Examining Exposure of Motorcycles at Signalized Intersections

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Crash statistics in Singapore from 2001 to 2005 have shown that motorcycles were involved in about 54% of intersection crashes. The overall involvement of motorcycles in crashes as the not-at-fault party was about 43%, but at intersections the corresponding percentage is increased to 57%. Quasi-induced exposure estimates have shown that the motorcycle exposure rate at signalized intersections was 41.7% even though motorcycles accounted for only 19% of the vehicle population. This study seeks to examine, in greater detail, the problem of motorcycle exposure at signalized intersections—in particular, the exposure caused by potential crashes with red-light-running vehicles from the conflicting stream. For that purpose, four signalized intersections are investigated. Results show that motorcycles are more exposed because they tend to accumulate near the stop line during the red phase to facilitate an earlier discharge during the initial period of the green, which is the more vulnerable period. At sites in which there are more weaving opportunities because the lanes are wider or there are exclusive right-turn lanes, the accumulation is higher and hence exposure is increased. The analysis also shows that the presence of heavy vehicles tends to decrease motorcycle exposure because motorcyclists' weaving opportunities become restricted and they are more reluctant to weave past or queue alongside the heavy vehicles; effects intensify for narrower lane widths.

Compared with other vehicle types, motorcycles have distinct advantages, such as affordability, mobility, and accessibility, but they have poor safety records. On the basis of 5-year Singapore crash statistics from 2001 to 2005, motorcycles constitute about 36% of total traffic crashes, even though their share in the vehicle population is only 19% (*1*). Moreover, motorcyclists account for almost 49% of fatalities and about 53% of injuries on the road.

The situation is even more acute at signalized intersections, which account for 33% of all crashes on the road network. Motorcycle crashes at signalized intersections represent about 54% of all crashes (*1*). Furthermore, although the involvement of motorcycles as the not-at-fault party is about 43% nationwide, the corresponding percentage at signalized intersections is higher at 57%.

The vulnerability of motorcycles at signalized intersections is affected by their risk as well as their exposure. They may be at a high risk for various reasons, for example, relatively low conspicuity leading to the apparent failure of motorists to see the motorcycles early. A number of studies (*2, 3*) have reported that drivers often overlook motorcyclists in the traffic stream. The motorcycles may also be subjected to a higher exposure at signalized intersections, but that has not been well explored in most safety studies, possibly because it is generally difficult to estimate the exposure from field studies.

One method to overcome the difficulty of measuring exposure is the quasi-induced exposure technique (*4–7*). By using this method, the quasi-induced exposure estimate of motorcycles at signalized intersections from the 5-year database is 41.7%, which is much higher than the expected 19% if exposure is based on vehicle distribution. Hence although it is often concluded that high motorcycle involvement is due to the higher risk in motorcycle riding [e.g., Mannering and Grodsky (*2*) and Rothe and Cooper (*8*)], this finding may suggest that the higher involvement rate may be due to a higher exposure as well. This paper examines whether motorcycles are indeed more exposed at signalized intersections. This aim is accomplished by conducting a detailed field study of motorcycle maneuvers at four signalized intersections. Before the field experiment is described in detail, the method of estimating induced exposure is explained, followed by a description of the way the data are collected and analyzed to verify whether motorcycles have a higher exposure at signalized intersections.

ESTIMATE OF INDUCED EXPOSURE

Exposure can be defined as the extent to which road users are exposed to the environment resulting in crashes. Measuring the exposure to crashes is a great challenge in traffic safety research. Several measures of exposure have been suggested, for example, vehicle mileage in network study, entry flow or product of conflicting flow for particular traffic location or traffic site [for a detailed review see Chapman (*9*)]. However, these measures require extensive data collection, which is time consuming. To circumvent that problem, the quasi-induced exposure technique [e.g., Carr (*4*), Stamatiadis and Deacon (*5, 6*), and DeYoung et al. (*7*)] has been used as an indirect measurement of exposure. The strength of this method is that it can make use of the crash data set, instead of exogenous estimates, such as vehicle miles traveled, to estimate the exposure experienced by different road users.

