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EFFECTIVENESS OF RED LIGHT CAMERAS ON THE RIGHT-ANGLE CRASH INVOLVEMENT OF MOTORCYCLES

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ABSTRACT

Red light cameras (RLC) have been used to reduce right-angle collisions at signalized intersections. However, the effect of RLCs on motorcycle crashes has not been well investigated. The objective of this study is to evaluate the effectiveness of RLCs on motorcycle safety in Singapore. This is done by comparing their exposure, proneness of at-fault right-angle crashes as well as the resulting right-angle collisions at RLC with those at non-RLC sites. Estimating the crash vulnerability from not-at-fault crash involvements, the study shows that with a RLC, the relative crash vulnerability or crash-involved exposure of motorcycles at right-angle crashes is reduced. Furthermore, field investigation of motorcycle maneuvers reveal that at non-RLC arms, motorcyclists usually queue beyond the stop-line, facilitating an earlier discharge and hence become more exposed to the conflicting stream. However at arms with a RLC, motorcyclists are more restrained to avoid activating the RLC and hence become less exposed to conflicting traffic during the initial period of the green. The study also shows that in right-angle collisions, the proneness of at-fault crashes of motorcycles is lowest among all vehicle types. Hence motorcycles are more likely to be victims than the responsible parties in right-angle crashes. RLCs have also been found to be very effective in reducing at-fault crash involvements of other vehicle types which may implicate exposed motorcycles in the conflicting stream. Taking all these into account, the presence of RLCs should significantly reduce the vulnerability of motorcycles at signalized intersections.

Key Words: Red light camera; Right-angle Crash; Field Investigation; Crash proneness; Motorcycle

INTRODUCTION

In Singapore, motorcycles form an important transport mode, accounting for 19% of the motorized vehicle population. They are also over represented in their crash involvement. Based on crash statistics from 1998 to 2002, motorcycles constitute of 35% of total vehicle crashes. Moreover, motorcyclists account for almost 45% of all road fatalities and about 51% of all road injuries. The fatality and injury rates of motorcyclists are respectively about 9.5 and 5.7 times higher than those of other vehicles. Several injury severity studies (e.g., Huang et al. 2008, Rifaat and Chin 2007, Tay and Rifaat 2007) in Singapore have also showed that the injury severity of crash-involved motorcyclists is likely to be higher than other motor-vehicle drivers.

Motorcycle crashes are also more evident at intersections. While about 36% of all crashes occur at intersections, motorcycle crashes represent about 57%. Yet it is interesting to note that while 43% of motorcycles are regarded as not-at-fault in all crashes, about 59% are not-at-fault in intersections. Yet while right-angle crashes represent about 63% of all intersection crashes only about 59% of crashes involved motorcycles. These statistics indicate that in terms of crashes, motorcycles behave rather differently at intersections, particularly in relations to right-angle collisions.

Motorcycle safety has been studied from different perspectives in last two decades. In recent years, a number of researchers (e.g., de Lapparent 2006; Quddus et al. 2002; Savolainen and Mannering 2007; Shankar and Mannering 1996) have attempted to quantify the effects of roadway, traffic, environmental, human and vehicle factors on motorcyclists' injury severity while others (e.g., Pai and Saleh 2008a; Pai and Saleh 2008b) have conducted similar studies at intersections. A number of studies (e.g., Williams and Hoffmann 1979; Yuan 2000) examined the crash risk of motorcycles due to conspicuity related issues while others (e.g., Lin et al. 2003; Mannering and Grodsky 1995; Rutter and Quine 1996) have examined the crash risk based on rider-motorcycle characteristics. These studies generally provide useful information on the crash risk and injury severity of motorcyclists. However, relatively a little research has been undertaken on the occurrence of motorcycle crashes at signalized intersections.

Motorcyclists are overrepresented in right-of-way violation crashes at intersections in which vehicles from the conflicting stream collide into the motorcycle entering the intersection (Clarke et al. 2007; Hurt et al. 1981). This may be because motorcyclists are often less noticed by other drivers (e.g., Hurt et al. 1981; Williams and Hoffmann 1979) and also drivers tend to under-estimate the speed of entry of the motorcycles (Crundall et al. 2008).

Haque et al. (2008) have reported that motorcycles are over exposed at signalized intersections because they tend to accumulate near the stop-line during the red phase and leading to an earlier discharge during the green phase. They have showed that wider lanes and the provision of right-turn lanes (in Singapore, the driving is on the left side of the road), both offering more weaving opportunities for motorcyclists to accumulate at the front of the queue, increase the exposure of motorcyclists particularly when in conflict with red light running vehicles from the opposing stream. This results in a high occurrence of right-angle collisions. On the other hand, Koh and Wong (2007) have reported that motorcycle riders are more likely to deliberate red-running which may also lead them to involve in right-angle collisions. Right-angle collisions involving motorcycles are more likely to result in serious injuries and even fatality.

Red-light cameras (RLC) have been commonly used to deter red-running in an attempt to reduce the number of right-angle collisions. A number of researchers (e.g., Chin 1989; Datta et al. 2000; Huang et al. 2006; Lum and Wong 2003; Retting et al. 2008) have evaluated the effect of RLC enforcement on the propensity of the red light running and concluded that RLCs are very effective in curbing red-light violations at signalized intersections. Similarly others (e.g., Erke

2008; Persaud et al. 2005; Shin and Washington 2007) have evaluated the RLC enforcement by before-and-after observational analyses or cross-sectional evaluation on crash frequencies. RLCs have been found to be an effective tool in reducing right-angle collisions (e.g., Erke 2008; Huang et al. 2006; Ng et al. 1997; Persaud et al. 2005; Shin and Washington 2007). However, critics also claim that the RLC enforcement often leads to an increase in rear-end collisions (e.g., Obeng and Burkey 2008; Persaud et al. 2005; Shin and Washington 2007).

