Quantitative Examination of Traffic Conflicts

HOONG C. CHIN, SER T. QUEK, AND R. L. CHEU

Traffic conflict studies have been undertaken in many countries to examine the level of safety on road intersections. Most of these studies involve some form of conflict counts based on rather subjective observations of traffic interactions. An objective way of defining conflicts is proposed along with two conflict measures. Instead of relying on conflict counts, the method uses the probability distribution of the conflict severity measures to derive the probability of a serious conflict. To do this, the severity of each conflict is obtained by first identifying the most serious instant of conflict occurrence according to the proposed measures. The method was applied by examining the relevant data from traffic movements at a merging area on an expressway.

For many years, accident statistics have been used to assess the safety level of roads and to evaluate road safety programs. The lack of good and reliable accident records in some cases has hampered proper analyses. To overcome this problem, attempts have been made to rely on nonaccident statistics. In a landmark paper published in 1968, Perkins and Harris of General Motors Corporation introduced the concept of traffic conflicts as a surrogate measure of accidents (*1*). Since then, studies have been undertaken in several countries to apply the traffic conflict techniques in analyzing the accident potentials at specific road intersections and interchanges (*2–5*).

One of the main problems encountered in most conflict studies is in defining the conflicts and hence developing the procedure for detecting conflicts. Perkins and Harris considered conflicts to be cases of vehicle interactions in which one of the vehicles takes evasive actions, such as braking or swerving (*1*). Such a definition requires, to a large extent, the subjective judgment of the observers. This is clearly unsatisfactory and has led to a wide range of measures of expressing conflicts and varied methods of making conflict observations. A general definition of conflict was finally agreed on at the First International Traffic Conflict Techniques workshop (*2*): a traffic conflict was considered to be "an observable situation in which one or more road users approaches each other in space and time to such an extent that a collision is imminent if their movements remain unchanged."

Even with this definition, the procedures of conducting traffic conflict studies adopted by various countries, along with the criteria for identifying and classifying conflicts and the methods of making conflict observations, remain varied. Most of the studies still rely very much on subjective measurement of conflicts, and this has made comparative studies difficult. This problem prompted a major calibration study (*6*) aimed at comparing the different observational techniques in use including a quantitative method of analysis (*7*).

H. C. Chin and S. T. Quek, Department of Civil Engineering, National University of Singapore, Kent Ridge Crescent, Singapore. R. L. Cheu, Institute of Transportation Studies, University of California, Irvine, Calif. 92717.

The search for an objective and quantitative definition of conflict began as early as 1971 when Hayward suggested the use of time-measured-to-collision as an indicator of the risk of a collision (*8*). The time-measured-to-collision, or time-to-collision (TTC), is the time taken for the following vehicle to collide with the leading vehicle if both vehicles continue in the same path without changing their speeds. This measure requires the two vehicles to be on the same path, such as when merging. The presence of conflict is not so obvious when one of the vehicles changes lanes. There are two important modifications to this definition: the minimum TTC (TTC_{min}) and the TTC at braking (TTC_{br}). The former is the minimum value of TTC obtained in an evasive maneuver, and the latter the value of TTC at the onset of braking of the following vehicle. TTC at the onset of braking is very much similar to the time-to-accident (TA), which is the time taken from the moment one vehicle initiates evasive action to the time of collision if no evasive action is taken (*9*).

In cases in which vehicles are crossing each other's paths, TTC may be infinite even when the collision is just avoided. Allen has proposed the use of postencroachment time (PET) to measure conflicts (*10*). This is the time difference between the arrival of the conflicted vehicle and the departure of the offending vehicle at the point of crossing. Although PET can be objectively measured, it is uncertain whether its magnitude truly represents the severity of the conflict or the willingness of the drivers in accepting the risk. This is because the most serious conflicts may have rather large PET values if evasive actions have been taken.

One way of overcoming this is to consider the gap time (GT), which is the difference between arrival times of the involved vehicles at the point of crossing if no evasive actions are taken by either vehicle (*11*). Glauz and Migletz have argued that this may indicate whether a potential conflict exists, but it is by no means a perfect measure of the severity of conflict since a zero-value GT can be recorded in two possible cases: one that involves an accident and the other in which early precautionary actions are taken (*12*).

