Estimating Roundabout Performance using Delay and Conflict Opportunity Crash Prediction

Douglas R. Kennedy, P.E.
Patton, Harris, Rust & Associates, PLC, Chantilly, VA.
and
Kristine M. Taylor, BSCE,
President, Traffic Safety Software, Scottsdale, AZ

Abstract

The general algorithms, assumptions, validations and example application are presented for estimating roundabout safety performance in comparison to signalized and unsignalized intersections using conflict opportunity technology rather than regression-based accident estimates. Comparison of conflict opportunity accident estimates versus on-site accident records for 100 signalized and unsignalized intersections are presented along with single and dual lane roundabouts accident comparisons compared to Maryland DOT data. For both intersections and roundabouts, annual accident prediction accuracies of approximately 80 percent for total accidents and 70 percent for angle and rear-end accidents was achieved compared to the 3-5 year average reported historical crash events. When combined with Highway Capacity Manual delay estimates and delay values, the conflict opportunity-based injury and HCM delay values can be combined into a Performance Index for comparing alternate traffic control scenarios. An example safety+delay performance evaluation of a single lane 15,000 ADT roundabout compared to Two and All-way stop and signalized control indicated that All-Way stop had excessive delay, a signal would not be warranted and of the remaining options, a roundabout provided annual safety+delay performance sufficiently comparable to Two-way stop control and was thus the developers preferred design alternate.

Introduction

In the past, the development of crash prediction models has relied on an assessment of before-and-after crash experience to generate linear regression models that are used predict future crashes, and from which potential crash mitigation can be suggested. However, such linear regression-based prediction models are often confounded among the variety of variables, as well as the variance in definitions and data elements in these variables that can include approach volume, speeds, geometry and lanes, as well as multiple traffic control strategies that generally have caused these models to generate a poor correlation to historical reported crash events. In addition, over-reliance on crash records (the crash result) often incorrectly assumes the “result” is also the “cause”, and most drivers and researchers recognize that crash “cause and effect” can be dissimilar events, where for instance a ran-off-the-road crash may have actually been caused by a failed passing attempt that is incorrectly reported. More importantly, in the past these regression models have relied on macroscopic variables such as average daily traffic (ADT) without specifying hourly lane assignments, knowledge of turn bay presence and length, approach speeds and other extremely sensitive variables. Most importantly where NHTSA predictions are that 1 of 84 children born today will die in an auto accident and 6 of 10 will be injured, it is easy to see that microscopic accident and injury prediction techniques are becoming essential to optimal intersection and roundabout performance planning and design.(1)

Numerous studies have reported on the correlation of conflicts to annual accidents at specific intersections and report only marginal success.(2-6) But this is not unexpected in correlating on-site conflict or brake-light application events to the crash record because the definition and observation of any on-road event is subjectively unique among both drivers and observers and influenced and confounded by human, vehicle, environmental and other competing factors, not to mention the lack of accuracy in the historical accident record itself.(7) Given these format and data inconsistencies and “cause and effect” redundancies, it is extremely desirable to replace actual conflicts with a more precise surrogate of theoretical conflict opportunities that are dependent only on more-stable operational measures.

Conflict Opportunity Disaggregate and Microscopic Statistical Algorithm and Assumptions

One of the first attempts to formulate an objective and quantifiable theoretical conflict opportunity surrogate to intersection annual crash prediction began with Perkins and Harris of General Motors who introduced the concept for discrete types of intersection conflicts such as angle, rear-end and sideswipe events.(8) This study was later followed by other theoretical formations, but none of these were able to integrate these individual conflict events to form an annual total accident expectation involving each of the major subtypes of crashes.(9-15). However, a unique relationship between competing probable conflict events was defined for passing accident prediction on two-lane highways and found to be reasonably well correlated to the annual crash record when conflicts are summed over the full year and calibrated to the historical record.(16) Using a variety of typical conflict types and a finite-element extension of this technique for each approach to an intersection or roundabout with summed annual conflict opportunities calibrated to annual rash events and speeds for different traffic control types, a good conformance to the historical crash record was achieved with the following general form: (17)

$$\text{Conflict Opportunity(Type)}_t = \text{E(Movement Opportunities)}_{ij} * \text{P(Arrival of Opposition to Movement)}_{kl}$$

where:

t = Specific Conflict Type such as passing on two-lane highway, intersection angle conflicts, merging/ diverging sideswipe conflicts, rear-end conflicts, fixed object vehicle conflicts, etc. per unit time,