Previous studies on the effectiveness of RLCs have been mainly concerned with all vehicle crashes. However, comparatively a few studies have been found about the impact of RLCs on motorcycle safety. In modeling the fault of motorcyclists involved in crashes, Haque et al. (2009a) have reported that RLCs are very effective in reducing the not-at-fault crash involvement of motorcyclists at intersections. In crash frequency modeling of motorcycle crashes at signalized intersections, Haque et al. (2009b) have reported that the presence of a RLC in any arm of a signalized intersection can reduce motorcycle crashes significantly at all arms of that intersection. However, the complete effect of RLCs on motorcycle safety has still not been well explored, especially the occurrence of motorcycle crashes from the viewpoint of right-angle collisions. Without addressing the issue of the effect of RLCs on different road user groups, the benefit of RLCs may not be justified properly.

The objective of this study is to examine the effectiveness of RLCs in right-angle crashes involving motorcycles. More specifically, this research seeks to evaluate right-angle collisions by comparing the exposure as well as the proneness of at-fault crashes of motorcycles with other vehicle types at RLC and non-RLC sites. To determine if the vulnerability of motorcycles at right-angle collisions is reduced in the presence of RLCs, a field study on motorcycle maneuvers at four signalized intersections was conducted.

In the following section, the method of measuring vulnerability and proneness of at-fault crash involvement is first explained, followed by a description on how the data are collected and analyzed to measure the crash-involved exposure of different vehicle types at signalized intersections. This is followed by a description of the field study of motorcycle maneuvers. Finally, in developing a complete view of the effect of RLCs on motorcycle safety, a discussion comparing the proneness of at-fault involvements at right-angle collisions of different vehicle types and the probability of right-angle collisions with motorcycles with or without RLCs is presented.

METHODOLOGY

The vulnerability of different road user groups can be estimated by measuring their exposure. Exposure can be defined as the extent to which road users are exposed to the environment resulting crashes. The frequency of crashes is likely to depend on the exposure. Several measures of exposure have been found in traffic safety studies, for example, vehicle mileage in network study, entry flow or product of conflicting flow for a particular traffic location or a traffic site (for a detailed review see Chapman, 1973). However, those exogenous estimates of exposure require an extensive data collection which is often time consuming and may be difficult to obtain.

To circumvent this problem, the quasi-induced exposure technique (e.g., Carr 1969; DeYoung et al. 1997; Stamatiadis and Deacon 1997) has been used as an indirect measurement of exposure. The strength of this method is that it can make use of the crash dataset to estimate the exposure experienced by different road user groups. A number of studies (Hing et al. 2003; Stamatiadis and Deacon 1995; Yan et al. 2005) have applied the quasi-induced exposure technique to analyze traffic crash risks of drivers and vehicles under a given set of environmental conditions by controlling for the exposure.

There are two major assumptions in this method: first, drivers and riders involved in multi-vehicle crashes can be identified as either at-fault or not-at-fault party; second, at-fault drivers and riders in crashes will "choose" their not-at-fault victims randomly from all vehicles present. Hence the distribution of not-at-fault drivers and riders will represent their exposure to crash hazards (e.g., DeYoung et al. 1997; Stamatiadis and Deacon 1997).

However Lyles et al. (1991) have highlighted several criticisms of this method. Among those, two important criticisms of this method are: (1) the issue of assigning fault and, (2) the validity of randomness of not-at-fault victims. The assignment of fault to a driver/vehicle unit may be questionable if there are contributing human factors (e.g., alcohol impairment) to the crash occurrence. To minimize the bias of the fault assignment, several researchers (e.g., Jiang and Lyles 2007; Stamatiadis and Deacon 1997) have advocated using "clean" crash records, i.e., to remove crash records involving human citations.

The assumption of the randomness of not-at-fault victims requires that each driver/rider has equal chance to be the victim of the at-fault drivers/riders. However not all parties can be classified as entirely at-fault or entirely not-at-fault. Furthermore not all driver/vehicle are uniformly exposed so that probability of chosen by at-fault parties is equal. For example, at signalized intersections motorcyclists usually weave through the traffic queue during the red phase to accumulate beyond the stop-line to facilitate an early discharge. The high concentration of motorcyclists discharging during the early period of green makes them more exposed to red runners from the conflicting stream. In other words, it increases their probability to be victims of red light running crashes. Hence the assumption of the randomness of not-at-fault victims is not valid here. Therefore, the quasi-induced exposure method may not be appropriate to measure the exposure and the propensity for different road user groups at right-angle collisions of signalized intersections. In fact, this is particularly true for sites where there are high motorcycle flows.

However the concept of quasi-induced exposure technique can still be useful to examine and compare the crash vulnerability and proneness of the crash involvement of different road user groups. This forms the basis of our approach.

Model Development

In this study, the crash vulnerability and at-fault crash proneness of different road user groups refer to their not-at-fault and at-fault crash distributions, respectively. Analogous to the “relative exposure” of the quasi-induced exposure technique, the relative crash vulnerability has been defined from their likelihood of not-at-fault crash involvements. Suppose, NF_j and NF_{all} denote the frequencies of the not-at-fault crash involvement at right-angle crashes in the category j and the entire population, respectively. Hence the relative crash vulnerability (*RCV*) at right-angle crashes of a specific road user group j is the ratio of the not-at-fault crash involvement in the category j to that in the entire population, i.e.,

$$RCV_j = \frac{NF_j}{NF_{all}} \tag{1}$$

The key assumption is that the distribution of not-at-fault drivers/riders at right-angle crashes closely represents the distribution of all drivers/riders exposed to the right-angle crash hazards. Hence, *RCV* reflects the relative opportunities for crashes of a certain type at a given time in a given area, i.e., crash exposure.