Another objective measure for vehicles approaching an intersection is the time-to-intersection (TTI_{br}), which is the time expected for a vehicle to enter the intersection at the constant instantaneous speed just at the onset of braking (*13*). This has been used for single-vehicle interaction at nonsignalized intersections (*10*).

Given that conflicts can be measured objectively and quantitatively, it is still necessary to determine a threshold value to distinguish a conflict serious enough to be detected. It is relatively simple to visualize and define the case of collision since all the quantitative measures must take on definite values (zero for TTC, PET, TTI, and GT). On the other hand, it is not so simple to specify a threshold value for a serious conflict or a near-collision. Various threshold values have been assumed for the different measures of conflict. It has been assumed that TTC can be related to the drivers' reaction times. Consequently, values of 0.5 to 1.5 sec of TTC have been used to define instances of near-collision (*8,14–16*). Some have assumed the threshold values to vary with the speeds of the vehicles (*15*). A value of 1.5 sec has been adopted by Hydén for TA (*17*), but he later assumed the threshold values to vary with speeds (*18*). For PET, values from 0 to 4 sec have been used to define the different levels of conflict severity (*10,11,19*). Values between 1.5 and 3.0 sec have been used for TTI in situations of vehicles yielding at nonsignalized intersections (*13*).

The foregoing indicates that attempts have been made to express conflicts quantitatively. However, many conflict studies still end up observing conflict counts on the basis of rather imprecise definitions of conflicts (*2–5*). In this paper, an objective way of defining conflicts is proposed along with two conflict measures, one related to TTC and the other to deceleration. Instead of making conflict counts, the method uses the probability distribution of the conflict measures to derive the probability of a serious conflict. Furthermore, since conflict encounters are really processes instead of events, the severity of each conflict is obtained by examining the proposed conflict measures continuously. To apply this technique, traffic movements at a merging area on an expressway were filmed using video cameras. The relevant data were then extracted by playing back the films in the laboratory.

STUDY METHOD

Derivation of Conflict Severity

Consider a situation on an expressway in which a pair of vehicles are involved in a merging process (one is merging and one is on the expressway). A possible conflict exists when the offending (merging) vehicle shares the same path as the conflicted (mainline) vehicle over a certain period of time. Suppose that at time t, the merging vehicle and the mainline vehicle are respectively at positions $x_m(t)$ and $x_e(t)$ downstream from the ramp nose on the expressway and at speeds $v_m(x)$ and $v_e(x)$ where $x_e(t) < x_m(t)$ (see Figure 1). We may also denote the time at which the merging vehicle to be at a specific point x on the expressway as $t_m(x)$ and the time for the mainline vehicle to be $t_e(x)$. Taking the physical length of the vehicles into consideration, we may consider $t_m(x)$ to be measured with reference to the rear bumper of the vehicle and $t_e(x)$ with reference to the front bumper of the vehicle.

In this study, two conflict measures are proposed; one related to the TTC and the other to the deceleration of the conflicted vehicle. TTC depicts the time proximity between vehicles before collision if both vehicles continue along the same path with unchanged speeds. However, as the severity of conflicts increases with decreasing values of TTC, it seems more appropriate to define a conflict measure as the reciprocal of TTC, that is,

$$c_1 = \left[\frac{v_e(x) - v_m(x + \Delta x)}{\Delta x(x)}\right] \quad (1)$$

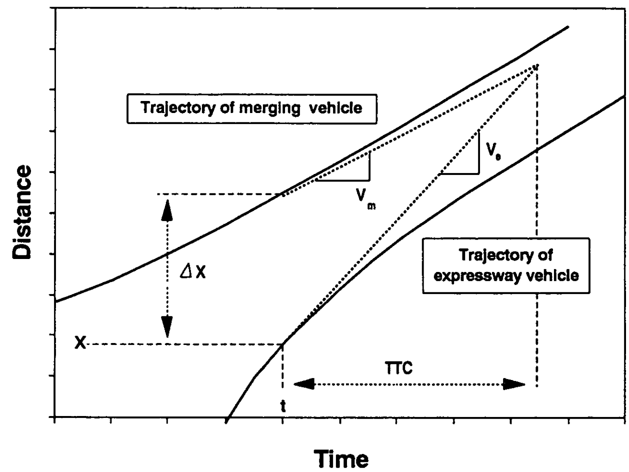

FIGURE 1 Space-time trajectories of vehicles.