Two major assumptions are made in this method: first, drivers and riders involved in multivehicle crashes can be identified as either the at-fault or the not-at-fault party and, second, at-fault drivers and riders in crashes will "choose" their not-at-fault victims randomly from all vehicles present. Hence the distribution of the not-at-fault drivers and riders will represent the exposure to the accident hazards [e.g., Stamatiadis and Deacon (*6*) and DeYoung et al. (*7*)].

According to Stamatiadis and Deacon (*6*), relative exposure as measured by the quasi-induced exposure technique, can be taken as the relative measures of the traffic exposure experienced by various driver and vehicle categories. Relative exposure (RE) for any road

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TABLE 1 Exposure Estimation by Quasi-Induced Method

Vehicle Type	Multivehicle Crash Involvement as Not-at-Fault Party at Intersections						Relative Exposure
	2001	2002	2003	2004	2005	Total	
Motorcycle	844	816	592	677	474	3,403	0.417
Light vehicle	863	894	689	733	506	3,685	0.451
Heavy vehicle	266	248	185	225	155	1,079	0.132

user group j can be estimated as follows. Suppose the actual exposures of category j and for the entire population are E_j and E_{all}, respectively. According to the second assumption, the probability of being involved in a crash as the not-at-fault party for unit exposure of any category is the same, say P_0. Hence, RE of road user group j is the ratio of the not-at-fault crash involvement in category j to that in the entire population, that is,

$$RE_j = \frac{E_j}{E_{all}} = \frac{E_j p_0}{E_{all} p_0} = \frac{F_j}{F_{all}} \quad (1)$$

where F_j and F_{all} denote the frequencies of the not-at-fault crash involvement in category j and in the population, respectively.

The exposure for different road user groups in Singapore is thus estimated using the crash data from 2001 to 2005. Among the 9,228 multivehicle intersection crashes, 8,167 cases of driver (rider) and vehicle units are identified as the not-at-fault party involved in crashes from a total of 19,052 driver (rider) and vehicle units. The RE estimation for three types of vehicles (i.e., motorcycles, light vehicles, and heavy vehicles) is presented in Table 1.

Table 1 shows that the highest relative exposure estimates are for light vehicles (RE = 0.451). This is expected because light vehicles constitute a majority of vehicles on the road. However, RE for motorcycles is 41.7%, which is rather surprising because motorcycles account for only 19% of the total vehicle population. This means that motorcycles are more vulnerable at signalized intersections because they experience a higher than expected exposure.

MEASUREMENT OF OBSERVED EXPOSURE

In most cases, crashes due to red light running affect the first few vehicles discharging from the stop line of the conflicting approach. Hence the vehicles queuing just behind the stop line of the approach during the red phase are most vulnerable. The zone behind the stop line can be considered the affected zone because the vehicles in this zone are more likely to be exposed to red light running crashes. Moreover, Huang et al. (*10*) have found that most red light running occurs during the first few seconds of red, and Bonneson and Zimmerman (*11*) have indicated that 98% of red light runners run within the first 4 s of red. It is generally difficult to identify the vehicles that are more exposed in red light running crashes because the crash potential is affected by the red light running behavior as well as the intersection geometry, both of which vary from site to site as shown in a number of studies [e.g., Chapman (*9*) and Lum and Wong (*12*)]. For the purpose of identifying the vehicles that are exposed to the red light running crashes, vehicles queuing within 6 m of the affected zone in the approach and discharging within the first 4 s of green are sampled.