i = Arrival Movement Type such as the vehicle desiring to pass, the vehicle(s) desiring to turn left, the vehicle(s) desiring to change lanes, the vehicle(s) desiring to stop, etc. per unit time,

j = Arrival Approach such as one lane of a two lane highway, or one lane of a specific intersection approach which may have two, three or more approaches,

k = Opposition Movement Type such as the vehicle opposing the passing vehicle on a two-lane highway, or the vehicle opposing an angle movement(s) within an intersection, the vehicle opposing a merge/diverge sideswipe movement(s) on a specific approach, the vehicle opposing a vehicle(s) desiring to stop (rear-end), etc. per unit time,

l = Opposition Approach such as the opposing one lane of a two lane highway in a passing maneuver, one lane of a specific intersection approach which is in opposition to a movement produced in another lane.

<u>E (Movement Opportunities)</u> $_{ij}$ = Expected number of vehicles per unit time from a specific movement type "i" (such as number of vehicles desiring to pass/hour in a given segment on a two-lane highway or the number of vehicles desiring to turn left or right on an approach to an intersection/hour or any other arriving movement) which may be exposed to an opposition movement on any particular roadway segment or intersection approach or adjacent lane "j", where each expectation follows the form:

E = P(Movement Opportunity/unit time) * (Vehicles performing this movement/unit time).

Often the probability of movement opportunity may be 1.0 where the conflict can occur at any particular time such as at a signalized intersection approach, or the probability may be a discrete unit as where there exists a finite probability that a following vehicle may desire to pass on a two lane highway and this probability depends on the volume of traffic in one direction on the advancing roadway segment.

<u>P (Arrival of Opposition to Movement)</u> $_{kl}$ = the probability of arrival of one or more vehicles during the specific time period of exposure to a particular type of conflict "k" (or the probability of opposition during the time of exposure of the arriving vehicle to a conflict situation "k"), on any particular roadway segment or intersection approach or adjacent lane "l", where using the Poisson or similar common distribution each probability function follows the general form:

$$P(\text{1 or more}) = 1 - P(0) = 1 - \frac{e^{-m}m^x}{x!} = 1 - \frac{(e^{-m} * m^0)}{0!} = 1 - e^{-m}$$

where for example in angle conflicts:

m = <u>angle conflict average arrival rate</u>:

= [(q veh/hour per lane per approach) * (t seconds of exposure time)]/3600; and for practical purposes, the angle conflict exposure or clearance time (t-seconds of exposure time) of the arrival vehicles are based on 1985 Highway Capacity Manual critical gap times for unsignalized intersections, under the assumption that these times adequately estimate vehicle exposures, even though new research continually improves exposure predictions.(18,19) For through movements, exposure times are calculated using safe stopping distances for through vehicles exposed to sidestreet conflicts (such as for an entering sidestreet vehicle stalling on acceleration). And theoretically, t seconds of exposure or clearance time may also be replaced by a continuous distribution of the form: $P(h \geq t_{Li})$ and $P(h \leq t_{Ui})$ where:

t_{Li} = Lower bound of exposure time on approach "i" (sec)
t_{Ui} = Upper bound of exposure time on approach "i" (sec).

With the above general formulation of competing probable events for each conflict type and their finite element expansion to multiple lanes of one approach and then to all approaches of an intersection, an annual conflict opportunity expectation may be developed representing the summation of individual conflict types of angle, rear-end, sideswipe and fixed-object/single-vehicle (other) events. And with the summation of all hours and days in a year, the process of predicting annual intersection accidents may be expressed as:

$$\text{Annual Accidents} = \left[\sum_{1}^{n} \text{Conflict Opportunities(Conflict Type/hour)}_t \right] * [\text{MODEL CO's/Accident}]$$

where:

n = Hours of the year for each Conflict Type of Angle, Rear-end, Sideswipe and Fixed Object or Single Vehicle or Other; and

[MODEL CO's/Accident] = a speed and visual perception-based calibrated linear regression relationship between all summed annual conflict opportunities by type and annual accidents for each traffic control type over all typical volumes, speeds, geometry, environments, drivers and vehicles. A more detailed discussion and example numeric application are referenced.(20)

To formulate the above theoretical formats into a practical working process for an intersection, a finite element analysis approach to intersection accidents is used that breaks the accident models and each intersection or roundabout into discrete elements based in part on the following assumptions:

1. Each access opening or intersection is assumed as sufficiently separated from adjacent openings such that the driveway or intersection under study is an isolated, mutually exclusive entity,
2. The terrain is assumed as level on all approaches such that no driveway aprons, sidewalks, valley gutters, or other obstructions interfere with normal operational maneuvers,
3. Sight distance is assumed as sufficiently clear on all approaches so as not to interfere with normal operational maneuvers,
4. All vehicles are normalized as typical vehicles used in AASHTO driveway, intersection and/or roadway planning and design, and conform to typical vehicle physical and performance characteristics such that the intersections or driveways where the algorithm and software are used have normal amounts of vehicle induced accidents (e.g. no excessive vehicle failures such as numerous "failed tires" or "vehicle fires"),
5. All drivers and passengers are normalized as typical drivers and passengers used in AASHTO driveway, intersection, and/or roadway planning designs such that the physical, mental, and emotional characteristics required to safely and efficiently accomplish the basic driving tasks of Control, Guidance, and Navigation are performed, and locations where the algorithm and software are used have normal amounts of human induced accidents (e.g. no excessive human failures such as alcohol or drug abuse, or excessive age or handicap impairments which may affect operational abilities and either of which may produce non-normal accident expectations),
6. The environment is normalized as the typical environment used in AASHTO driveway, intersection and/or roadway planning and design such that the driveways, intersections and/or roadways where the algorithm and software are used have normal amounts of environmentally induced crashes (e.g. no extremely unusual weather conditions which may produce non-normal accident expectations),
7. Other normalizing assumptions pertinent to each particular driveway, intersection or roadway and traffic control type (e.g. Drivers Perception/reaction time, vehicle length, stop sign setback, turning radii, turn bays, speeds, signal timing, etc.) which are user-defined within the algorithm and software,
8. In the formulation of the conflict/accident relationships, and because existing accident databases generally segregate accident occurrence into four major categories which include angle, sideswipe, rear-end, and fixed object and/or single vehicle (other) accidents, only these four accident types are used. Thus each of the following assumed mutually exclusive types of accidents are assumed as additive given the used of a common statistical (Poisson or other) format within each term (aka: nested regression):

   <u>Accidents/year = f{Conflicts[(Angle)+ (Rear-end)+ (Sideswipe)+ (Fixed Object/SV/other)]}</u>

9. In defining annual injury accidents, a stable relationship is assumed between speed, annual accidents, and injury accident occurrence of the following form: (21,22)

   Injury Accidents/year = f{Accidents/yr., speed, accident:injury ratio}
10. Both annual accident and injury accident events are population-based in that a linear relationship exists between urban area population and the number of accident and injury accidents/yr in any given urban area.
11. Calculation of annual roundabout accidents and injury accidents is identical to the “All-Way-Stop” conflict opportunity algorithm except that “Stop” critical gaps are replaced by “Yield” critical gaps for right turns from the minor movement (see 1985 HCM-Unsignalized). Also a distance-based algorithm is added to “within the roundabout” accidents to generate sufficient internal sideswipe merge and weave accidents and thus conform with American and European accident expectations “within” the roundabout. Roundabout left turns travel 2x further than right turn movements and are thus assumed exposed to more frontal angle or sideswipe events by a factor of 6 from calibration, and similarly for through and right turn movements.
12. Calculation of roundabout delay follows the HCM 2000 procedure except that all critical gaps use only the HCM lower bound of 4.6 seconds and because the flow is uninterrupted, each critical gap is a mutually exclusive decision for each driver and thus there can be no follow-up gap.
13. In calculating roundabout approach and intersection Level of Service, calculations are identical with 1997 HCM All-Way-Stop procedures except that 5 seconds is added to convert stopped delay to control delay, and the 2000 HCM LOS Criteria are used for each approach with volume-weighted averaging to achieve the intersection LOS, thus conforming with HCM procedures for other intersection types.
14. For roundabout fixed object/single vehicle accidents, the accident rate for a roundabout is approximately ½ that of a traditional intersection given the low operating speed while the percentage of accidents which are fixed object/single vehicle are assumed as 20% compared to about 10% for traditional stop control intersections.

Note that the violation of any one or more of the above assumptions should generally lead to an increase in annual accident and injury predictions, and thus the estimates of annual accidents and involvements with a conflict opportunity algorithm should generally produce conservative annual estimates.