where

$$\Delta x(x) = x_m[t_e(x)] - x \quad (2)$$

For a particular merging encounter, the value of c_1 computed for that pair of vehicles will change continuously during the entire process of merging. It is obvious that the most serious instant of conflict between the pair of vehicles occurs when c_1 is at a maximum or when TTC is at a minimum. Consequently, the severity of conflict s_1 for that merging as measured by c_1 will be

$$s_1 = \max_x \{c_1\} \quad (3)$$

The second conflict measure is associated with the magnitude of the average deceleration that the conflicted vehicle is required to take just to avoid a collision. Provided that TTC is positive, the mainline vehicle will avoid a collision if its speed can be reduced to that of the leader by the application of a constant deceleration. The second proposed measure defined as the deceleration to avoid a collision is given by

$$c_2 = \left\{\frac{|v_e(x) - v_m(x + \Delta x)|\,[v_e(x) - v_m(x + \Delta x)]}{2\Delta x(x)}\right\} \quad (4)$$

As in the previous measure, the corresponding severity of the conflict defined by the second measure will be

$$s_2 = \max_x \{c_2\} \quad (5)$$

Evaluation of Conflict Probability

The conflict measures as defined in Equations 1 and 4 imply that a conflict exists only when $c > 0$. Equations 3 and 5 also signify that the maximum instantaneous conflict value in any merging process represents the severity of conflict of the merging encounter. Suppose an appropriate threshold value for the severity of the conflict, s^*, can be identified. Then it is also possible to clearly distinguish the serious conflicts objectively by considering quantitatively the cases in which $s > s^*$. Traditionally, in most conflict studies, one would determine the probability of occurrence of a serious conflict by simply noting the proportion of cases in which s exceeds s^*.

Another method is used here. Because the conflict measures are well defined, it seems more appropriate to use as much information as possible from the data gathered instead of limit the analysis to obtaining counts of serious conflicts. Logically, the two proposed measures of conflict severity should follow some probability distribution, and it is possible to obtain a suitable mathematical distribution to describe s, from the data gathered for the two measures. Hence, if the positive values of s follow a probability density function $g(s)$, then the cumulative distribution function of s, $F(s)$, may be defined as

$$F(s) = p_0 + (1 - p_0)\int_0^s g(z)dz \qquad s > 0 \tag{6}$$

where p_0 is the probability that s is negative. The probability of a serious conflict may be derived given the threshold value s^*. However, the ability to avoid a collision is very much dependent on the drivers and their vehicles, which means that the value of s^* is not likely to be unique in general. Supposing that the threshold follows a probability density function $h(s^*)$, then the probability of the occurrence of a critical conflict will be

$$p_s = \int_{s=0}^{\infty} [1 - F(s)]h(s)ds \tag{7}$$

When TTC is used to measure conflicts, the threshold selected to distinguish serious conflicts has often been taken to be a function of the driver's reaction time. A single value of the threshold ranging from 0.5 to 1.5 sec has been employed (*13–17*). In this study, the driver's reaction time is also used in conjunction with the first measure of conflict severity. However, instead of relying on a single value of the threshold, a distribution of s_1^*, that is, $h(s^*)$, is used; this may be suitably derived from the distribution of driver's reaction time.

For the second conflict measure, a serious conflict is one in which the deceleration needed is excessive for comfort and safety. Since drivers and passengers can comfortably tolerate quite a high level of deceleration, especially if it is over a very short period, it is more appropriate to select a threshold on the basis of safety considerations. At high deceleration, the driver loses control of the vehicle if the braking force exceeds the skidding resistance between the tires and the pavement. Hence, if the critical conflict is considered to be one in which the vehicle will skid on the road surface should the driver brake excessively to avoid a collision, an appropriate distribution of the threshold would be the distribution of the skid resistance between the tires and the road surface.