The relative crash proneness (*RCP*) at right-angle crashes of a specific road user group j is the ratio of the at-fault crash involvement in the category j to that in the entire population, i.e.,

$$RCP_j = \frac{AF_j}{AF_{all}} \tag{2}$$

where, AF_j and AF_{all} are the frequencies of at-fault crash involvement at right-angle crashes for the road user category j and the entire population respectively. It is assumed that among at-fault drivers/riders involved in right-angle crashes, the proportion represented by a particular road user group will reflect the proneness of that group in right-angle crash involvements.

RCV and *RCP* estimates would be helpful to compare the vulnerability and at-fault crash proneness of different road user groups, respectively. The effect of a RLC can be explored by estimating those estimates for Non-RLC and RLC sites. The Chi-square test of independence has been used to test the significance of various road user categories and their interaction with the presence of a RLC.

Preparation of Crash Dataset

In estimating the crash vulnerability and at-fault crash proneness of different road user groups, the issue of assigning fault is very important. The definition of at-fault or not-at-fault of drivers or riders follows that incorporated in the traffic police crash report. The at-fault drivers or riders are those who were mostly responsible for the crash occurrence and the not-at-fault drivers or riders are those who were not responsible or less responsible for the crash occurrence. The assignment of fault to a driver in a multi-vehicle crash may be biased by the traffic police if that driver is issued a citation. For example, the police officer may assign at-fault to a crash-involved driver if he or she found to have another type of violation (e.g., driving under influence of alcohol, using phone whilst driving etc.). The same is true for hit-and-run crashes where hit-and-run driver may be biased to be at-fault. These types of fault assignments may not truly reflect the hazardous driving actions. Hence “clean” crash records, as suggested by several researchers e.g., Jiang and Lyles 2007; Stamatiadis and Deacon 1997, have been used to estimate the crash vulnerability and at-fault crash proneness of different road user groups.

For this study, the Singapore crash data maintained by the Singapore traffic police from 1998 to 2002 have been used. During this 5-year period, there were 8,880 two-vehicle crashes at intersections of which about 74.9% crashes were right-angle collisions. To simplify the assignment of fault in a crash, the analysis is restricted to two-vehicle collisions at intersections. Moreover, to get "clean" crash records the following crashes have been eliminated: hit-and-run crashes, crash-involved drivers received any citation (e.g., intoxicated due to alcohol or drug, phone using etc.), missing information on fault assignment, vehicle type, and/or presence of red light camera. Following this data filtering, clean two-vehicle crashes comprise about 97% of total such crashes at intersections. For the comparison purpose, vehicles are classified into three categories: motorcycles including scooters, light vehicles including passenger cars, pick-up trucks and vans, and heavy vehicles such as buses, lorries, container trucks and trailers.

VULNERABILITY AT RIGHT-ANGLE COLLSIONS

Right-angle Crash Vulnerability

The effects of different vehicle types on the right-angle crash vulnerability have been found to be statistically significant (Chi-square = 571.8, p-value <0.001). The estimated results of relative crash vulnerability at right-angle collisions of different vehicle types are plotted alongside with the vehicle proportion in Figure 1. Results show that motorcycles experience the highest crash vulnerability (*RCV* = 0.522) at right-angle collisions at intersections though their share in the vehicle population is only about 19%. This excess crash-involved exposure of motorcycles at right-angle collisions may be due to their higher accumulation in front of the traffic queue which leads them to be more exposed to the conflicting traffic stream (Haque et al. 2008).

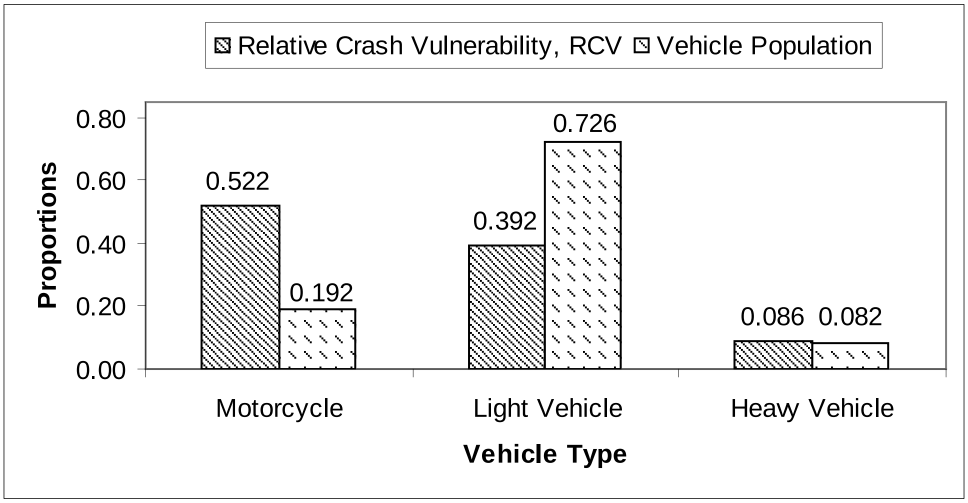

Figure 1: Relative Crash Vulnerability at right-angle crashes

The next step is to examine the effect of RLCs on the vulnerability of motorcycles at right-angle collisions. The interaction between RLCs and vehicle types on the crash vulnerability at right-angle collisions has also been found to be significant (Chi-square = 27.9, p-value < 0.001). The *RCV* estimation on right-angle crashes for different vehicle types with the effect of RLCs is presented in Figure 2. The results clearly show that the crash vulnerability or crash-involved exposure of motorcycles at right-angle collisions is significantly reduced from non-RLC sites with *RCV* = 0.532 to RLC sites with *RCV* = 0.414.

