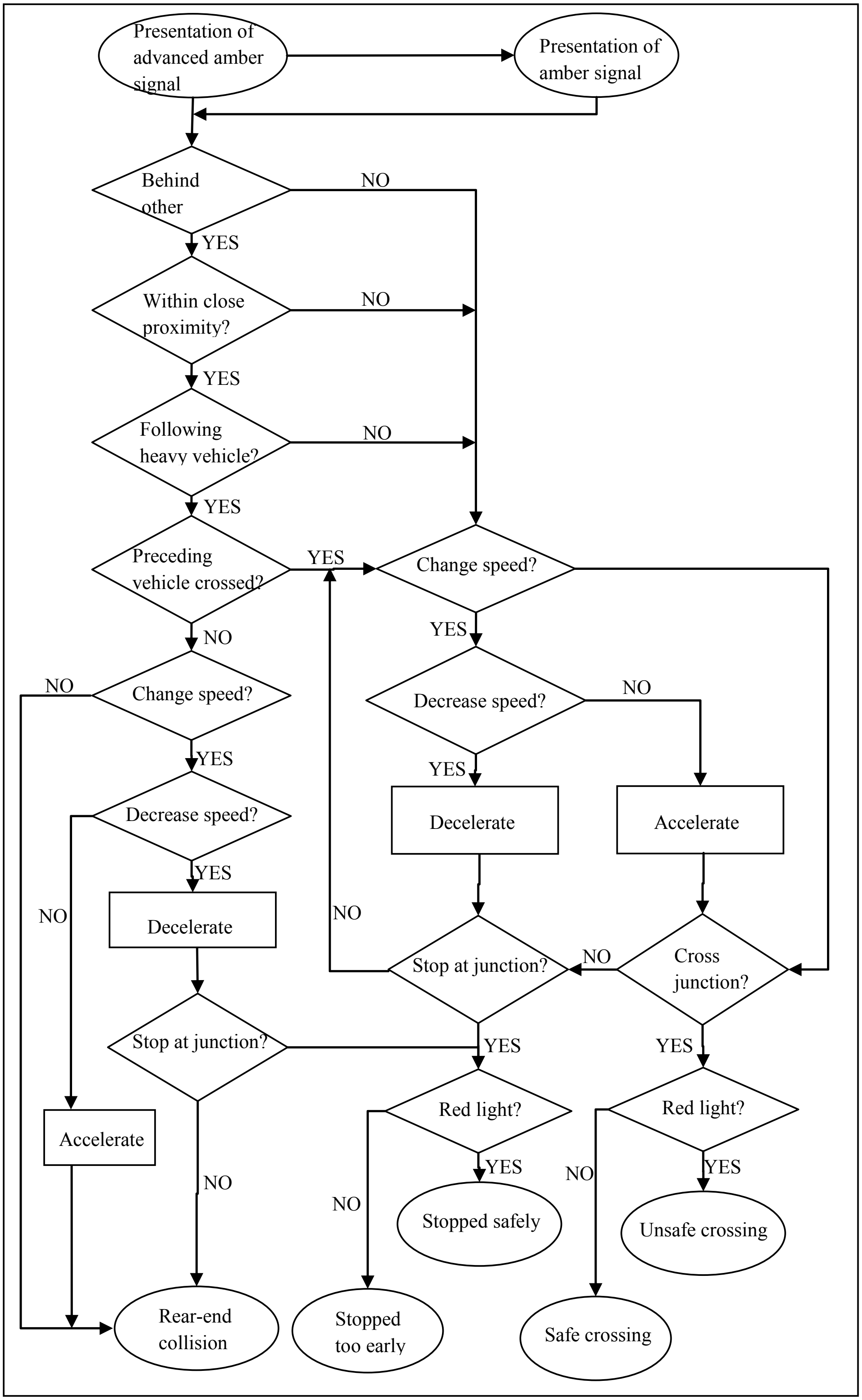


Figure 10.2: Conceptual framework of driver decision behaviour in response to the advanced signal intervention

10.3. Future research

This research work indicates that the STISIM driving simulator can be used as an effective tool to aid the evaluation of driver's safe and unsafe responses, and their driving performances. The framework of the driving decision model in this research may be applied to model other driving contexts such as the inclusion of the interactions with pedestrians and the turning manoeuvre on the driving route, which have been identified respectively as the contextual and physical variables (c.f. Chapter 3) that are more likely to contribute to a more accurate driver decision model. The application of the driving decision model is however not limited to the interventions in this research; the model can be applied to other interventions.

The positive effects of the advanced signal intervention suggest that driver decision may be improved with advanced information on the signal status. The intervention is therefore required to be repeatedly tested for its validity and to identify if the positive effects of the intervention would be dissipated over time. This research also provides an insight on the impact of the locations of the alerting devices to improve driver decisions; for instance, the effectiveness of the advanced signal intervention may be attributed to the location of the device upstream of the junction. The design of the location of the signal display therefore needs to be reviewed. Similarly, braking responses to the flashing amber intervention may be re-examined by replacing the standalone flashing amber light at some distances upstream of the junction. The findings from this future research are hoped to reveal different aspects of the designed interventions that could be improved to reduce unsafe stopping decisions. Also, larger samples of drivers could be employed for improved reliability in future research.

10.4. Conclusion

The underlying objective of this thesis was to attempt to integrate knowledge gained from different sources; in particular the theoretical knowledge gathered from the literature, findings from the field observations, and the perspectives provided by the results of the simulator experiments. This thesis provides a framework for improving driver decision behaviour in response to the amber onset. It addresses some critical aspects required in designing a conceptual intervention and may be used as a reference in assessing driving performance to other safety interventions.

Appendix A

Table A.1: Test Statistics[a] for Speed, Distance & Time between vehicle types

	Speed	Estimated time to stop line	Distance at amber
Mann-Whitney U	43932.000	41537.500	44974.500
Wilcoxon W	54663.000	226065.500	55705.500
Z	-.986	-.151	-.562
Asymp. Sig. (2-tailed)	.324**	.880**	.574**

[a.] Grouping variable: Heavy vehicle or passenger car
** denotes insignificance at 0.05 level

Table A.2: Test Statistics[a] for time headway between successive vehicles

	Headway between vehicles
Mann-Whitney U	30019.000
Wilcoxon W	35905.000
Z	-2.935
Asymp. Sig. (2-tailed)	.003

[a.] Grouping variable: Heavy vehicle or passenger car as preceding vehicle

Table A.3: Vehicles travelling behind a Heavy Vehicle

		Headway 3 sec		Total
		Leading	Following	
Stop or Cross	Cross	13	44	57
	Stop	32	19	51
Total		45	63	108

*70% of vehicles crossed when following a heavy vehicle with headway of less than 3 secs.

Table A.4: Leading and Following vehicles (with headway of 2 sec)

		Headway 2 sec		Total
		Leading	Following	
Stop or Cross	Cross	354	134	488
	Stop	263	30	293
Total		617	164	781

*82% of vehicles crossed when following a preceding vehicle with headway of 2 sec or less

Table A.5: Variables in the Equation for vehicles in Straight movement

		B	S.E.	Wald	Df	Sig.	Exp(B)
Step 1[a]	Distance	.175	.014	147.222	1	.000	1.191
	Speed	-.370	.059	38.733	1	.000	.691
	Psn3(1)	1.497	.281	28.420	1	.000	4.467
	Constant	-3.309	.555	35.476	1	.000	.037

Psn3 takes binary value of 0 as following vehicle, or value 1 as leading vehicle
B is the coefficient for the constant
S.E. is the standard error around the coefficient for the constant
Exp(B) is the odd ratio

Table A.6: Variables in the Equation for Left turning vehicles

		B	S.E.	Wald	Df	Sig.	Exp(B)
Step 1[a]	Distance	.140	.021	42.509	1	.000	1.150
	Speed	-.342	.123	7.684	1	.006	.711
	Ped_L(1)	-1.264	.547	5.335	1	.021	.283
	Constant	-.056	1.165	.002	1	.962	1.057

Ped_L takes binary value of 0 when pedestrian was observed crossing or waiting to cross the University Road, or value 1 without pedestrian
B is the coefficient for the constant
S.E. is the standard error around the coefficient for the constant
Exp(B) is the odd ratio

Table A.7: Observed and predicted frequency of stopping and crossing vehicles

Observed			Predicted (Not following closely after HV)			Predicted (Following closely after HV)		
			Stop or Cross		Percentage Correct	Stop or Cross		Percentage Correct
			Cross	Stop		Cross	Stop	
Step 1	Stop or Cross	Cross	8	3	72.7	39	3	92.9
		Stop	0	28	100.0	3	15	83.3
	Overall Percentage				92.3			90.0