EXPERIMENTAL DATA

To examine the suitability of the proposed conflict measures, traffic maneuvers at the Paya Lebar on-ramp into the westbound direction of the Pan Island Expressway were monitored (*20*). At this merging area (see Figure 2), the acceleration lane—which is aligned at a horizontal angle of 3 degrees to the expressway—is about 100 m long, tapering from a width of 5.8 m at the ramp nose. The nearside lane of the three westbound lanes on the expressway is 3.8 m wide. The expressway at this point has a straight horizontal alignment and a 3 percent downgrade about 100 m upstream of the ramp nose. Traffic interruptions due to geometric changes are unlikely, if at all possible, because the geometric features of the sections immediately upstream and downstream of the merging area are generally consistent with those of the merging area.

Most of the vehicles merging into the expressway at this location do so within the first 50 m from the ramp-nose, so it is sufficient to observe traffic maneuvers within the 100-m stretch downstream of the expressway and on-ramp with reference to the ramp nose. The movements of the vehicles within this study area were recorded with video cameras from a tall building nearby for recording periods of about an hour. Taking into account the variation in traffic volumes during the day, eight recording periods were made so that both peak and off-peak conditions during daylight were covered. The time periods during which the data were obtained are shown in Table 1.

In order to obtain the space-time relationships of each pair of vehicles involved in the merging encounter, markers at 10-m intervals were set up on both sides of the expressway. From these markers, 11 lines across the expressway and the ramp were constructed on a 100-in. screen in the video playback. The arrival times of the vehicles $t_m(x_i)$ and $t_e(x_i)$ at Marker i were then extracted from the video playback, which

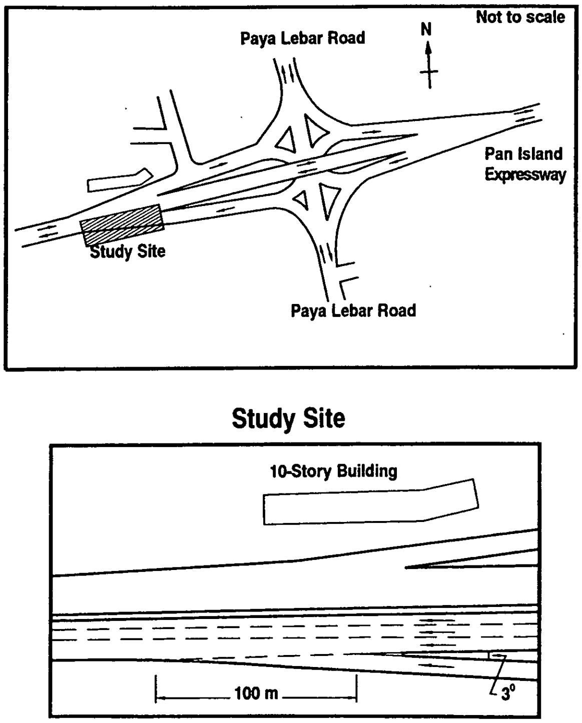

FIGURE 2 Location of study site (not to scale).

TABLE 1 Information on Sets of Data Used in Analysis

Data set	Date	Time
Set 1	8 Jun 88	0700-0800
Set 2	8 Jun 88	0800-0900
Set 3	15 Apr 88	0900-1100
Set 4	5 May 88	1130-1230
Set 5	5 May 88	1230-1330
Set 6	4 May 88	1500-1700
Set 7	28 Sep 88	1700-1800
Set 8	28 Sep 88	1800-1900

was run on a slow speed of 2.5 frames per second to achieve the desired accuracy in the arrival times. A controlled study was also undertaken to minimize the errors of measurement and observer bias (*20*).

ANALYSIS OF CONFLICT DATA

On the basis of the space-time data extracted from the video films, the kinematics of the vehicles involved in the merging process can be derived. These data form a useful data base for investigating the mechanics of vehicle interaction during merging. In particular, it is possible to determine for each merging encounter the values of the proposed conflict measures c_1 and c_2 as given in Equations 1 and 4.