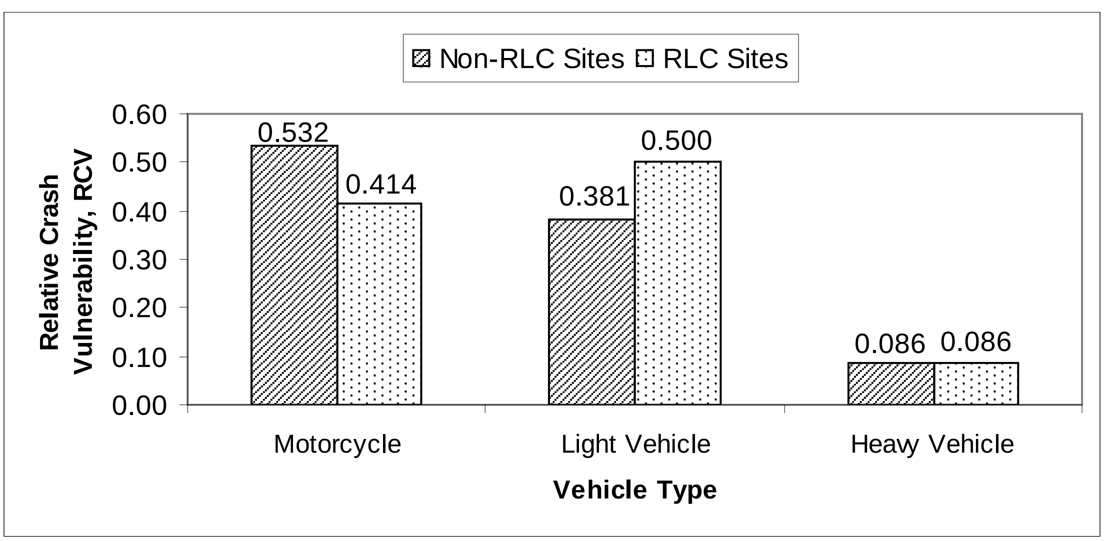

Figure 2: The effect of RLCs on the vulnerability of different vehicle types at right-angle crashes

To explain the influence of RLCs on the exposure of motorcycles, consider a typical signalized intersection shown in Figure 3. Suppose that the subject arm A is equipped with a RLC so that red light violations will reduce at arm A. This will reduce the not-at-fault crashes for motorcycles from arm B. While the RLC are expected to reduce not-at-fault crash involvements of all vehicles, the effect is likely to be higher for motorcycles as they mostly discharge in the early period of green. Furthermore, the presence of the RLC may also cause motorcycles to be more restrained discharging from the queue during the green. To confirm this, a field study is conducted, as described in the following section.

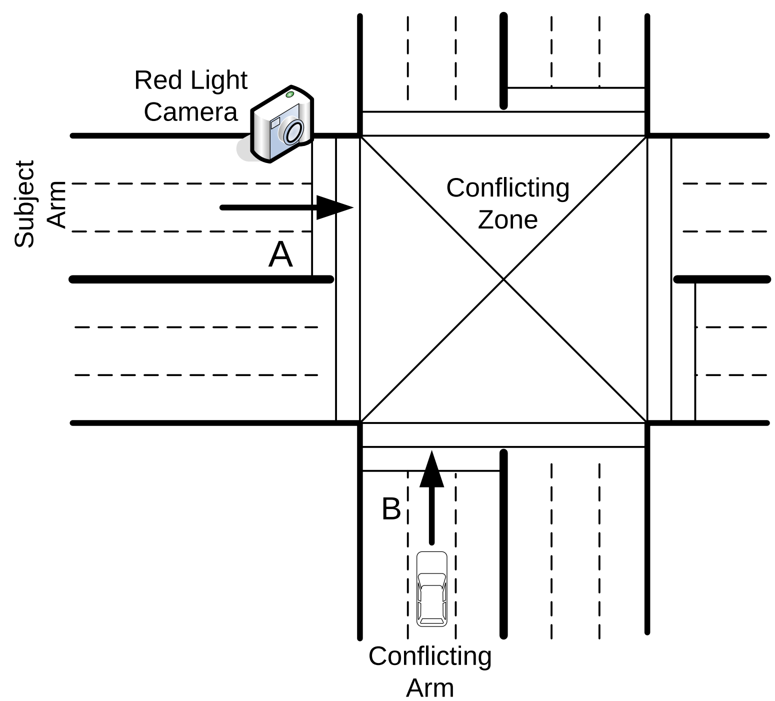

Figure 3: A typical signalized intersection with a red light camera

Measurement of Observed Exposure

Vehicles discharging from the stop-line during the initial green period are more prone to be crashes with red light runners from the conflicting arm. These are more likely to be the not-at-fault party in the right-angle collisions. Bonneson and Zimmerman (2004) have indicated that

98% of red runners do so during the first four seconds of red. In a similar study, Huang et al. (2006) have confirmed reported this for the Singapore context.

To assess the exposure of motorcycles, four arms from different signalized intersections with high motorcycle usage were filmed and the traffic flows in each signal cycle studied. The percentage of motorcycles using those roads varied from 10% to 18%. The geometric characteristics of the selected arms of study are generally similar. The characteristics of these arms are shown in Table 1. Of the four arms, two are equipped with the red light camera.