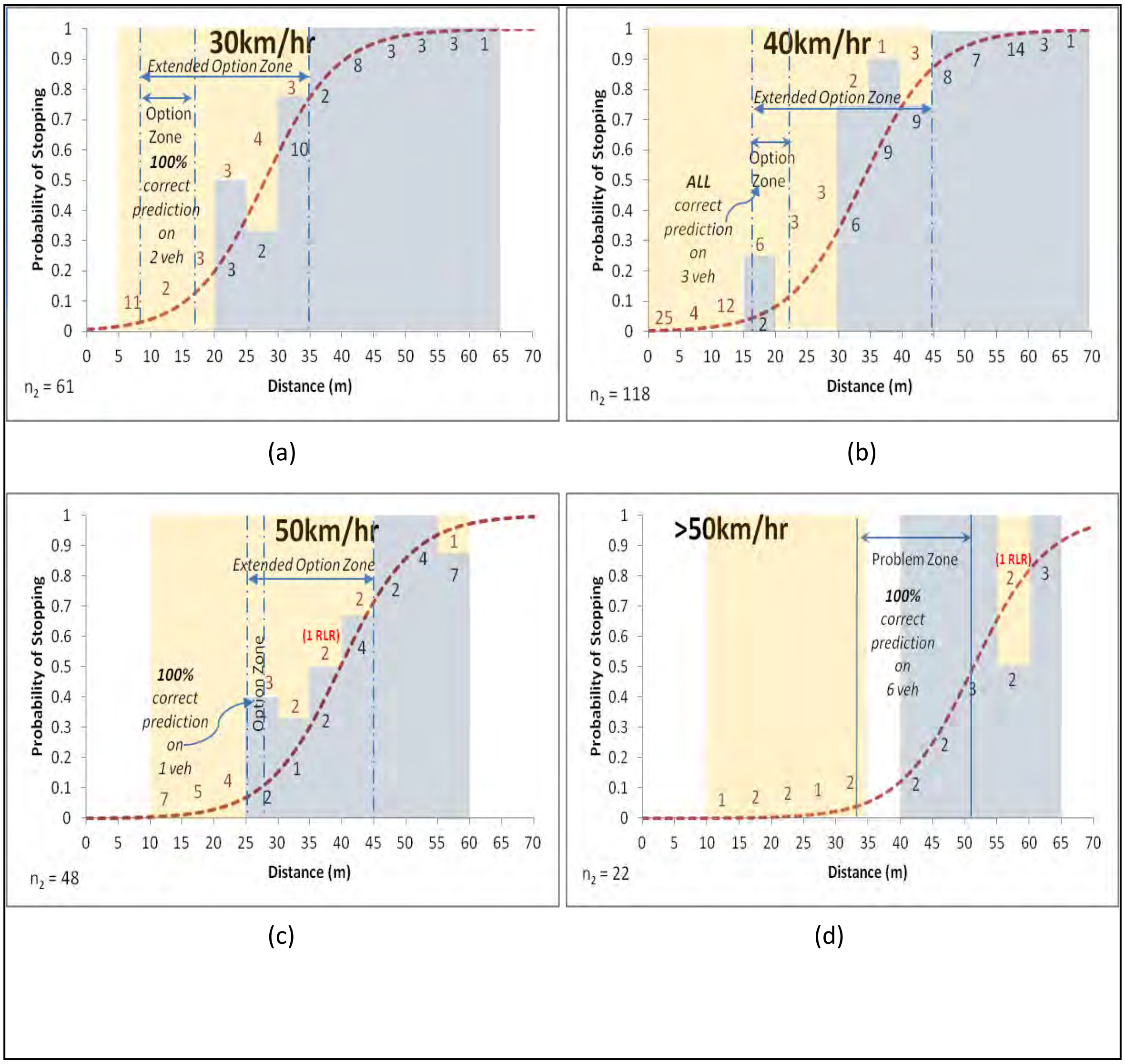


Figure A.1: Observed and predicted probability of stopping for Scenario II (Straight and Leading)

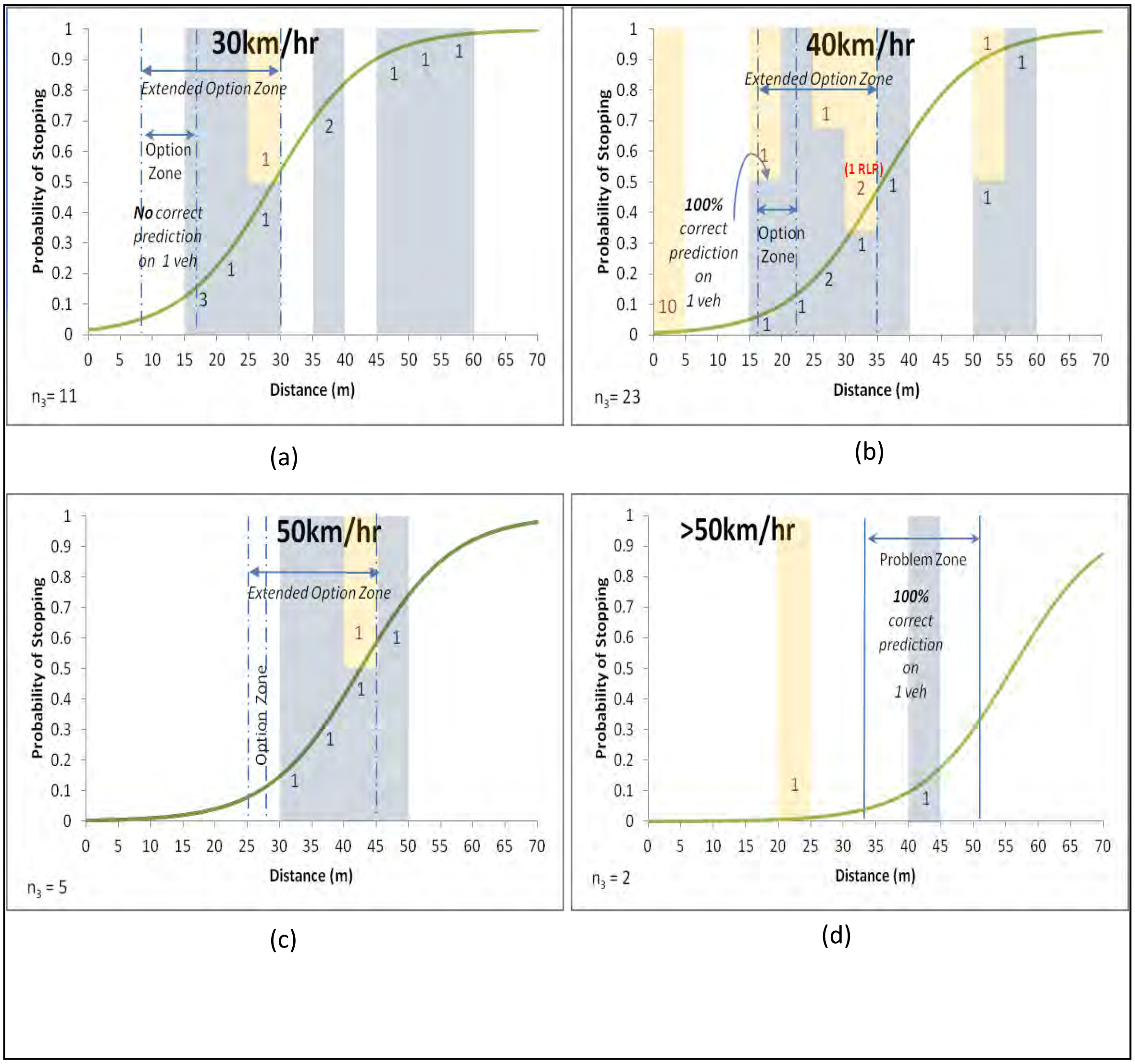


Figure A.2: Observed and predicted probability of stopping for Scenario III (Left turn with Pedestrian(s))

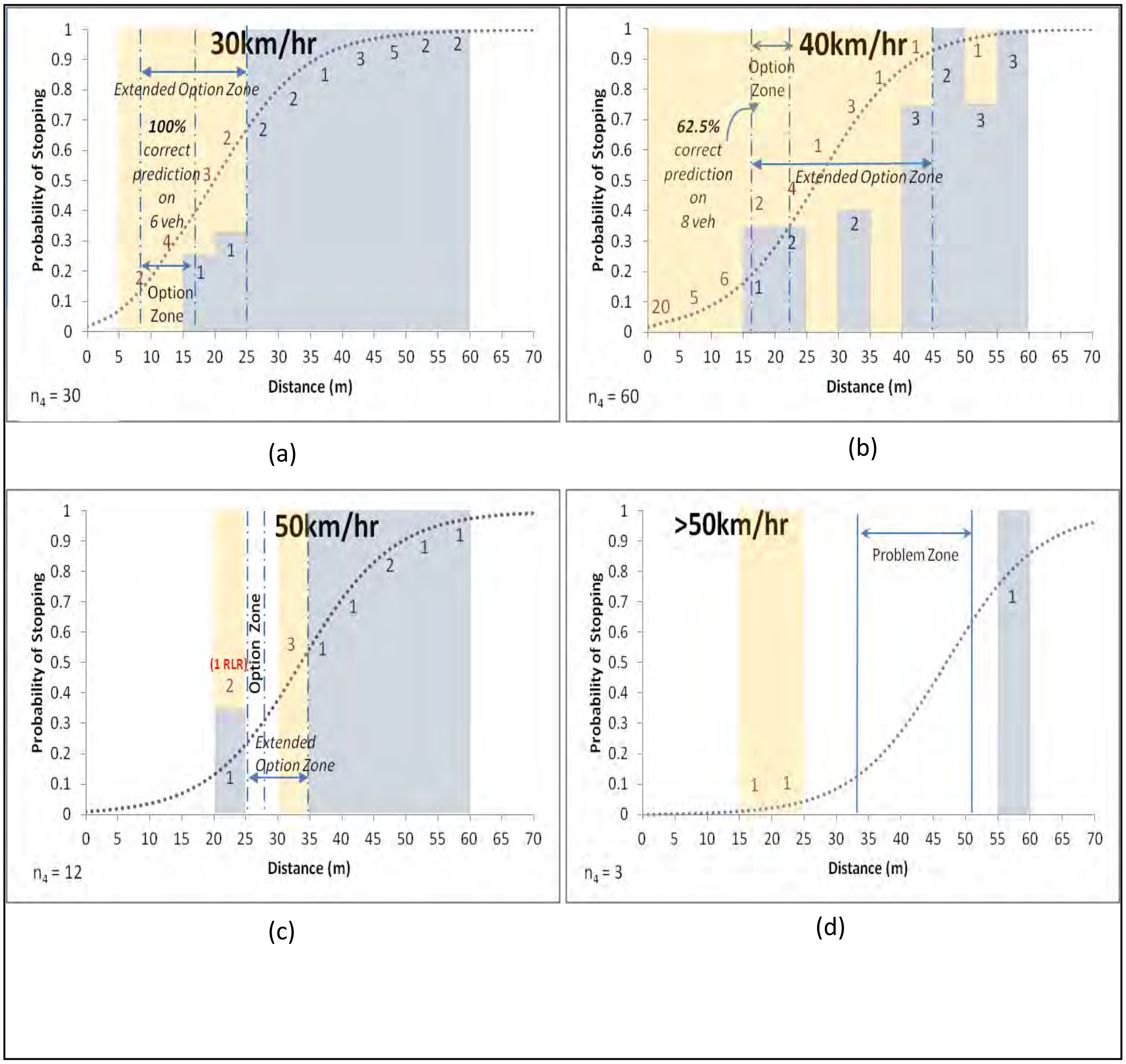


Figure A.3: Observed and predicted probability of stopping for Scenario IV (Left turn with no pedestrian(s))

Appendix B

Table B.1: Difference in vehicle's distance from junctions on commencement of amber light

		Rural		Sub-urban	Urban
	Junction	B	C	D	E
Rural	A	*		*	*
	B		**		*
	C			*	*
Sub-urban	D				*

*indicates significantly further distance from Junction i (in row) than Junction j (in column)
**indicates significantly shorter distance from Junction i (in row) than Junction j (in column)
where i=A to D, j=B to E

Table B.2: Test statistics of vehicle's distance from junctions, between four different driver groups

	Distance upstream of junction when amber light commences				
	Junction A	Junction B	Junction C	Junction D	Junction E
Chi-Square	4.739	12.515	18.795	17.237	8.687
Df	3	3	3	3	3
Asymp. Sig.	.192	.006*	.000*	.001*	.034*

*indicates significant difference in distance from the stop line between driver groups

Table B.3: Test statistics on driver's approach speeds between crossing and stopping vehicles

Junction	A	B	C	E
Z	-1.219	-1.938	-1.659	-.031
Asymp. Sig. (2-tailed)	.223	.053	.097	.975
Exact Sig. [2*(1-tailed Sig.)]		.052[a]	.103[a]	.987[a]

p-value < 0.05 in the 2nd last row would indicate a significant difference between crossing and stopping vehicles.