Reciprocal of TTC as First Conflict Measure

The use of TTC in describing a conflict implies that a conflict exists only when the expressway vehicle is traveling at a higher speed than the merging vehicle. To observe how the reciprocal of TTC—that is, c_1—varies in a merging process, a few merging encounters are presented as typical examples. As seen in Figure 3, when the interaction between vehicles results in little or no danger of collision, the variation of c_1 is small and fluctuates around the zero level. As the severity of the conflict increases, so does the fluctuation. Where a precautionary action is taken so that a serious conflict is avoided, a slight dip in c_1 is observed. For a serious but short conflict in which definite corrective actions are taken, the drop in c_1 can be considerable.

By considering the maximum of c_1, that is, s_1 in each case of merging for a particular time period observed, it is possible to establish the distribution of s_1. For each period of observation, various mathematical functions have been tested to fit $g(s)$ in Equation 6. The function for $g(s)$ that most suitably fits the empirical data is found to be the Weibull distribution, a largest-value extremal function given by

$$g(s) = \left[\frac{k}{w}\right](s/w)^{k-1}\exp[-(s/w)^k] \tag{8}$$

The parameters of the Weibull distribution and the goodness-of-fit statistic as judged by the Kolmogorov-Smirnov test are presented in Table 2 for each of the periods studied. The results indicate that the data fit the Weibull distribution well. A typical distribution of s_1 along with the best-fit Weibull distribution is plotted in Figure 4.

TABLE 2 Parameters of Weibull Distribution, Goodness-of-Fit Value, and Computed Conflict Probabilities for s_1

Data set	p_o [a]	k [b]	w [b]	D_c [c]	p_{s1} (X10^{-3}) [d]
Set 1	0.180	1.080	0.153	0.065	0.538
Set 2	0.184	1.238	0.184	0.054	0.512
Set 3	0.137	1.289	0.156	0.037	0.126
Set 4	0.256	1.007	0.115	0.024	0.185
Set 5	0.319	1.079	0.104	0.036	0.040
Set 6	0.276	1.054	0.146	0.064	0.450
Set 7	0.245	1.154	0.135	0.045	0.124
Set 8	0.324	1.064	0.118	0.030	0.111

[a] Proportion of non-conflicts
[b] Parameters of Weibull distribution (Eq. 8)
[c] Kolmogorov-Smirnov test value
[d] Probability of serious conflict

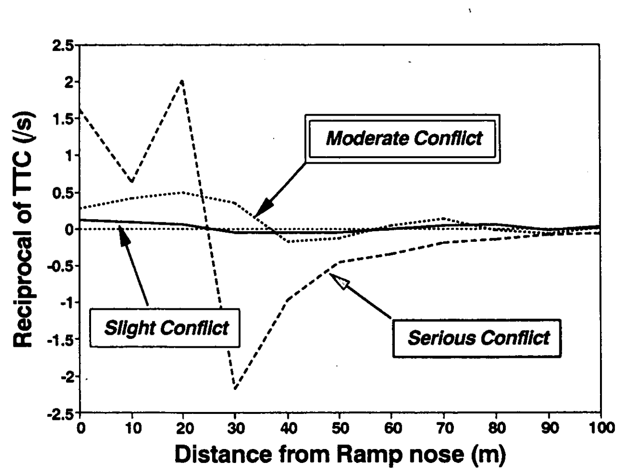

FIGURE 3 Variation in conflict measure c_1 during typical merging encounters.

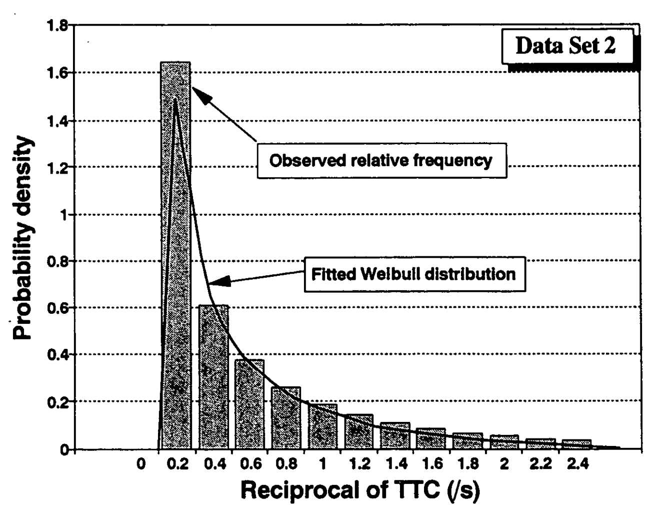

FIGURE 4 Distribution of severity measure s_1.