General Intersection and Roundabout Annual Accident Prediction Validation

A. Signalized Intersections - Figures 1-5 present a comparison of the total annual average crash accident history and conflict opportunity predictions at each of 100 randomly selected signalized intersections. The 100 intersections were from a pool of over 1200 signalized intersections within one major urban area in Virginia. This comparison indicates that in general conflict opportunity technology provides a prediction with an approximate 15 percent error from the 3-year historical accident average. It may be noted that if certain of the data points were determined as hazardous and removed from the data as “outliers”, the accuracy of the average predictions would increase. In comparison to the historical standard deviation at each site, more than 80 percent of the predictions are within 1 standard deviation of the of the 3-year historical mean, with more than 50 percent within 1/2 standard deviation, and only 8 predictions beyond 3 standard deviations indicating the possibility that the accident prediction for approximately 8 sites may be significantly different from their historical mean or that these may be hazardous sites in terms of accident quantity.

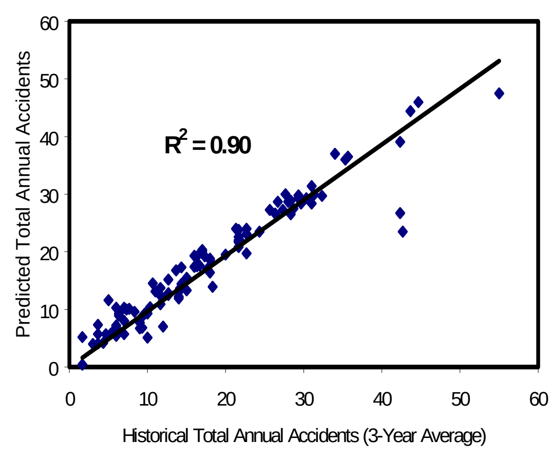

FIGURE 1 Accuracy of Signalized <u>Total</u> Annual Crash Predictions vs Accident Record

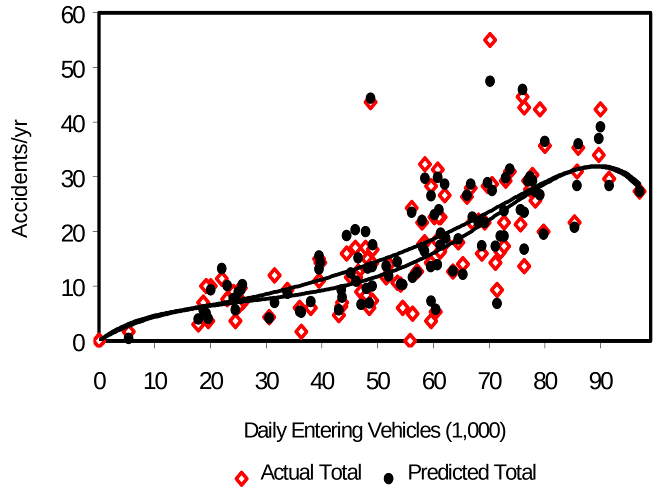

FIGURE 2 Comparison of Signalized Total Annual Crash Prediction vs Accident Record

Often comparisons of actual to predicted annual accidents only compare total accidents, and if a true comparison is to be made, all of the major contributing predictions should also provide good accuracy performance within each of the individual major crash types including angle, rear-end, sideswipe, and single-vehicle/fixed-object accidents. To augment the above accuracy, the results of each of these comparisons are included in the following:

1. Angle Accident Accuracy – Given a 5-year accident history (to more clearly capture the rare-event nature of each crash type), Figure 3 presents a comparison of predicted versus actual angle accidents that indicate a close correspondence with an approximate 75 percent accuracy. In this comparison, over 65 percent of the predictions are within 1 standard deviation of the historical mean and a plot of the actual and predicted angle accidents and regression (cubic) models in Figure 4 indicate the regressions track one another closely providing a visual comparison of how well the conflict opportunity technology operates over the over the range of traffic volumes. Of course such visual comparison of comparable regression models indicate only an average trend and do not speak to the variance of the data which developed each model, and thus caution is required in drawing performance conclusions, but the close proximity of many actual and predicted data points (at the same volume) can be seen clearly in Figures 4 and 6 and to a lesser extent in Figures 8 and 9 which provide strong evidence that prediction and recorded annual crash events are close to one another.