Table B.4: Test statistics between crossing and stopping vehicles on their distances from the stop line

Junction	A	B	C	E
Z	-1.180	-1.938	-1.659	-.062
Asymp. Sig. (2-tailed)	.238	.053	.097	.951
Exact Sig. [2*(1-tailed Sig.)]		.052[a]	.103[a]	.963[a]

Table B.5: Frequency of stopping and crossing vehicles

Junction		Red Light Running		Total
		No	Yes	
A	Cross	1	12	13
	Stop	67	-	67
Total		**68**	**12**	**80**
B	Cross	0	5	5
	Stop	75	-	75
Total		**75**	**5**	**80**
C	Cross	0	3	3
	Stop	77	-	77
Total		**77**	**3**	**80**
D	Cross	0	0	0
	Stop	80	-	80
Total		**80**	**0**	**80**
E	Cross	1	1	2
	Stop	78	0	78
Total		**79**	**1**	**80**

Table B.6: Test statistics of driver's approach speeds between four different driver groups

	Speed when amber light commences				
	Junction A	Junction B	Junction C	Junction D	Junction E
Chi-Square	5.308	12.253	18.880	17.188	9.250
Df	3	3	3	3	3
Asymp. Sig.	.151	.007*	.000*	.001*	.026*

*indicates significant difference in approach speed between driver groups

Table B.7: Test statistics of differences in stopping vehicle's distances from junctions between four different driver groups when the amber light commences

	Distance upstream of junction when amber light commences				
	Junction A	Junction B	Junction C	Junction D	Junction E
Chi-Square	6.075	12.312	17.924	17.237	10.397
Df	3	3	3	3	3
Asymp. Sig.	.108	.006*	<.0001*	.001*	.015*

*indicates significant difference in trigger distance between driver groups

Table B.8: Difference in approach speeds between different driver groups

	Speed when amber light commences											
	Rural						Sub-urban			Urban		
	Junction B			Junction C			Junction D			Junction E		
	YM	OF	OM	YM	OF	OM	YM	OF	OM	YM	OF	OM
YF		*	*		*	*			*			*
YM			*		*	*			*		*	*
OF												

*indicates significantly higher approach speed from driver group m (in row) than driver group n (in column) where m= {YF, YM, OF} and n= {YM, OF, OM}

Table B.9: Difference in stopping vehicle's distances from junctions between different driver groups when amber light commences

	Distance upstream of junction when amber light commences											
	Rural						Sub-urban			Urban		
	Junction B			Junction C			Junction D			Junction E		
	YM	OF	OM	YM	OF	OM	YM	OF	OM	YM	OF	OM
YF		*	*		*	*			*			*
YM			*		*	*			*		*	
OF												

*indicates significantly longer distance from driver group m (in row) than driver group n (in column) where m= {YF, YM, OF} and n= {YM, OF, OM}

Table B.10: Test statistics of maximum deceleration rates between four different driver groups

	Maximum deceleration rates at junction when amber light commences				
	Junction A	Junction B	Junction C	Junction D	Junction E
Chi-Square	8.138	12.851	9.676	10.011	4.980
Df	3	3	3	3	3
Asymp. Sig.	.043*	.005*	.022*	.018*	.173

*indicates significant difference in maximum deceleration rates between driver groups

Table B.11: Test statistics of braking response times between four different driver groups

	Braking response times at junction to the onset of amber light				
	Junction A	Junction B	Junction C	Junction D	Junction E
Chi-Square	2.62	.445	3.712	7.936	6.783
Df	3	3	3	3	3
Asymp. Sig.	.454	.931	.294	.057	.079

p-value (last row) greater than 0.05 indicates insignificant difference between the four driver groups

Table B.12: Test statistics of the magnitudes of problem/option zones between four different driver groups

	Magnitudes of problem/option zones				
	Junction A	Junction B	Junction C	Junction D	Junction E
Chi-Square	4.688	2.527	.785	4.976	15.294
Df	3	3	3	3	3
Asymp. Sig.	.196	.470	.853	.174	.002*

*indicates significant difference in magnitudes of problem/option zones between driver groups

Table B.13: Difference in magnitudes of problem/option zones between driver groups at Junction E