To obtain the probability of a critical conflict, the distribution of drivers' reaction times reported by Johansson and Rumar (*21*) as reproduced in Figure 5 is used to derive $h(s_1^*)$. Applying numerical integration to Equation 7 and using the best-fit Weibull distribution derived earlier for Equation 6, the probability of a critical conflict for each period can be determined and shown in Table 2. The values of p_{s1} computed for the different periods vary from 0.000040 to 0.000538. Because the probability estimates are small, it may not be appropriate to compare the values of p_{s1} numerically. It may be best just to consider that p_{s1} is of the order of magnitude of 10^{-4}.

Deceleration To Avoid Collision as Second Conflict Measure

Comparison between c_1 and c_2 in Equations 1 and 4 shows that c_2 is a weighted function of c_1. Therefore, the variation of c_2 during a merging process will be quite similar to that of c_1 as seen in Figure 6 in relation to Figure 3 for the same sets of vehicles. Again, in the more serious cases of conflict, the variation in c_2 is high. Compared to c_1, the variation of c_2 is more pronounced at higher values of c_2. The effect of this is a greater spread in the distribution of s_2.

The data values of s_2 have also been used to fit to a number of mathematical distributions, and the Weibull distribution again gives the best fit. The parameters of the distribution are shown in Table 3 with the Kolmogorov-Smirnov goodness-of-fit statistics. Although the Weibull distribution is acceptable in describing the distribution of s_2 for all the data sets, compared with s_2 it appears not to fit as well. Figure 7 shows the distribution of s_2 and the fitted Weibull distribution for the same set of observations that are used to generate the distribution of s_1 in Figure 4.

To obtain the distribution of skid resistance, the British pendulum tester was used at the site under dry pavement conditions as a measurement of the coefficient of static friction between the tires and the pavement. The mean British pendulum number obtained from 12 points in the study site was 65.2, and the standard deviation was 6.2. Using the exponential model of skid variation proposed by Shah and Henry

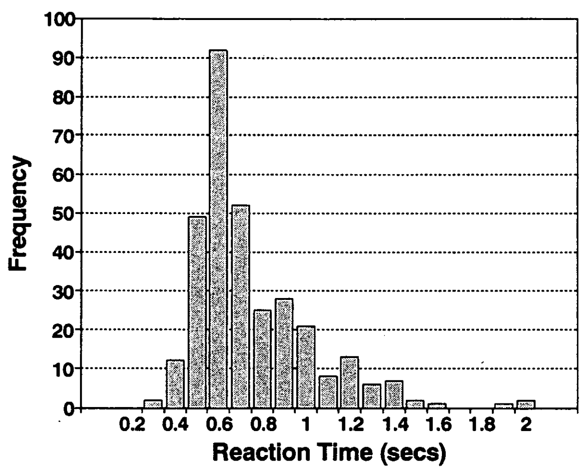

FIGURE 5 Distribution of drivers' reaction times (*21*).