2. Rear-End Accident Accuracy - Given a 5-year accident history for rear-end accidents, a comparison of historical and predicted accidents is presented in Figure 5 and again indicate a close correspondence between actual and predicted rear-end events with an accuracy of approximately 78 percent. Over 80 percent of the predictions are within 1 standard deviation of the historical mean and using identical linear (cubic) regression models of the predicted and actual data, a visual comparison in Figure 6 indicates how closely the rear-end accident predictions and regression model track the historical data and model, and again how well conflict opportunity technology predict rear-end accident events. Of interest in comparing Total Accidents in Figure 2 to Figure 4 and 6 is that the high accident sites of Figure 2 appear to be caused by high angle accidents as opposed to high rear-end accident events. This capability of conflict opportunity prediction technology to identify the cause of inordinate accident occurrences at a specific site is a significant contributor to understanding the causes of existing accidents and to predicting safety defects in the design of new intersections.

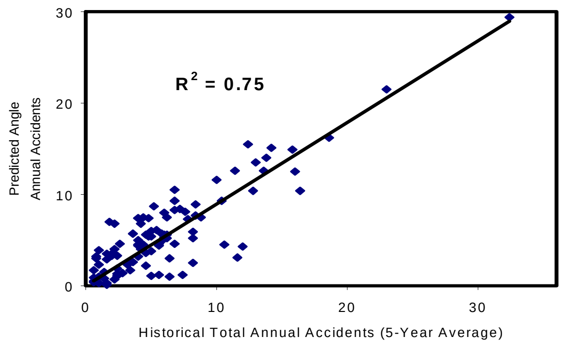

Figure 3 Accuracy of Signalized <u>Angle</u> Annual Crash Prediction vs Accident Record

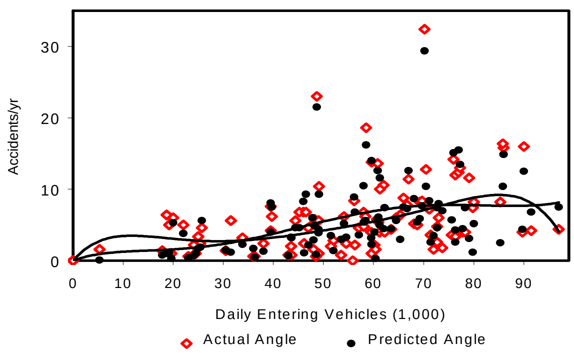

Figure 4 Comparison of Signalized <u>Angle</u> Annual Crash Prediction vs Accident Record

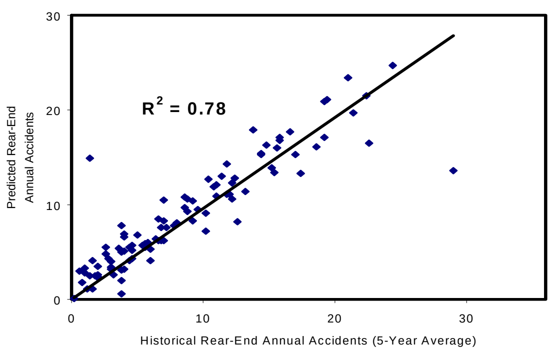

Figure 5 Accuracy of Signalized <u>Rear-End</u> Annual Crash Prediction vs Accident Record

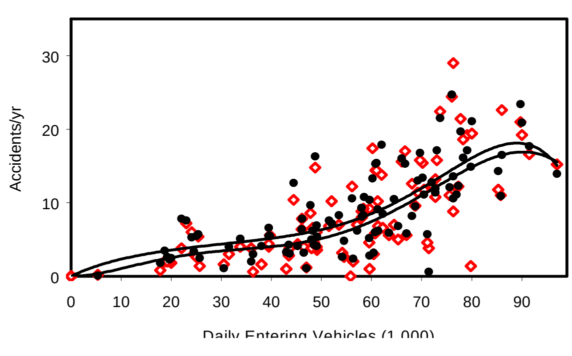

Figure 6 Comparison of Signalized <u>Rear-End</u> Annual Crash Prediction vs Accident Record

3. Sideswipe Accident Accuracy - Similarly, a comparison of historical and predicted sideswipe accidents is presented in Figure 7 and indicates a relatively close correspondence considering the small size of sideswipe accident events (generally less than 5 accidents in 5 years at each site). Although the accuracy is lower than angle and rear-end correlation coefficient (R^2) comparisons, approximately 50 percent of the predictions are within 1 standard deviation of the historical mean with the visual comparison of predicted and actual regression models in Figure 8 indicating how closely the sideswipe predictions and regression model track the historical data and regression model over the range of volumes. Future improvements to this rare-event conflict opportunity model should can provide an improved accuracy.