Intersection Name	**Arm Video Filmed**	**No. of Lanes**	**No. of Exclusive Right-turn lane**	**No. of Shared lane (Right & Through)**	**% of Avg. Motorcycle Flow**	**Presence of Red light camera**
Woodland Ave2 & Woodland Ave7	Woodland Ave2	4	1	1	18	No
Woodland Ave9 & Riverside Road	Woodland Ave9	4	1	1	10	No
Yio Chu Kang Rd & Buangkok Green	Yio Chu Kang Rd	4	1	1	17	Yes
Bukit Panjang Rd & Upper Bukit Timah Rd	Upper Bukit Timah Rd	4	1	0	12	Yes

Table 1: Site Location and Characteristics of Video Data Collection

In the field study, vehicles accumulated beyond 6m upstream from the stop-line of an arm and discharging within the first few seconds of green are sampled. As data are grouped by signal cycles, it mattered little when the observation is made. Nevertheless, to ensure a good vehicle queue in each cycle and a high proportion of motorcycles in the traffic, the morning period was chosen. A total of 25 signal cycles were observed at each of the site.

Observed Motorcycle Behavior

Visual observations from the video films show that during the red phase, motorcycles weave through the traffic queue at a reduced speed to reach the stop-line. In the presence of an exclusive right-turn lane (in Singapore, driving is on the left side of the road), motorcyclists also use that lane as a bypass if it is not fully utilized. In general, the straight-through lane fills up before the right-turn lane is full. At arms where there is no RLC, motorcyclists usually move ahead of the traffic queue and stop beyond the stop-line to allow them to start ahead of other vehicles at the onset of green. However in the presence of a RLC, they are found to restrain queuing beyond the stop-line as shown in Figure 4.

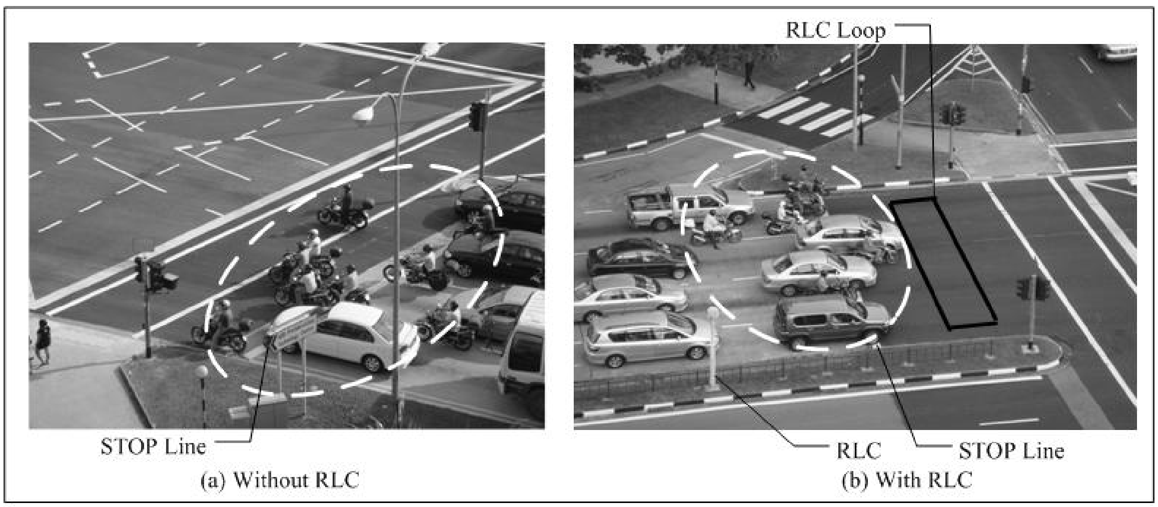

Figure 4: Accumulation of motorcycles in front of the queue of signalized intersections

Accumulation of Motorcycles in Front of the Queue

The accumulation of motorcycles (measured as the percentage of motorcycles to total vehicles beyond the 6-m upstream from the stop-line) at the different sites is plotted against the percentage of time into the red period and shown in Figure 5. The front wheel of any vehicle crosses the imaginary line of 6-m upstream from the stop-line is assumed to be accumulated. Results show that the accumulation grew steadily but reached a higher maximum at non-RLC sites (69%) than at RLC sites (51%). The higher accumulation at non-RLC sites is achieved because motorcycles queue beyond the stop line not only increasing the queuing space for motorcyclists but also increasing the number of motorcycles at the head of the queue. The higher concentration of motorcycles at the head of the queue will increase the exposure of motorcycles to vehicles in the conflicting stream. On the other hand, the RLC has reduced the exposure thereby lowering the opportunities for right-angle collisions.