TABLE 3 Parameters of Weibull Distribution, Goodness-of-Fit Value, and Computed Conflict Probabilities for s_2

Data set	p_o [a]	k [b]	w [b]	D_c [c]	p_{s2} ($\times 10^{-3}$) [d]
Set 1	0.180	0.585	0.167	0.077	0.549
Set 2	0.184	0.707	0.304	0.058	0.606
Set 3	0.137	0.675	0.231	0.047	0.310
Set 4	0.256	0.572	0.161	0.038	0.601
Set 5	0.319	0.592	0.115	0.034	0.065
Set 6	0.276	0.582	0.158	0.067	0.419
Set 7	0.245	0.632	0.165	0.051	0.138
Set 8	0.324	0.628	0.163	0.037	0.131

[a] Proportion of non-conflicts
[b] Parameters of Weibull distribution (Eq. 8)
[c] Kolmogorov-Smirnov test value
[d] Probability of serious conflict

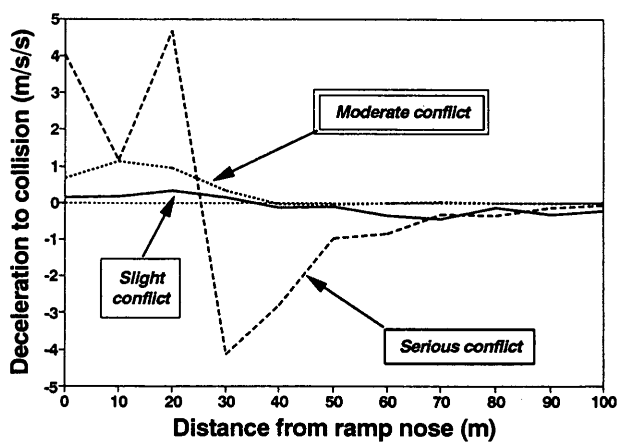

FIGURE 6 Variation in conflict measure c_2 during typical merging encounters.

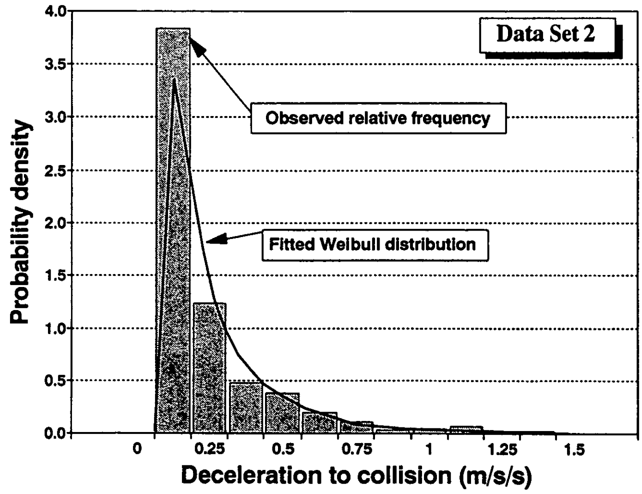

FIGURE 7 Distribution of severity measure s_2.

(22) and a measured average speed of expressway vehicles of 49.3 km/hr, the coefficient of braking friction works out to a mean of 0.52 and a standard deviation of 0.05. Taking the coefficient of braking friction to be normally distributed and the threshold s_2^* to be the braking skid resistance, it is possible to derive $h(s_2^*)$. By applying the best-fit Weibull distribution to Equation 6 and the distribution with $h(s_2^*)$ to Equation 7, the probability of a critical conflict, p_{s2}, can then be determined for all the periods. From the computed values of p_{s2} shown in Table 3, it can be seen that p_{s2} ranges from 0.000065 to 0.000606, giving slightly higher values than p_{s1}. As in the first conflict measure, p_{s2} may be considered to be of the order of 10^{-4}. A comparison between p_{s1} and p_{s2} shows that in general p_{s2} is about 1½ times larger than p_{s1}. It may be argued that a larger p_{s2} is not surprising because the chances for skidding are likely to be higher than those for collision.

CONCLUSIONS

Using two ways of defining conflicts, this paper illustrates how the probability of a serious conflict can be determined. This method differs in several respects from a number of other conflict studies in the manner by which conflicts are studied. First in this study, conflicts are examined objectively using quantitatively measurable observations. Second, the severity of a conflict is not measured at a particular point in space or time but rather determined by examining the process of vehicle interaction and identifying the most serious instant of conflict. Third, rather than relying on mere conflict counts, which requires only a simple "yes" or "no" treatment of conflict observations, the proposed method uses the full range of observations to determine the distribution of conflict severity. Finally, the threshold to identify the critical cases of conflict is taken to be a distribution instead of a single value.

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