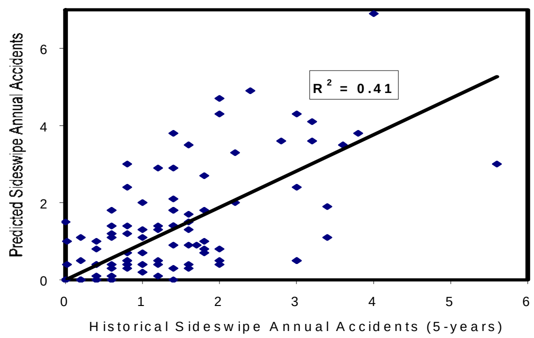

Figure 7 Accuracy of Signalized <u>Sideswipe</u> Annual Crash Prediction vs Accident Record

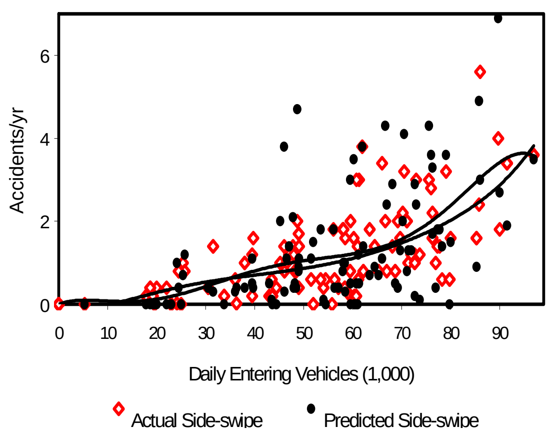

Figure 8 Comparison of <u>Sideswipe</u> Annual Crash Prediction vs Accident Record

4. Fixed-object/single-vehicle accident accuracy – These are the least numerous of reported crash events in comparison to the above and as presented in Figure 9, offer a slightly weaker correspondence between actual and predicted events because an exposure-based (speed, volume variables only) as opposed to conflict opportunity-based models are used to predict these events. While the conflict opportunity technology was originally designed to accommodate fixed object/single vehicle/other prediction, collection of extensive fixed-object data was found to be very time and cost-intensive for the marginal loss of accuracy compared to the use of a simple exposure model that required little data collection. This approach provides a reasonable accuracy for these type of crash predictions with approximately 65 percent of the predictions within 1 standard deviation of the historical mean (accuracy figure omitted for brevity) and a visual comparison of predicted and actual models in Figure 9 indicate the predictions track the historical data reasonably well over the range of volumes.

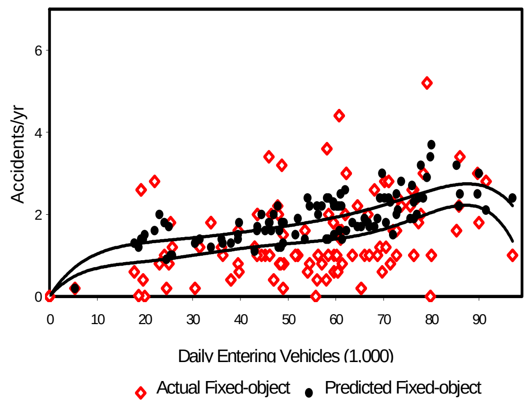

Figure 9 Comparison of <u>Fixed Object or Single Vehicle</u> Annual Crash Models

<u>B. Unsignalized Two-Way Stop Intersection Crash Prediction Validation</u> -
Although predicting signalized intersection accidents is complex with the myriad of timing and phasing options required throughout the day, in predicting annual accidents at unsignalized intersections this complexity changes in context. Often at signalized intersections, sufficient accident samples exist to estimate actual historical accidents, but at stop-controlled intersections, traffic volumes entering from the sidestreet are often very small in comparison to the mainline volume with a resulting accident history that is almost always less than 5 per year and generally less than 2-3 per year. Obviously this is why these intersections remain unsignalized and why this lack of reliable data causes unsignalized intersection accident events to be considered "rare". Predicting rare-events is challenging and thus there should be little expectation that accident prediction capability will surpass that of signalized intersections. However with this understanding, 65 unsignalized two-way stop controlled intersections were selected for validation to the conflict opportunity software with all site selections and data provided by the Florida DOT and their traffic engineers.(23) As with the signalized intersections, these intersections were composed of a wide variety of cross-sections and geometry, volumes, and speeds almost all with generally flat terrain.