To assess the level of exposure of motorcycles at signalized intersections, four signalized intersections were selected and the traffic flow in each signal cycle video filmed. These intersections tend to have a high concentration of motorcycle use and have different geometric conditions that may affect motorcycle maneuvers. Because the data are to be grouped on a signal cycle basis, it mattered little when the observation was to be made. Nevertheless, to ensure a good vehicle queue during each cycle and a high proportion of motorcycles in the traffic, the morning period was chosen because the flow of motorcycles and other vehicles tend to peak together in the morning. A total of 25 signal cycles were observed at each of the sites. Table 2 shows the intersection characteristics.

The four intersections are taken from various locations in Singapore. All have four lanes for straight-through and right-turn movements. Woodlands (W) and Riverside (R) have one shared lane and one exclusive right-turn lane; Jurong (J) and Ang Mo Kio (A) have one exclusive right-turn lane. Woodlands, Jurong, and Riverside have standard lane widths, giving an average value of 3.6 m; Ang Mo Kio has a narrower approach width, averaging 3.3 m per lane. The percentage of motorcycles using the intersections varies from about 10% to 20%,

TABLE 2 Site Location and Characteristics of Video Data Collection

Intersection	Data Collection Approach	Location in Singapore	% of Avg. MC Flow	Avg. Lane Width (m)	No. of Right-Turn Lanes	Category[a]
Woodland (W)	W Ave2	North–West	17.6	3.6	2	HM-HF
	W Ave7		19.8	3.6	2	
Jurong (J)	J Town Hall Rd	South–West	15.1	3.6	1	MM-MF
	J East Ave1		13.0	3.6	1	
Riverside (R)	R Rd	North–West	10.3	3.6	2	LM-HF
	W Ave5		10.1	3.6	2	
Ang Mokio (A)	AM Ave3	North–East	16.2	3.3	1	MM-LF
	AM Ave6		15.4	3.3	1	

[a]HM-HF: high motorcycle flow, high freedom; MM-MF: medium motorcycle flow, medium freedom; LM-HF: low motorcycle flow, high freedom; and MM-LF: medium motorcycle flow, low freedom.

with Woodlands having the highest percentage and Riverside the lowest. On the basis of the average lane width and number of right-turn lanes, the sites are categorized into high, medium, and low degrees of freedom for motorcycle maneuvers, that is, HF, MF, and LF. Similarly the sites are also grouped according to high, medium, and low percentage of motorcycles, that is, HM, MM, and LM.

RESULTS

Observed Motorcycle Behavior

Visual observation from the video films shows that motorcyclists travel at their desired speed to the back of the queue of traffic. Within the vehicle queue, they weave through the queue of vehicles at a reduced speed to reach a position as close to the stop line as possible. This common behavior is also observed elsewhere (*13*). It is noted that if an exclusive right-turn lane exists (in Singapore, driving is on the left side of the road), motorcyclists will make use of the lane as a bypass if it is not fully utilized. Because it is common for the right-turn phase to follow the straight-through phase, the straight-through lane will fill up first before the right-turn lane. Hence the unoccupied right-turn lane offers an added opportunity for motorcyclists to move to the front of the queue, including the use of the right-turn lane for a straight-through movement.

Motorcycle Accumulation in the Approach

The accumulation of motorcycles in the first 6 m of the approach during the red phase is graphically presented in Figure 1. Accumulation is measured as the percentage of motorcycles of the total vehicles queuing in the 6-m zone from the stop line. To make a meaningful comparison between intersections that have different cycle and red times, the accumulation is plotted against the percentage of time into red.

Results show that in general the motorcycle accumulation increases with time into the red. However, Ang MoKio (A) reaches a maximum accumulation percentage much earlier. The maximum accumulation appears to depend both on the degree of freedom for motorcycles to weave to the front of the queue and the percentage of motorcycles in the traffic. The high- to medium-freedom sites have final motorcycle accumulation percentages ranging from 53% to 71%, with those having higher motorcycle proportions giving higher accumulation percentages (71% for HM-HF, 65% for MM-MF, and 53% for LM-HF). But for low-freedom sites, although the flow of motorcycles is as high at 15.8% of all vehicles, the final accumulation of motorcycles is lower at only 39%. This maximum accumulation is also reached earlier. All these results show that a higher number of motorcycles will concentrate near the stop line if there is sufficient opportunity to weave through the queue.