	YM	OF	OM
YF		*	*
YM		*	*
OF			

*indicates significantly larger problem/option zone from {YF, YM} than { OF, OM}

Appendix C

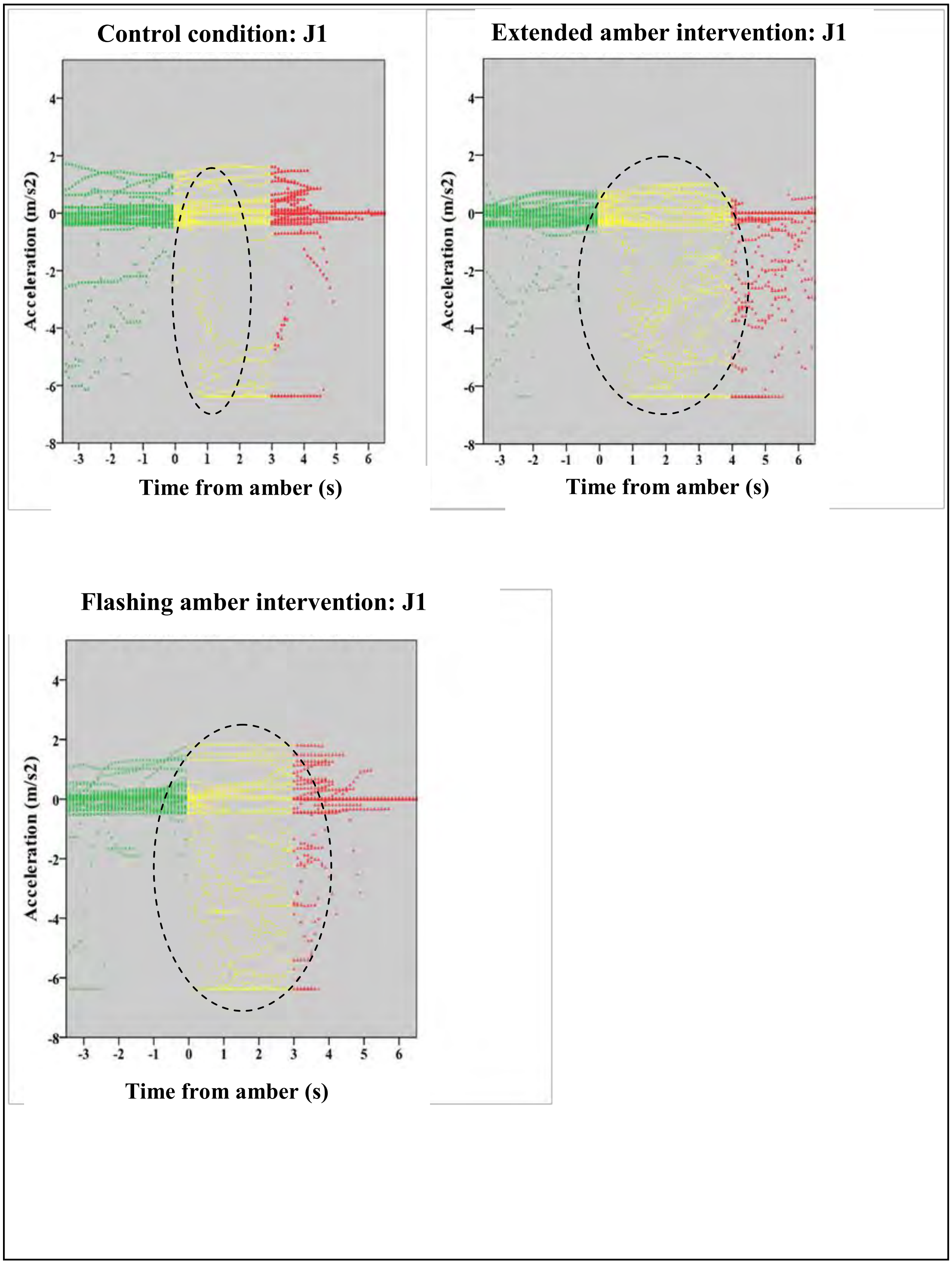


Figure C.1: Acceleration profiles for Junction J1

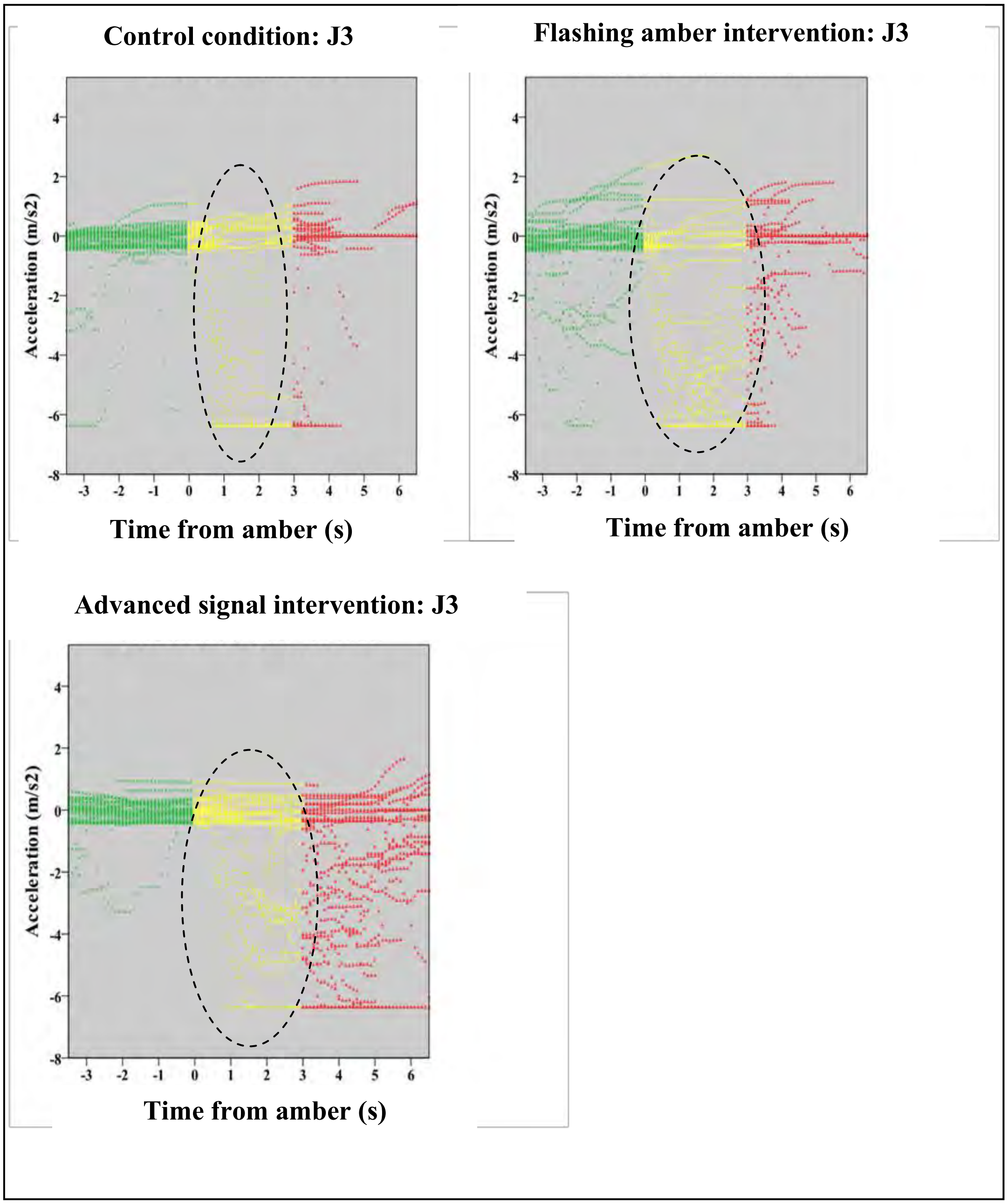


Figure C.2: Acceleration profiles for Junction J3

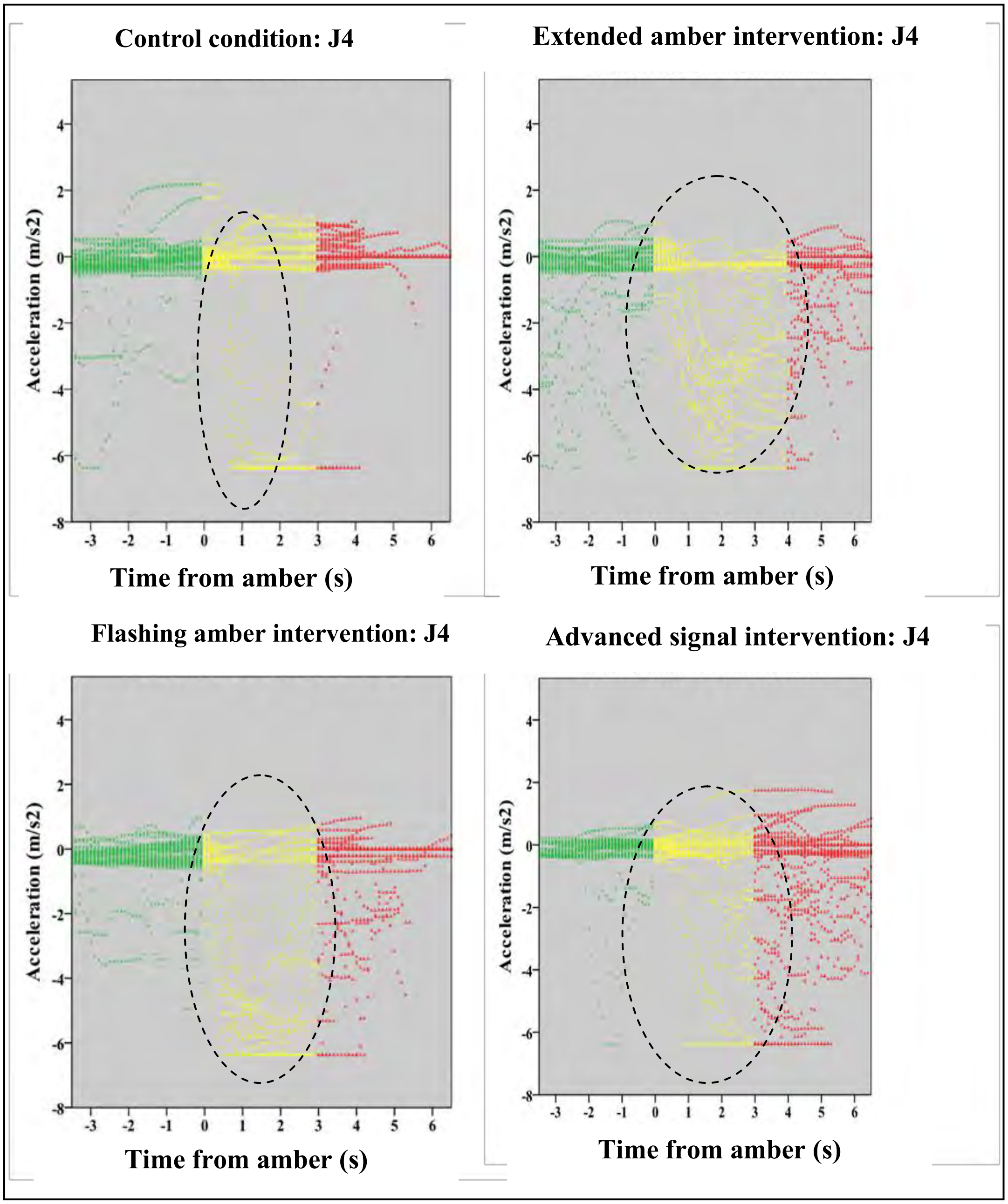


Figure C.3: Acceleration profiles for Junction J4