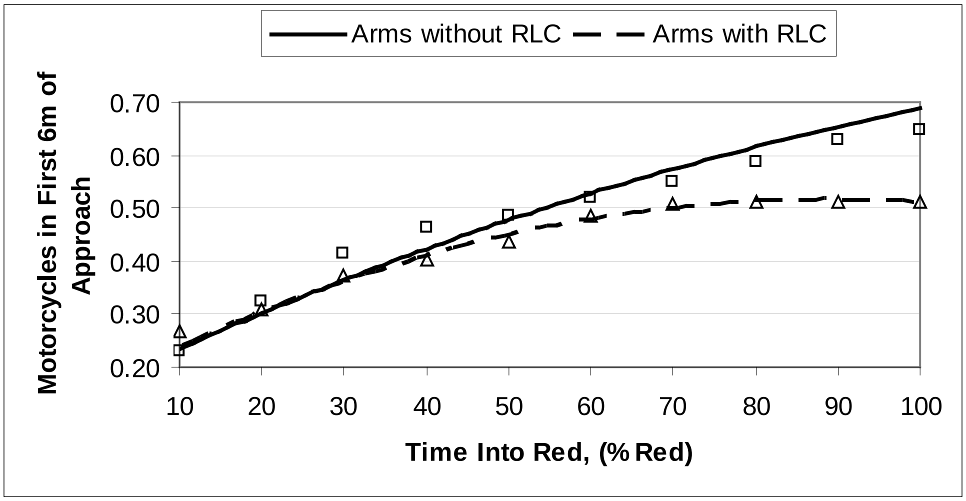

Figure 5: Accumulation of motorcycles in front of the queue

Observed Motorcycle Exposure

Figure 6 shows the discharge pattern of motorcycles (plotted as the ratio of queued motorcycles entering the intersection) during the initial period of the green at the non-RLC and RLC sites. The observed exposure of motorcycles at each second of green refers to the ratio of the number of motorcycles entering to the intersection in a specific time to the total number of queued motorcycles. It is obvious that a majority of the motorcycles enter the intersection during the first few seconds of the green and this is largely to do with the motorcycles having a higher power-to-weight ratio and hence acceleration capability (Elliott et al. 2003). During this initial period, motorcycles are more critically exposed to red-runners from the opposing arm as most of the red light running instance take place during the early period of red (e.g., Huang et al. 2006; Retting and Williams 1996; Zimmerman and Bonneson 2005). The RLC appears to have restrained the discharge of motorcycles resulting in a significant reduction in exposure of motorcyclists to the risk of right-angle collisions.

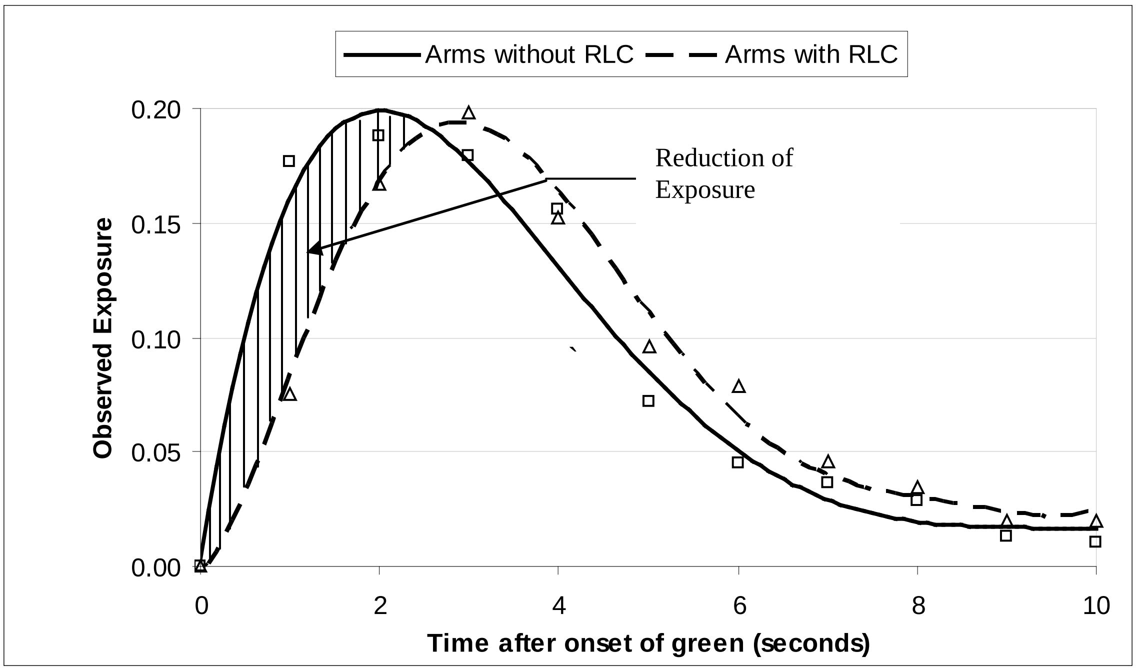

Figure 6: Observed exposure of motorcycles at each second of green

Specifically, for the sites investigated, motorcycles at RLC sites compared to non-RLC sites have a lower exposure by about 10% during the first second of green and 13% in the first 2.5 seconds of green. This restraint is a result of two phenomena. First, at RLC sites, motorcyclists were less willing to queue beyond the stop line thereby reducing the number of motorcycles discharging ahead of other vehicles. Second, the motorcyclists were also less likely to jump start prior to gaining the right of way.

PRONENESS OF AT-FAULT RIGHT-ANGLE COLLISIONS

From the results of both not-at-fault crash analysis and field study, it is clear that RLCs are effective in reducing the vulnerability of motorcycles at right-angle collisions. However motorcycles may also be involved at right-angle collisions as the responsible or at-fault parties. Hence it would be worthy to study the proneness of different vehicle types in involving at right-angle collisions as the at-fault party at intersections.

Using the relative crash proneness (*RCP*) model, the at-fault crash proneness of different vehicle types at right-angle collisions can be determined. The Chi-square test has been used to test the significance of vehicle types on the at-fault crash proneness of right-angle crashes. The results as shown in Figure 7 are significant (Chi-square = 571.8, p-value < 0.001). Among the different types of vehicles, motorcycles have one of the lowest *RCP* (=0.191) values indicating that motorcycles are one of the least likely parties to cause right-angle crashes. On the other hand, light vehicles have a *RCP* value of 0.690 while heavy vehicles have a value of 0.119. Hence, compared to motorcycles, light vehicles are about 3.6 times higher prone to cause right-angle collisions at signalized intersections. It is noteworthy to mention that the RCP values of different vehicle types are almost similar to their proportions in the vehicle fleet.