Motorcycle Discharge from Stop Line

It is also likely that motorcycles will enter into the intersection earlier than other vehicle types because they form a higher concentration in the front of the queue. Motorcycles tend to accelerate from stop earlier and at a higher rate because of their higher power-to-weight ratio compared with other vehicles (*14*). To observe the discharge behavior, the distribution of motorcycle flow (veh/s) is plotted against the initial period of green in Figure 2. The figure shows that motorcycle flow increases rapidly in the first few seconds. In fact for the high- and medium-freedom sites, motorcycle queues have fully discharged after about 12 s. For the low-freedom site, the motorcycle queue has discharged during a significantly longer period with a well-defined maximum value. The flow profile follows the typical discharge pattern of other vehicles during the green phase.

The discharge profiles of motorcycles shown in Figure 2 imply that motorcycles are spatially distributed differently, depending on the degree of freedom to weave through the queue. In circumstances in which weaving is highly restricted, the pattern follows the usual flow profile of other vehicles as shown by the solid line in Figure 3. In circumstances in which there is greater freedom, the profile will follow the pattern indicated by the dashed line in Figure 3. A comparison of the two curves in Figure 3 shows that given the freedom to weave through the queue, motorcycles will use the early portion of the green. This has a significant impact on their exposure to right-angled collisions during the phase-change periods.

Estimation of Observed Motorcycle Exposure

Assuming that the critical period of conflict is within the first 4 s of green, the observed relative exposure of motorcycles can be computed as the probability of motorcycles being found in this initial

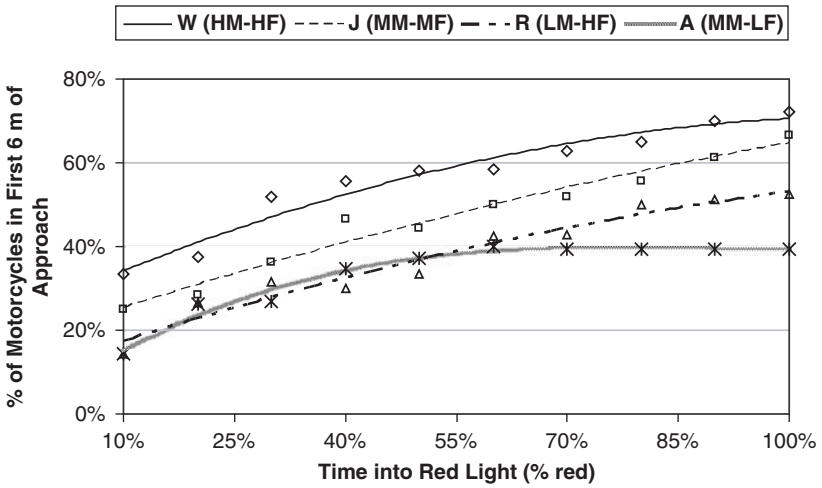

FIGURE 1 Accumulation of motorcycles in the front of the queue.