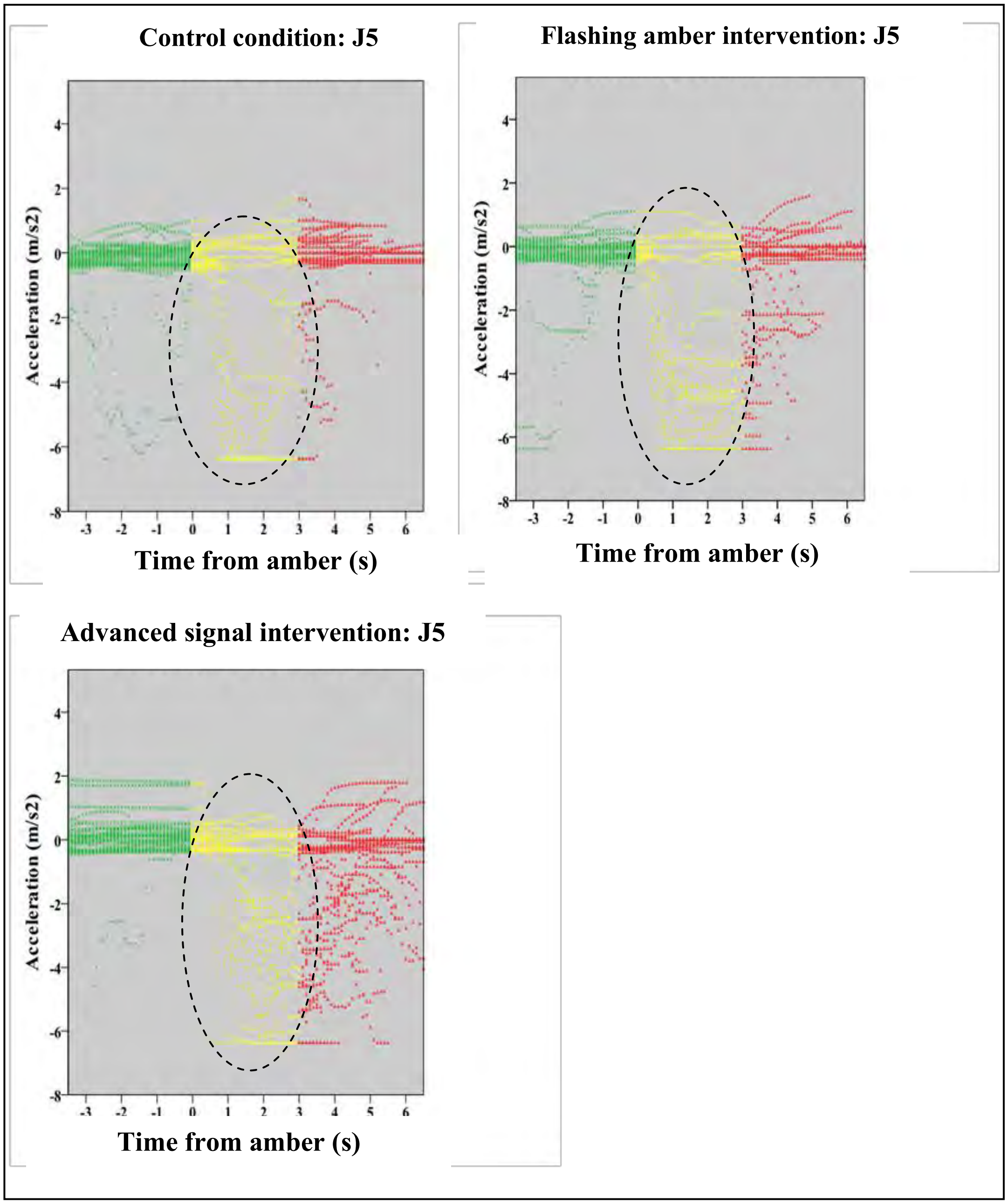


Figure C.4: Acceleration profiles for Junction J5

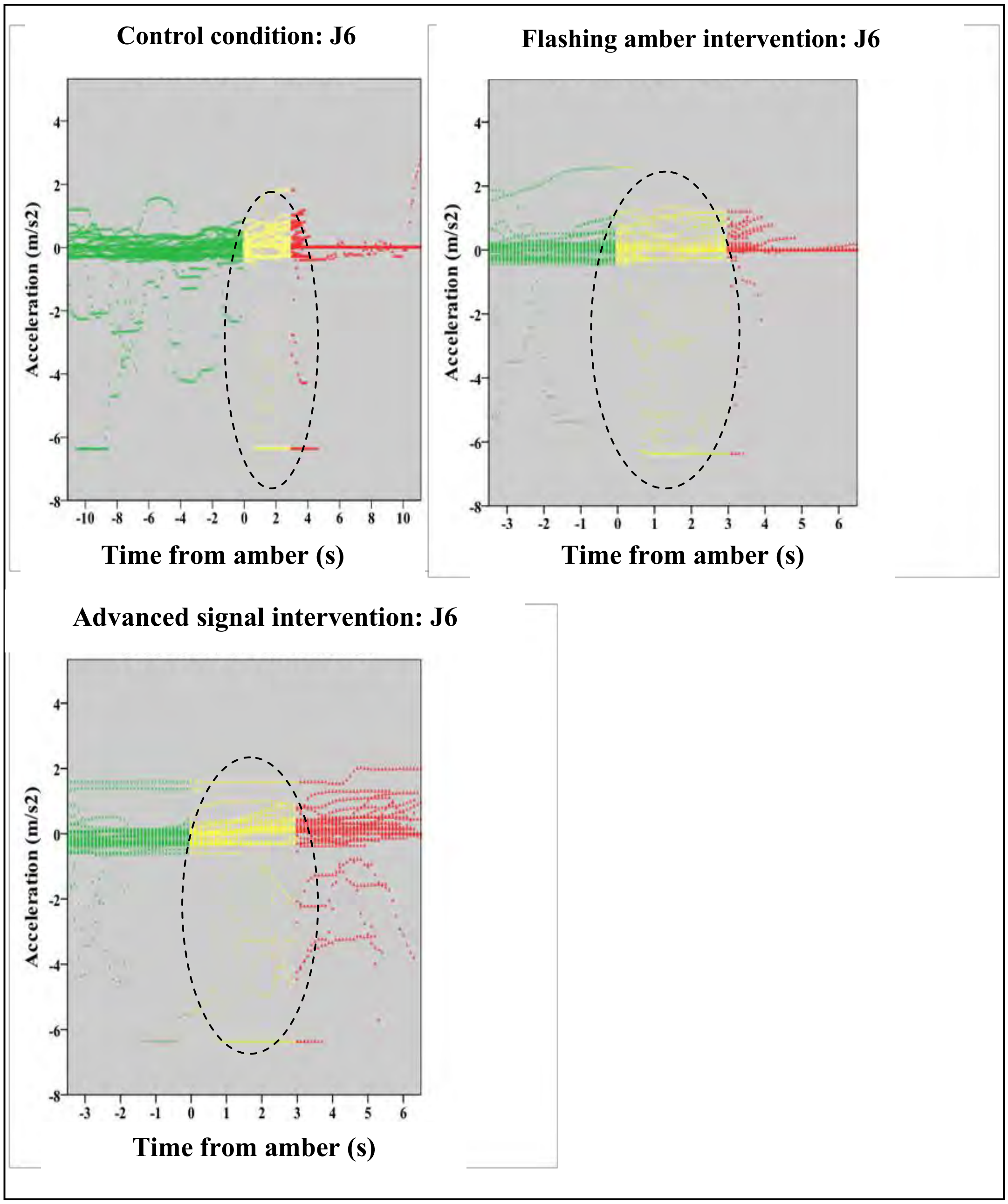


Figure C.5: Acceleration profiles for Junction J6

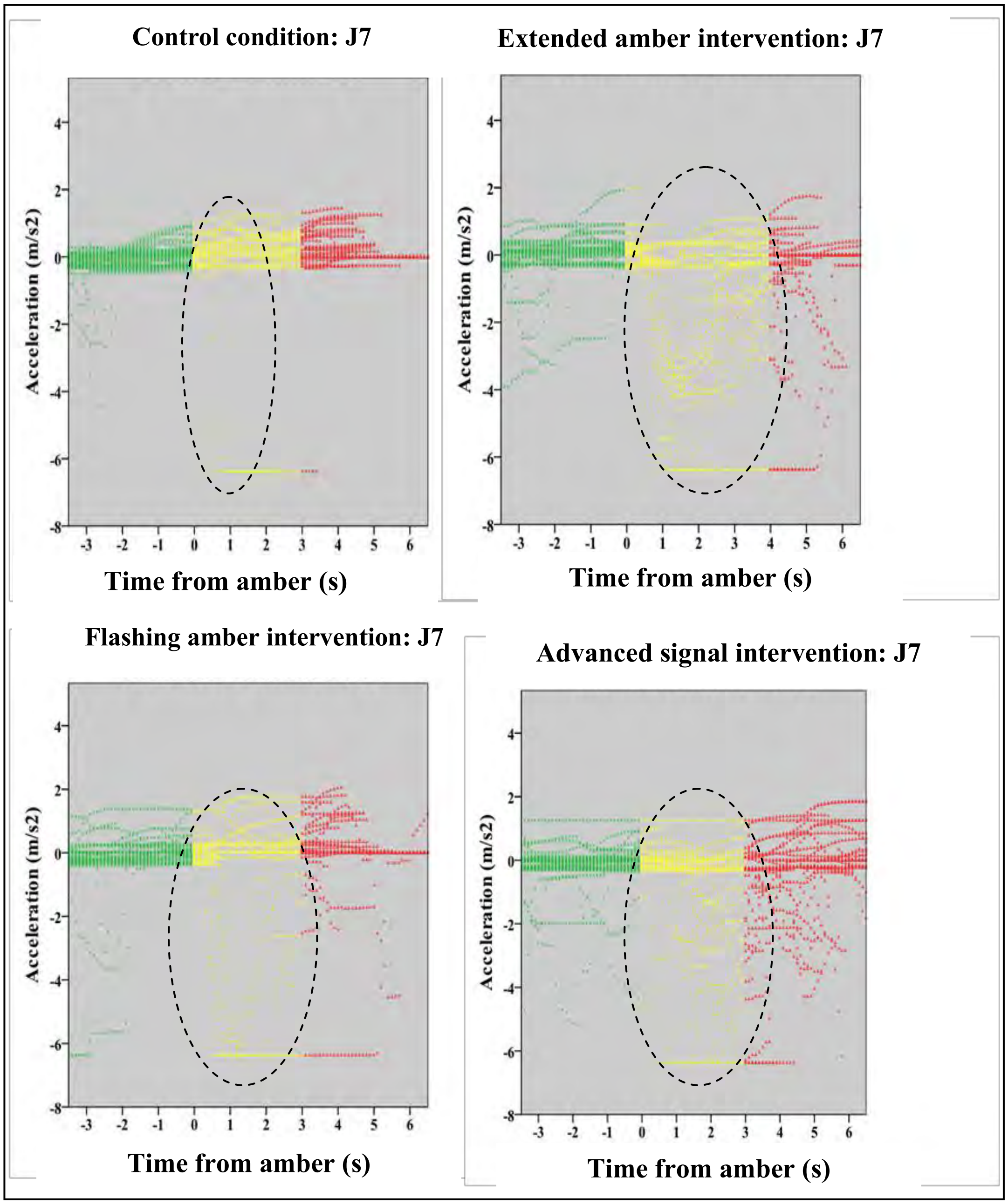


Figure C.6: Acceleration profiles for Junction J7

Appendix D

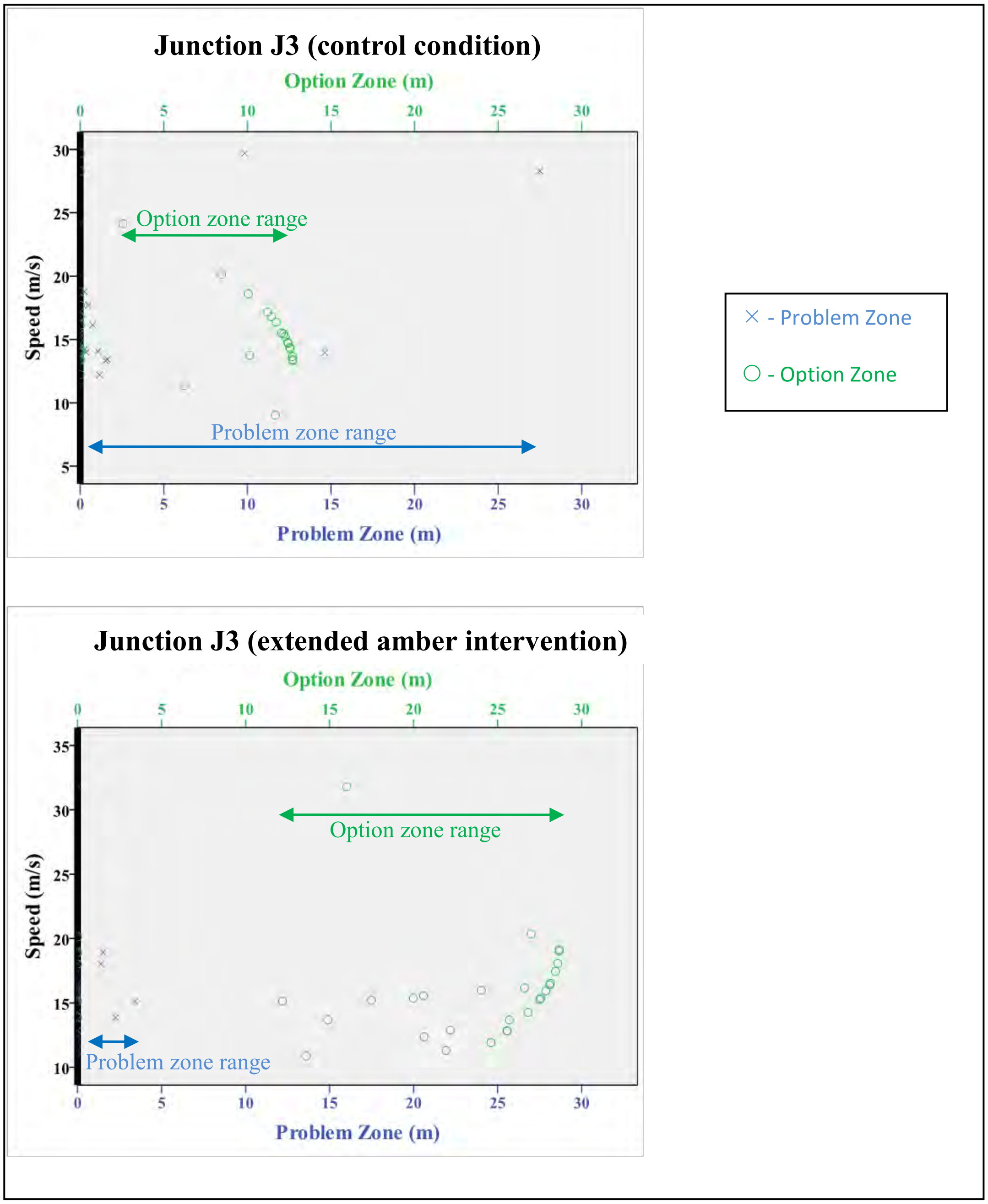


Figure D.1: Problem and option zones for Junction J3 (control and extended amber)