The results of this analysis are presented in Figure 10 and indicate as expected that the number of annual accidents are generally below 2-3 per year, but with several sites where the actual history reached 5 accidents per year and in one case (not displayed) 6 per year. Using software to balance the turning movements on a daily basis ("Turns") along with a 5-year accident history to accommodate the need for greater data for "rare event" analysis (as opposed to a preferred 3-year history with volume data from the middle-year), a comparison of historical and predicted total accidents in Figure 10 indicate a good correspondence between actual and predicted events with over 70 percent of the predictions within 1 standard deviation of the historical average accident history. As with signalized intersections, using identical linear regression models of the predicted and actual data, a visual comparison indicates the conflict opportunity predictions closely track the regression model of the on-site actual accidents.

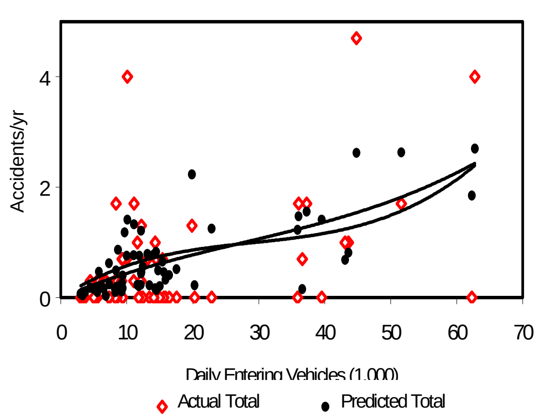

Figure 10 Comparison of <u>Un-Signalized, Two-Way Stop Total</u> Annual Crash Models

C. Roundabout Crash Prediction Validation

With respect to roundabout intersections, Table 1 presents some of the most recent average accident and injury accident data for 13 roundabouts constructed by the Maryland DOT.(24) While 3 of the 13 roundabouts may be characterized as traffic circles because their volume is less than approximately 7,000 ADT, the remaining 11 appear as typical roundabouts with geometric characteristics that reflect increasing ADT's for primarily single lane roundabouts but with 2 samples that also reflect dual lane roundabouts to over 50,000 ADT. Of note is that all of the single lane roundabouts replaced two-way stop control intersections and rather than using actual site turning movement which were not available, Am and Pm turning volumes were estimated using volume balanced (right turn=returning left turn) flows, assuming a linear relationship between major and minor ADT's, and %lefts and %rights on the minor flow are linear with increasing minor flow both of which models were developed from a sample of 50 stop controlled (3 and 4 leg) intersections, and also assuming a directional flow of 0.58 and generally an Am K-factor = 0.09 and Pm = 0.10 which are proportioned throughout the day to generate the entering peak volumes and ADT reported for each site. In general, these turning movement models for TWSC appeared more reliable than actual site turning movement data for relatively low-volume intersections given the variability of entering flows over the week and months of the year. Both dual lane roundabouts replaced signalized intersections and for these a 60/40 split was assumed for major/minor ADT's, with a directional flow of 0.50 and 20% left and 10% right turns on the minor approaches which are balanced with major turning movements, and similar K-factors proportioned throughout the day to generate the entering peak volumes and ADT reported for each site.

In drawing a conclusion from Table 1, it must be recognized that as with two-way stop accident models, any event with a very small probability of occurrence is a rare event, and since actual historical records of crash and injury events do not necessarily relate "cause to effect" where the cause of the crash (eg: sideswipe aversion) may be unrelated to the outcome crash event (ran-off-the-road or rear-end), it becomes important in rare event analysis to use predicted as opposed to actual data to examine any potential relationships. For this reason the predicted average accident and injury crashes per year are presented in Table 1 using the average accident rate of 0.48/mev for annual accidents and 0.11/mev for injury accidents as reported by MDOT for single lane roundabouts.