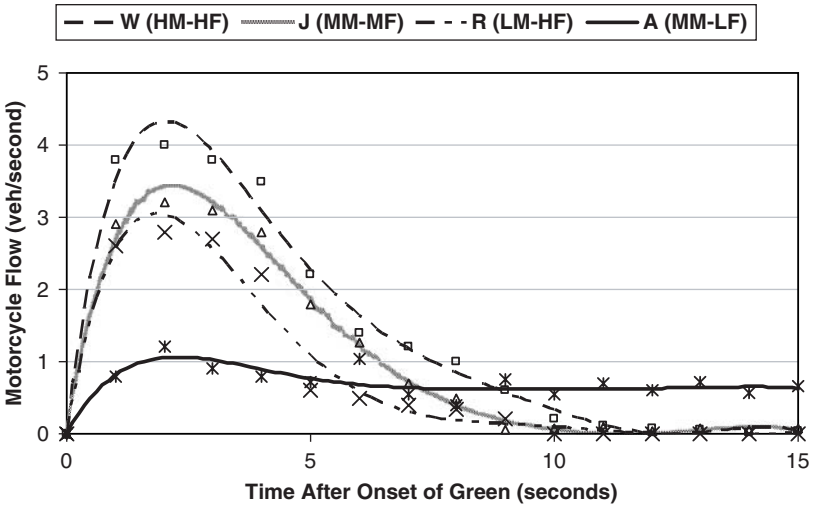

FIGURE 2 Motorcycle flow distribution after onset of green.

green period. The results are plotted in Figure 4. For comparison, the probability of a motorcycle being found in the traffic stream, as determined by the ratio of motorcycles to the total vehicles during the cycle, is plotted alongside the observed relative exposure. The observed relative exposure is higher among the high- and medium-freedom sites (from 0.675 to 0.755). This is marginally dependent on the proportion of motorcycles in the traffic stream (0.10 to 0.19) but is at a significantly increased rate. However, the low-freedom site gives a lower observed relative exposure (0.383) even though this is still higher than the proportion of motorcycles during the cycle (0.16).

In all cases, the relative exposure is significantly higher than the proportion of motorcycles in the traffic stream. Hence even if the motorcycle crash risk is the same as for other vehicles (which is not necessarily true), a higher motorcycle involvement rate is expected because of the high relative exposure. This finding is consistent with Preusser et al. (*15*), who reported that motorcyclists are over-involved in collisions at signalized intersections, particularly when there are violations by the opposing traffic.

Results also indicate that the crash problem is more acute at sites at which there is a higher degree of freedom for motorcycle weaving because of an increased observed relative exposure. If the motorcycles are completely restricted from weaving through the queue, that is, they will queue just like any other vehicles, the observed relative exposure would be the probability of motorcycles found in the traffic. Hence for high- and medium-freedom sites, the observed relative exposure has increased by about 0.56 whereas for the low-freedom site, it has increased by 0.22.

DISCUSSION OF RESULTS

From the results it is clear that motorcyclists tend to accumulate in the front of the queue for earlier access to the intersection, but this behavior leads them to be highly exposed to red light runners from the conflicting stream. It would be useful if the influential factors, that is, those affecting the accumulation of motorcycles, could be analyzed systematically.

The relationship between the number of motorcycles accumulated in the first 6 m of the approach and motorcycle flow is established for each of the sites and presented in Figure 5. For every site, each

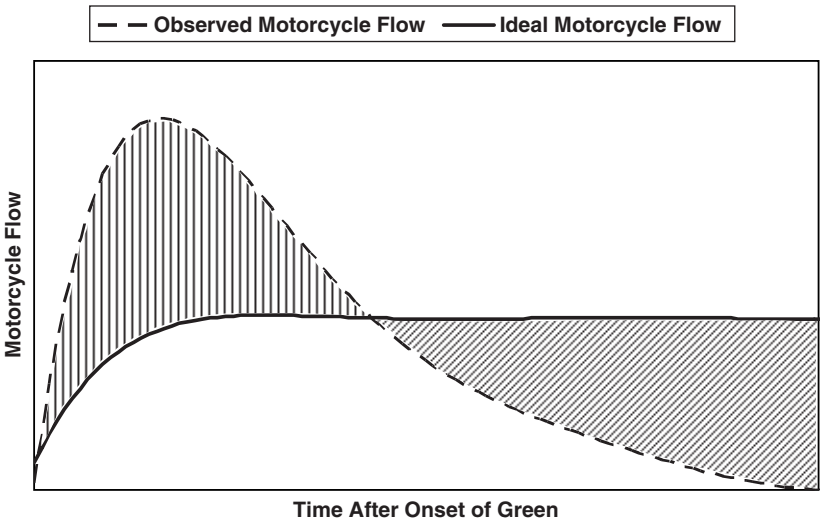

FIGURE 3 Motorcycle exposure at signalized intersections.