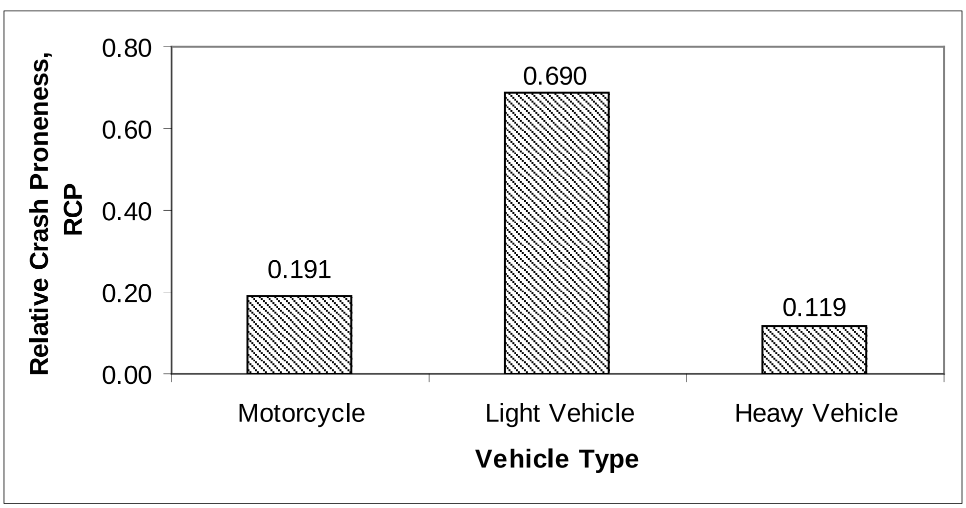

Figure 7: Relative crash proneness of different vehicle types for at-fault right-angle collisions

The proneness of light and heavy vehicles to collide with not-at-fault motorcycles at right-angle crashes can be examined by analyzing such crashes involving two vehicles using the contingency table analysis. As presented in Table 2, both light (Chi-square = 546.7, p-value <0.001) and heavy vehicles (Chi-square = 219.6, p-value <0.001) are found to be the responsible parties in collisions with not-at-fault motorcycles. Light and heavy vehicles are respectively about 8.4 and 5.9 times more likely than motorcycles to collide with an exposed motorcycle at right-angle collisions. This may be due several reasons, e.g., these vehicles may be running the red or they do not see the motorcycles well or they may be less able to judge the motorcycle entry speeds. Hence any measure to curb the propensity of these vehicles, for example, installation of RLCs, may enhance motorcycle safety at signalized intersections.

At-fault Vehicle Types	Is not-at-fault vehicle a motorcycle?		Odds Ratio	Chi-square	p-value
	Yes	No			
Motorcycle	124	694	Reference		
Light Vehicle	2373	1581	8.40	546.68	<0.001
Heavy Vehicle	335	320	5.86	219.59	<0.001

Table 2: Two-vehicle right-angle crash analysis

The effect of RLCs on the at-fault crash proneness of different vehicle types in right-angle collisions is evaluated using the contingency table analysis and presented in Table 3. Using the log-linear analysis, the interaction between vehicle types and the presence of RLCs is found to be significant (log-likelihood ratio = 639.6, p-value <0.001). Clearly the odds of colliding with a not-at-fault motorcycle are higher for both light and heavy vehicles at non-RLC sites than RLC sites. For light vehicles, the odds ratio of at-fault right-angle collisions to collide with not-at-fault motorcycles is 9.14 for non-RLC sites while the corresponding odds ratio for RLC sites is only 4.03. For heavy vehicles, the likelihood of collisions with not-at-fault motorcycles at RLC sites is not found to be significantly different from that of at-fault motorcycles. However, the corresponding odds ratios for at-fault heavy vehicles are found to be lowered by about 63% from non-RLC sites to RLC sites. Hence, the use of RLCs is an effective measure to reduce not only the exposure of motorcycles as discussed in the previous section, but also the at-fault crash proneness of light and heavy vehicles in right-angle collisions with motorcycles.

Site Types	**At-fault Vehicle Types**	**Is not-at-fault vehicle a motorcycle?**		**Odds Ratio**	**Chi-square**	**p-value**
		Yes	**No**			
Non-RLC Sites	Motorcycle	107	618	Reference		
	Light Vehicle	2201	1390	9.14	525.01	<0.001
	Heavy Vehicle	324	299	6.26	213.73	<0.001
RLC Sites	Motorcycle	17	76	Reference		
	Light Vehicle	172	191	4.03	25.84	<0.001
	Heavy Vehicle	11	21	2.34	3.55	0.060

Table 3: Two-vehicle right-angle crash analysis with the effect of RLCs

PROBABILITY OF POTENTIAL RIGHT-ANGLE COLLISIONS

The probability of potential right-angle collisions involving motorcycles can be investigated by considering the likelihood of red running and the exposure of motorcycles to these red runners. Using a fitted multinomial logit model of observed Singapore driver behavior during the phase change period, Huang et al. (2006) have derived the probability of red running for both RLC and non-RLC arms. Specifically, they have categorized every driver, approaching to the junction during the amber period, to be any of these three categories: would-be red runners or would-be non-red runners if he or she has decided to cross the junction during amber; otherwise stopped group. The would-be red runners were those whose estimated time to stop-line at onset of amber is greater than amber duration while would-be non-red runners were those whose corresponding time is less than amber duration. A variety of geometric (e.g., intersection width), traffic (e.g., cycle time, presence of RLC) and situational variables (e.g., approach speed) have been used to calibrate the multinomial logit model. Based on the calibrated model, the probability of would-be red runners, i.e., red-running probabilities for both RLC and non-RLC arms have been estimated at different time periods (See *Figure 2* of Huang et al. 2006).