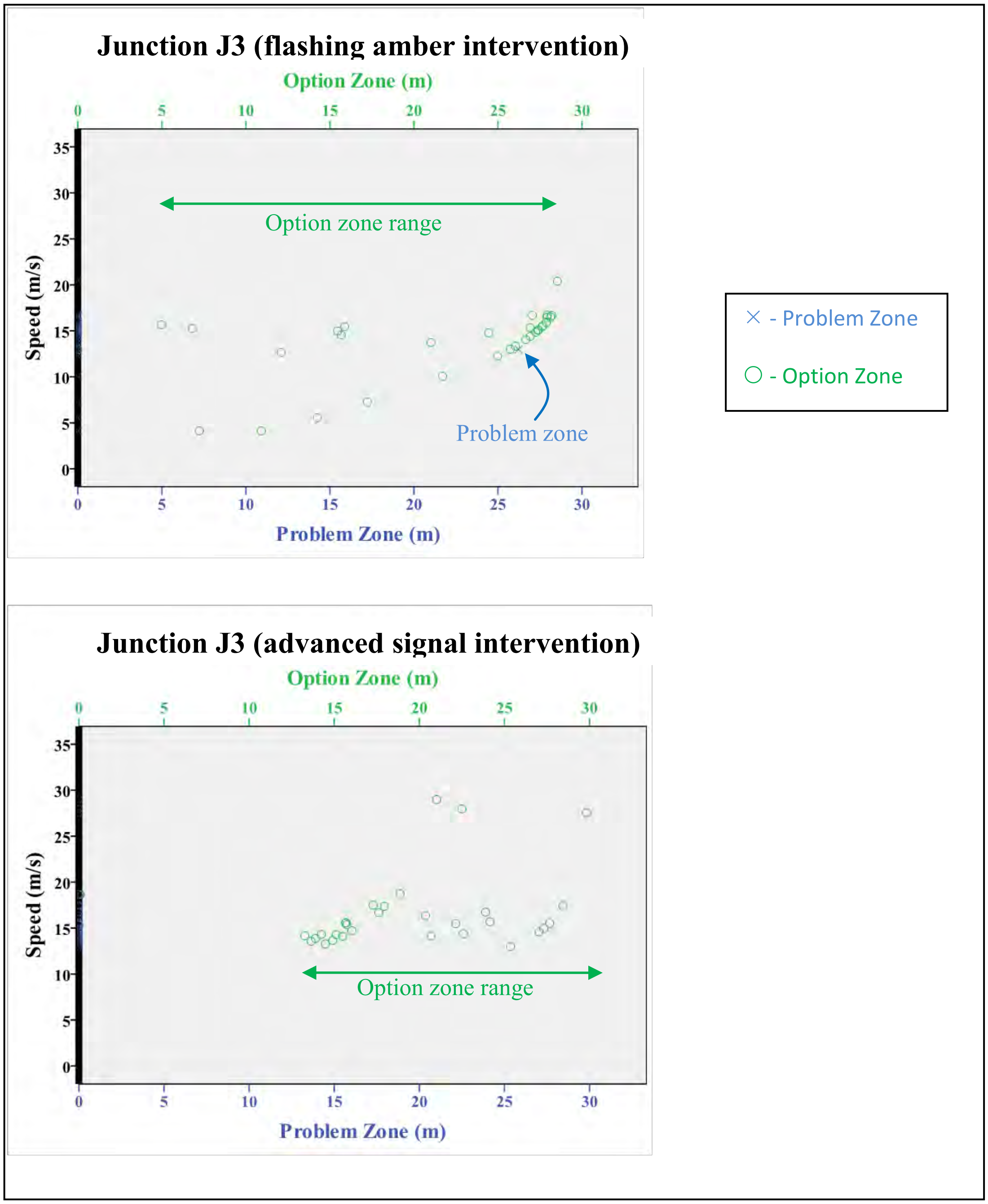


Figure D.2: Problem and option zones for Junction J3 (flashing amber and advanced signal)

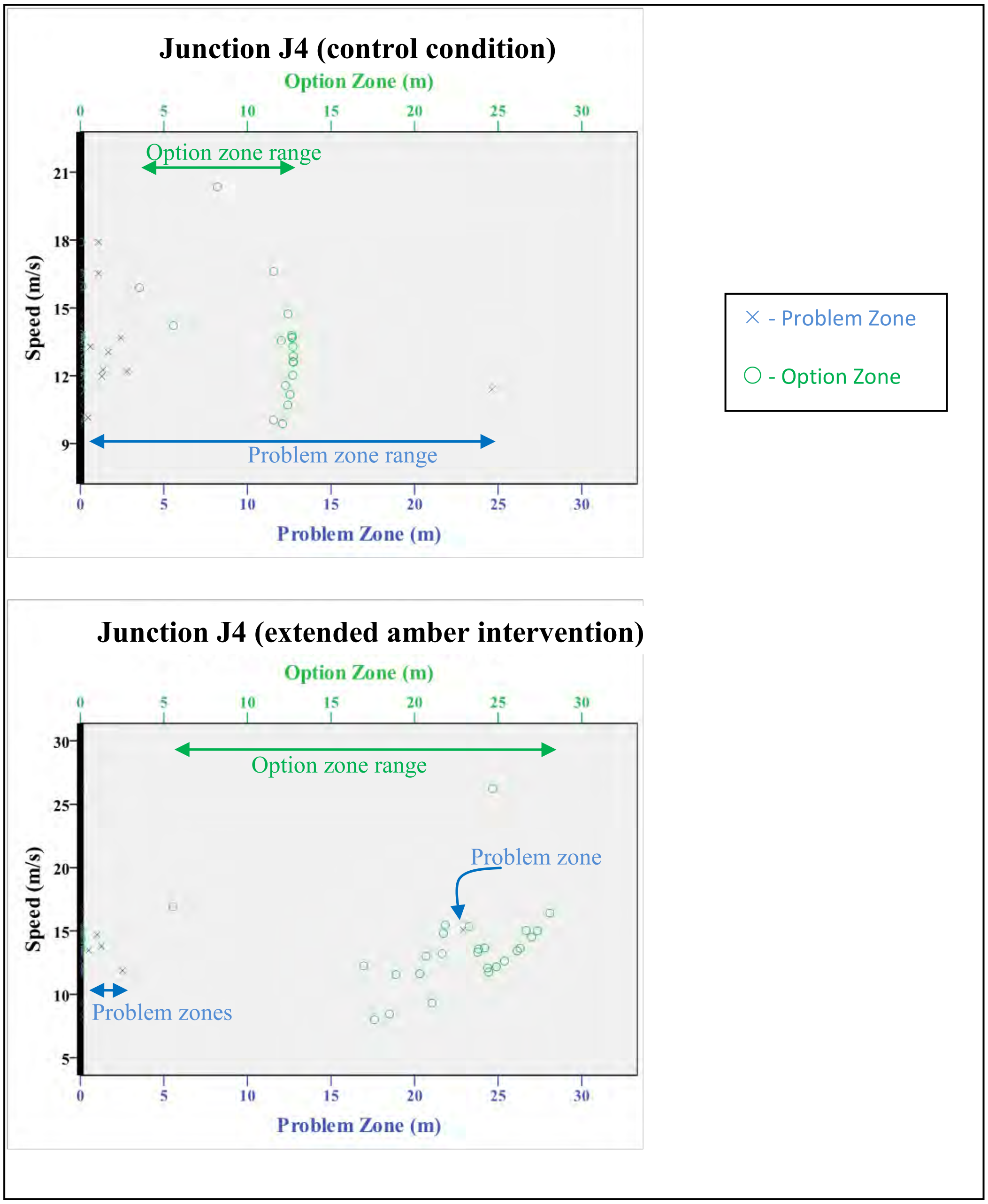


Figure D.3: Problem and option zones for Junction J4 (control and extended amber)

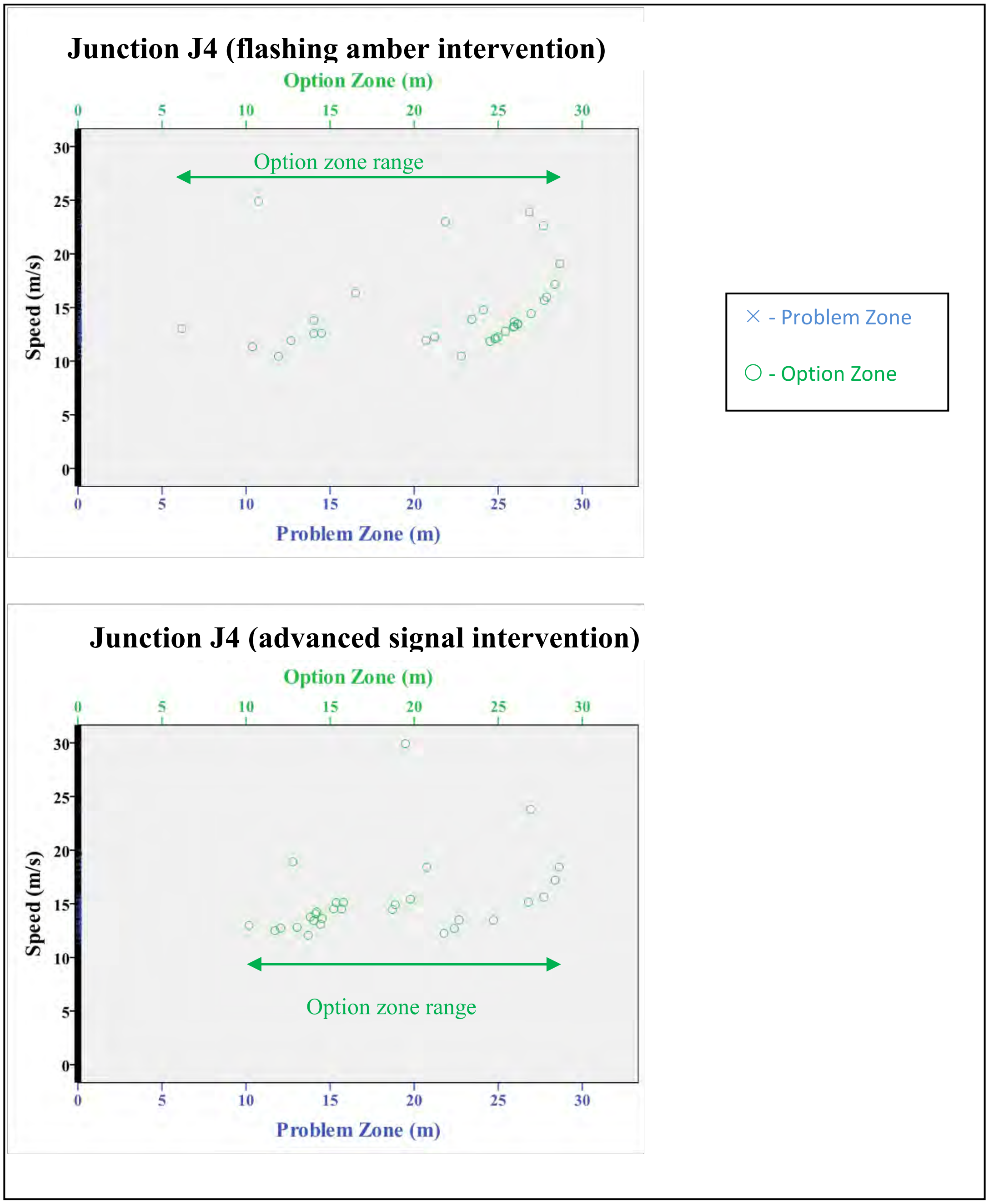


Figure D.4: Problem and option zones for Junction J4 (flashing amber and advanced signal)