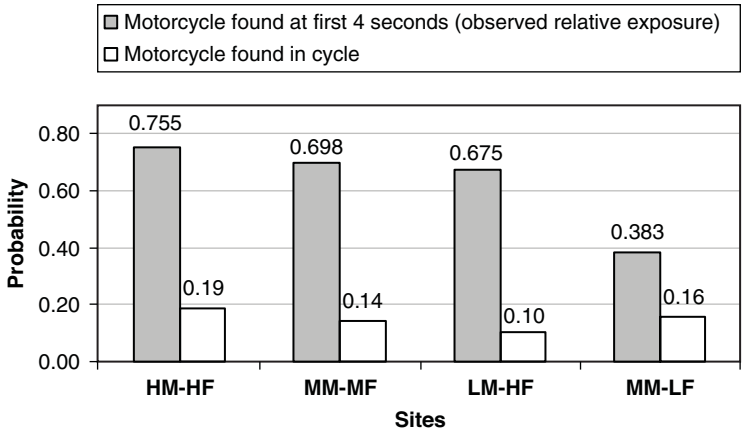

FIGURE 4 Observed motorcycle exposure at different sites.

data point in this figure represents the average number of accumulated motorcycles grouped at intervals of 5 vehicles per hour motorcycle flows. The relationship for each of the sites is found to be highly correlated (R^2 ranging from 0.49 to 0.77). The regressed line for each of the intersections demonstrates the effect of motorcycle flow and geometry (governed by the lane width and the number of right-turn lanes).

From Figure 5, it can be seen that generally, the accumulation of motorcycles is found to increase with motorcycle flow. A higher accumulation is found in the three sites (W, J, and R) that correspond to the cases in which the average lane width is 3.6 m. In contrast, the site with a narrower average lane width (3.3 m) experiences a lower accumulation value. The sites with wider lanes also experience a higher rate of accumulation. This is reasonable because there is a higher opportunity for motorcycles to move to the front of the queue if the lanes are wider. Notice also, that the number of right-turn lanes appears to affect the rate of increase in the accumulation, that is, J and A have lower slopes compared with W and R.

A similar graph plotting the accumulation of motorcycles against the percentage of heavy vehicles in the traffic stream is shown in Figure 6. For the purpose of examining the trend, the accumulation data are grouped at intervals of 2% of heavy vehicles. The effect of heavy vehicles on motorcycle accumulation is shown by the slopes of the regressed lines in Figure 6. Generally the accumulation of motorcycles decreases with the increasing percentage of heavy vehicles. For the sites with high and medium freedom of motorcycle weaving (i.e., W, J, and R), the slopes are almost similar and gentler than that of the site with low freedom of weaving (i.e., A). The findings reflect the restriction on motorcycles to move to the front of the queue as well as the reluctance of motorcyclists to pass or queue alongside heavy vehicles. The effect of lane width intensifies this phenomenon, resulting in a steeper reduction in accumulation with the increased presence of heavy vehicles.

CONCLUSION AND RECOMMENDATIONS

This study attempts to examine the exposure of motorcycles at signalized intersections. To achieve this aim, the motorcycle movements at four selected signalized intersections were observed. By using the phase-change period as a measure of opportunity for potential conflicts between opposing traffic and the accumulation of vehicles during the red phase and discharge of vehicles during the initial period of green as measures of exposure, the study shows that motorcycles are more exposed at signalized intersections compared with other vehicles.