Based on the results of red running probabilities of Huang et al. (2006) and the exposure profile in Figure 6, the probability of a potential right-angle collision for a given instance of an exposed motorcycle can be estimated as shown in Figure 8. The probability of a potential right-angle collision at each second of green is the product of red running probability and exposure of motorcycles at that time. It is worth mentioning that probabilities of potential right-angle collisions are only useful to compare for different configuration of RLCs at interacting arms of a signalized intersection. Four configurations are investigated: both interacting arms are without RLC, only the subject arm is installed with a RLC, only the conflicting arm is installed with a RLC and both interacting arms are with RLC.

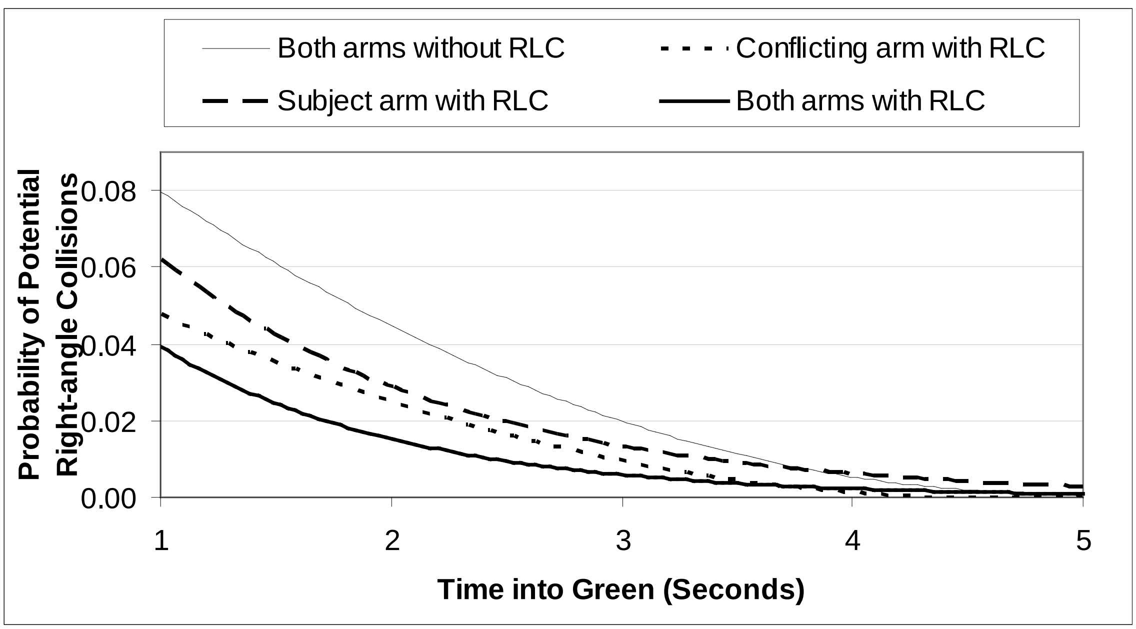

Figure 8: Effects of RLCs on the probability of right-angle collisions with motorcycles

Figure 8 shows that for all configurations, the probability of potential right-angle collisions decreases with time into the green period. Clearly the collision probability is higher when none of the interacting arms are installed with a RLC. The collision probability is lower when a RLC is installed on the subject arm and this is because a lower motorcycle exposure. However, beyond about 4 seconds into the green, the collision probability is slightly higher than in the case when no

RLC is installed in either arm. This is a result of a redistribution of the motorcycle exposure during the initial green period as shown in Figure 6.

When there is a RLC on the conflicting arm, the collision probability is lower than in the case of a RLC on the subject arm. This is the case because the reduction in propensity due to the RLC in the conflicting arm has a greater effect than the reduced motorcycle exposure on the subject arm when a RLC is installed. When both arms are installed with RLC, there is a combined effect of reduced motorcycle exposure in the subject arm and reduced propensity of red-running in the conflicting arm. The result is a greater drop in probability of potential right-angle collisions.

CONCLUSION

This study investigates the effectiveness of RLCs in reducing right-angle collisions involving motorcycles. This is done by comparing the exposure and at-fault crash proneness of motorcycles with other vehicle types in right-angle interactions.

The study shows that motorcycles experience a higher exposure than other vehicles at right-angle collisions because of the tendency of motorcycles to queue in front of other vehicles and even beyond the stop line as well as to discharge earlier than other vehicles at the onset of green. However this exposure is reduced on the arm where a RLC is installed because motorcyclists are more restrained in both queuing beyond the stop line and discharging early.

The at-fault crash proneness of motorcycles at right-angle collisions is found to be lower than that of other vehicle types. Every thing else being equal, motorcycles are therefore more likely to be victims than the offending parties in right-angle crashes. Also, light and heavy vehicles are more likely than motorcycles to be responsible in right-angle crashes with motorcycles from the interacting arm. The study shows that RLCs are effective in reducing the proneness of at-fault right-angle crash involvements of light and heavy vehicles and hence the vulnerability of motorcyclists in right-angle collisions.

The probability of potential right-angle collisions is reduced when RLCs are installed in any or both of the interacting arms. The combined effect of reduced motorcycle exposure on the subject arm and the reduced propensity of light and heavy vehicles on the conflicting arm due to the RLCs should make motorcycles less vulnerable to right-angle collisions.

The study highlights that motorcyclists are more likely to be at not-at-fault in right-angle crashes. Hence as a vulnerable group, they should be accorded higher priority for safety improvement which, as indicated in this study, can be achieved with the installation of RLCs. Therefore, at sites where there is a high motorcycle presence, highway authorities should consider the use of RLCs as a countermeasure reducing right-angle collisions.

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