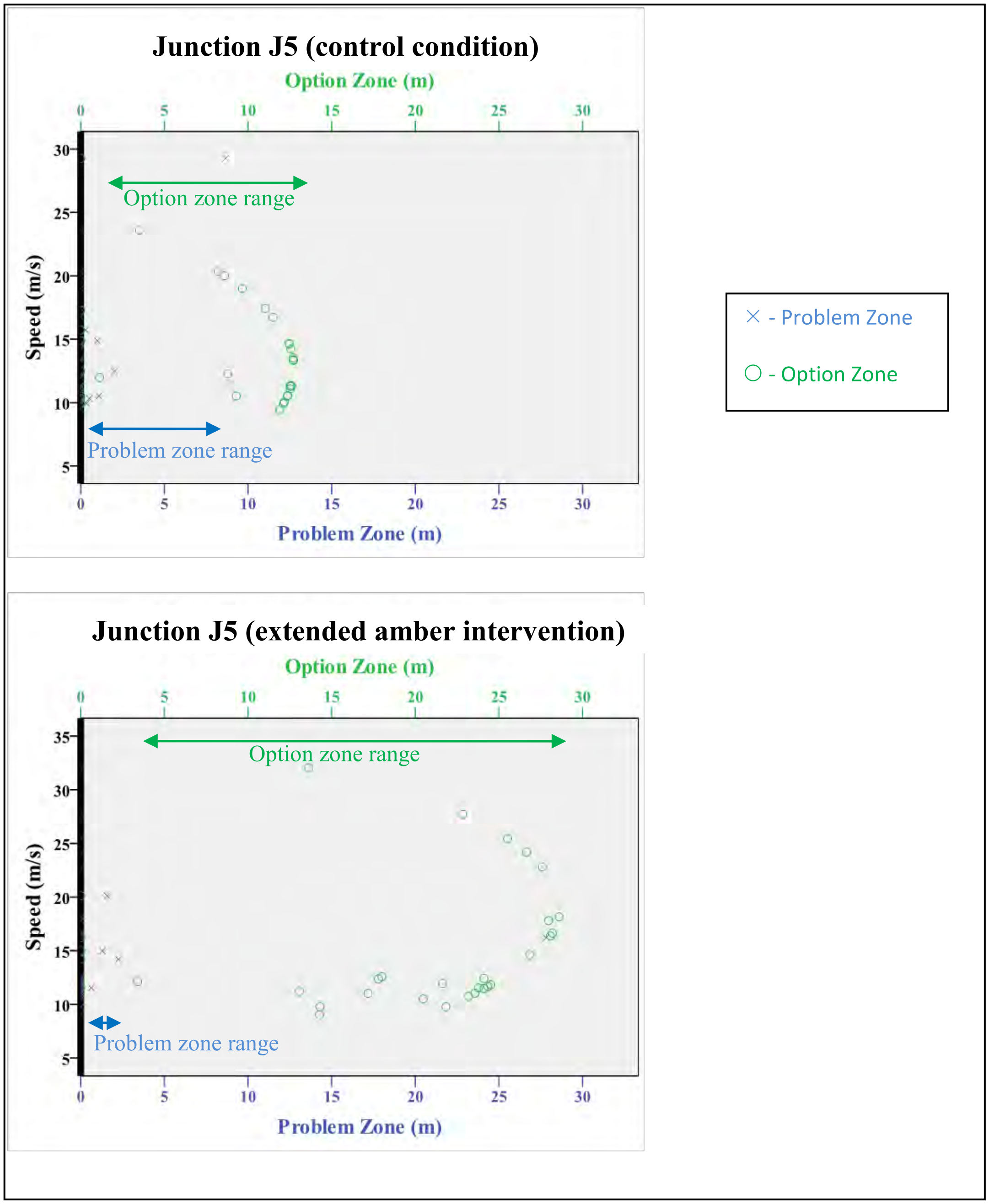


Figure D.5: Problem and option zones for Junction J5 (control and extended amber)

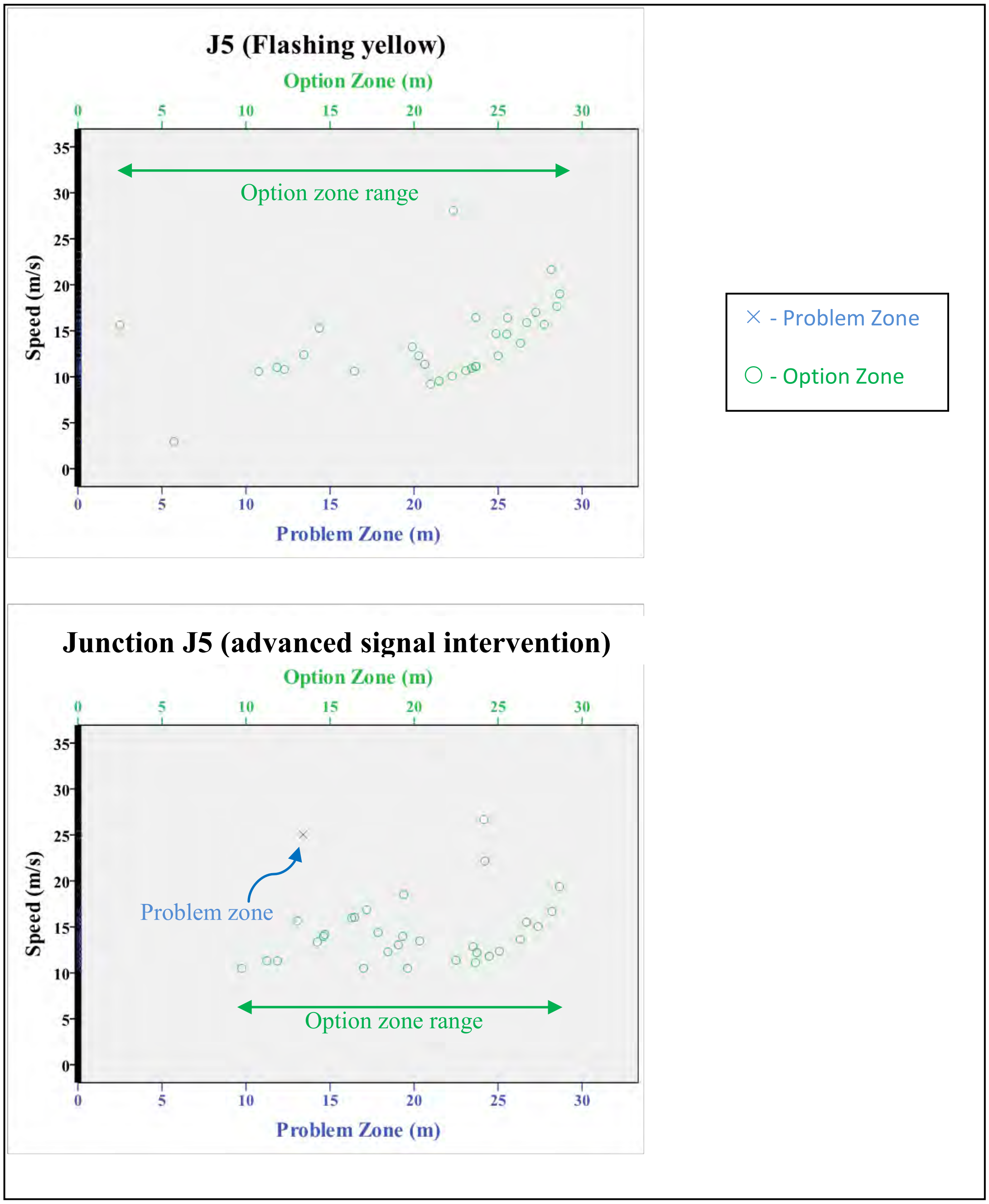


Figure D.6: Problem and option zones for Junction J5 (flashing amber and advanced signal)

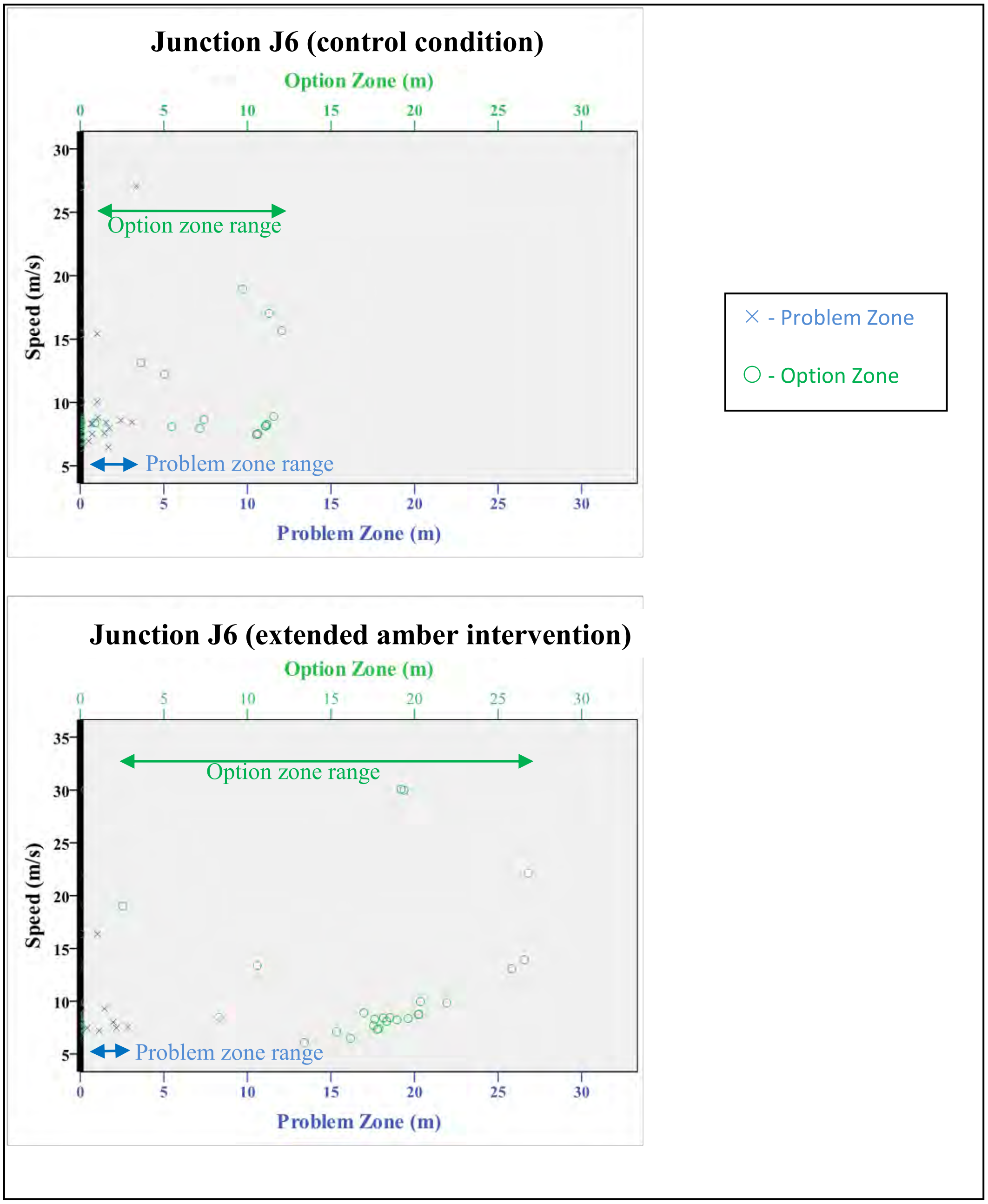


Figure D.7: Problem and option zones for Junction J6 (control and extended amber)