The increased exposure may be due to a number of factors. The tendency of motorcycles to move to the front of the queue increases

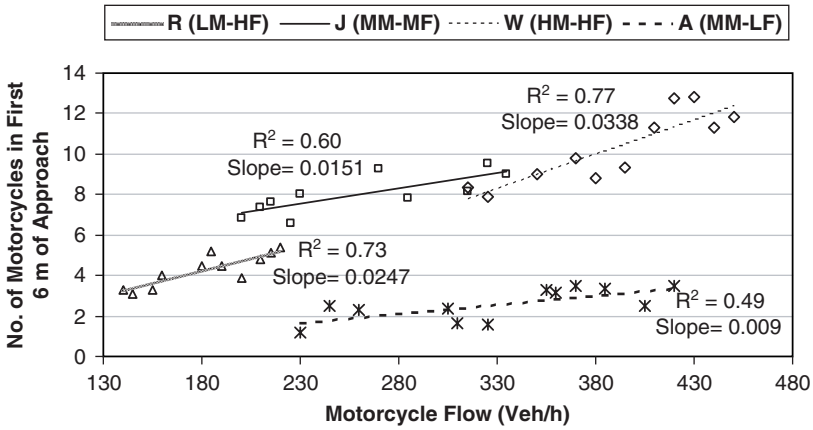

FIGURE 5 Frequency of motorcycles in the front of the queue as a function of motorcycle flow for different sites.

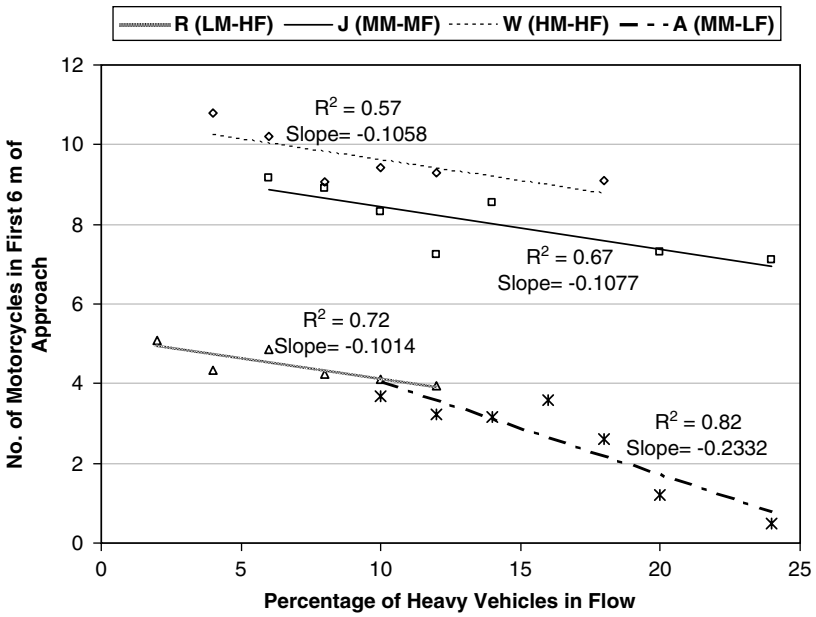

FIGURE 6 Frequency of motorcycles in the front of the queue as a function of heavy-vehicle percentage.

the likelihood of a higher motorcycle discharge during the initial period of green. Furthermore, the ability of motorcycles to accelerate faster and easier makes them more prone to be involved in crashes during the initial period of green. Wider lanes and the provision of right-turn lanes will enable motorcycles to weave more easily to the front of the queue and hence increase the level of exposure. The presence of heavy vehicles in the traffic stream has a restricting effect on motorcycle weaving maneuvers and hence exposure, and this effect is even more acute when the lanes are narrower.

Crash statistics show that more than 60% of motorcycles involved in crashes at signalized intersections are involved in right-angled crashes. In regard to right-angled crashes at signalized intersections, restricting motorcycle accumulation during the red phase may be an effective way of reducing motorcycle exposure to crashes. That may lead to a reduction in motorcycle right-angled crash involvement, but may be difficult to implement. More innovative research could be conducted to find a way to stop motorcycles' accumulation in front of the queue at signalized intersections.

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