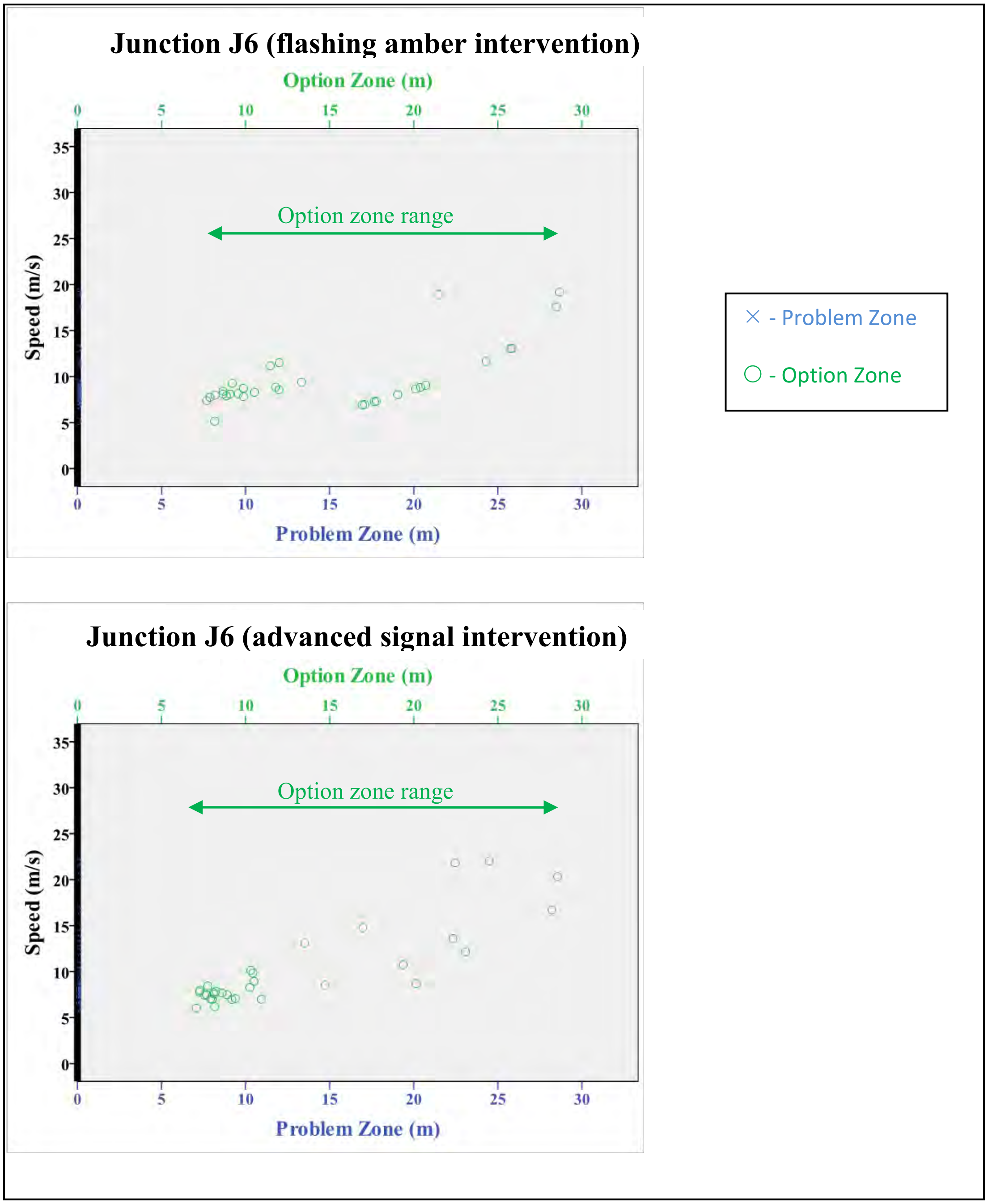
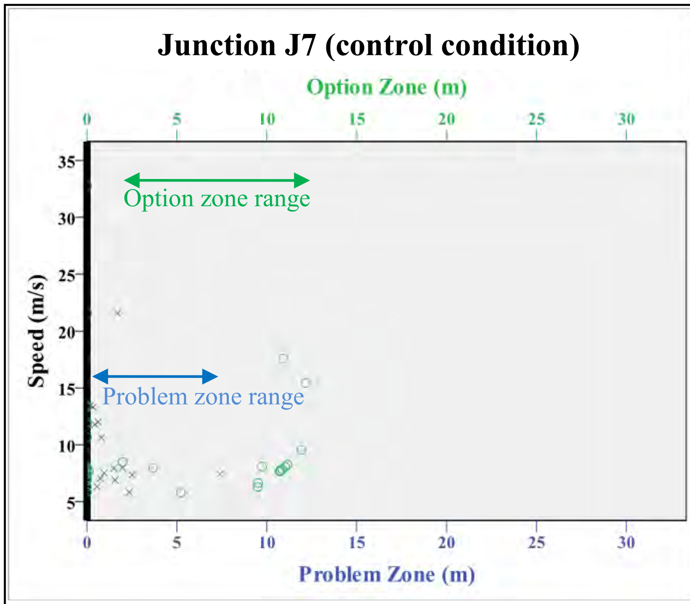
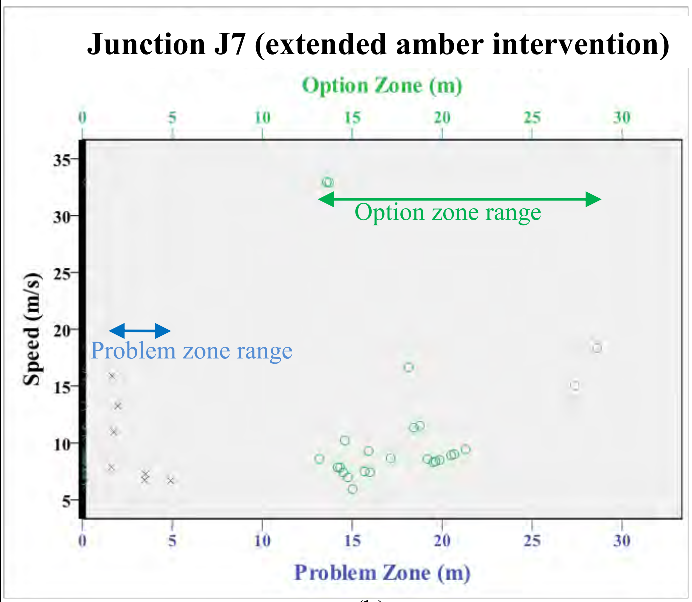


Figure D.8: Problem and option zones for Junction J6 (flashing amber and advanced signal)



(a)



(b)

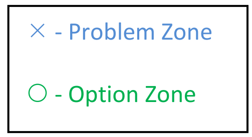


Figure D.9: Problem and option zones for Junction J7 (control and extended amber)

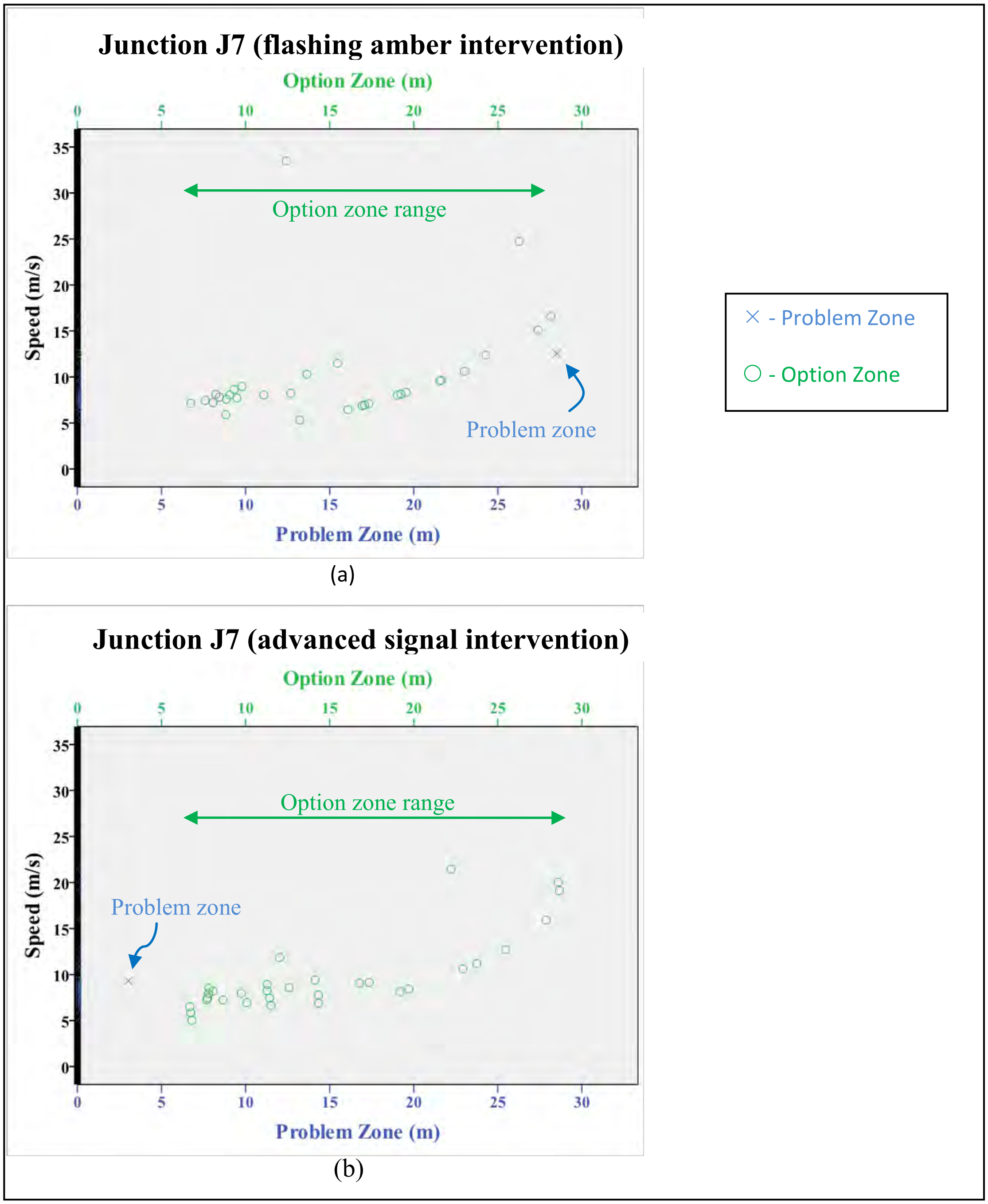


Figure D.10: Problem and option zones for Junction J7 (flashing amber and advanced signal)

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