Table 1

Accident Validation for Roundabout Intersections (stratified by increasing predicted injury)

Site #	Daily Entering Volume (1,000)	Inscribed Diameter/ Central Island (approximate)	Assumed Operating speed (mph)	Estimated Average Crashes/yr Using MDOT Exposure Rate(29)	Forecast Conflict Opportunity Crashes/yr	Estimated Average Injury Crashes/yr Using MDOT Exposure Rate(29)	Forecast Conflict Opportunity Injury Crashes/yr
1	5	110/30	15	0.88	0.6	0.20	0.14
2	6.3	100/40	15	1.58	1.0	0.36	0.24
3	8.1	110/54	20	0.79	1.2	0.18	0.31
4	8.3	100/40	20	1.78	1.2	0.41	0.31
5	7.1	120/60	20	1.34	1.2	0.31	0.33
6	8.0	120/64	20	1.40	1.4	0.32	0.39
7	9.4	130/64	20	1.78	1.4	0.41	0.41
8	12.0	125/61	20	2.30	2.5	0.53	0.76
9	13.5	150/66	20	2.64	2.5	0.61	0.76
10	14.0	110/30	20	2.45	2.6	0.56	0.76
11	15.0	120/60	20	3.12	3.1	0.72	0.96
			Average=	**2.13**	**1.90**	**0.48**	**0.54**
12[a]	24.0	178/114	20	5.28	4.0	0.84	1.37
13[a]	52.0	200/123	20	11.53	11.9	1.84	4.39

a. Dual lane Roundabouts, all others are single lane.

From Table 1, it may be noted that the typical single lane roundabout for this data has approximately 11,000 ADT and generates estimate 2.1 (exposure-based) or 1.9 (conflict-based) predicted accidents and an average of 0.48 (exposure-based) or 0.54 (conflict-based) injury accidents per year both of which agree with the expectation of 2.4 accidents and 0.50 injury accidents reported by other research.(30) In addition, the average injury accident/roundabout of 0.48 from MDOT or 0.54 from conflict opportunity estimates compare relatively well to

Australian estimates of 0.60/roundabout but poorly to France with 0.15 and UK with 3.31 injury accidents/roundabout, suggesting that Australian experience with roundabouts may be more representative of anticipated US experience.(25) Similarly from Table 1 dual lane roundabouts, both sites reflect that increasing entering ADT results in increasing accidents and injury accidents with the annual accident expectation for a large roundabout of 15.3 accidents/yr which compares well with the actual experience of 16.5, while both the exposure estimate of 11.5 and conflict opportunity estimate of 11.9 reflect an expectation for less accidents.(25) However the annual dual lane injury accident expectation of 4.0 (FHWA) is not reflected in the actual experience of 1.5 injury accidents/year but is reflected in the conflict opportunity estimate of 4.39/yr.(25)

In general, the above signal, two-way stop and roundabout validations provided good fidelity to historical accident records and were superior to the best statistically formulated annual accident exposure or “rate-based” regression models created from the original accident because the software through it’s finite-element construction eliminates statistical “outliers” (non-responsive and irregular data points which become critical elements in “rare-event” regression modeling, and because the software has a wide variety of data input which permits development of a “Response Envelope” compared to simplistic exposure-based or linear regression models. Most importantly, the software unlike normal regression requires no prior knowledge of actual site accidents, nor any “spilled-blood” to create annual accident forecasts.

<u>Example Optimal Roundabout/Intersection Performance Selection</u>

To test the potential usefulness of the conflict opportunity algorithms for selecting an optimal traffic control strategy for an intersection, the software was used to estimate annual conflict opportunities, delay, annual value and the combined Safety+Delay value (or Performance Index) for a new development intersection in Northern Virginia. The proposed intersection selected for this analysis was opposite the new Dulles Air & Space Museum with Am and Pm entering volumes as presented in Table 2. (26)

Table 2. Projected Hourly Traffic Volumes – 2026 Dulles Discovery Rezoning Development

Hour	EB			NB			WB			SB			TOTALS
	Lt	Thru	Rt	Lt	Thru	Rt	Lt	Thru	Rt	Lt	Thru	Rt	
1 AM	0	5	0	0	1	38	14	2	2	2	1	0	65
2	0	1	0	0	2	25	8	3	0	4	2	0	45
3	0	1	0	0	1	16	6	2	0	2	1	0	31
4	0	1	0	0	1	20	9	4	0	3	1	0	39
5	0	2	0	0	1	35	19	7	0	5	1	0	71
6	0	7	0	0	1	135	84	32	3	20	5	0	288
7	0	19	0	2	3	311	227	87	8	47	12	0	716
8	0	35	1	33	4	494	418	161	15	74	19	0	1224
9	0	24	0	2	3	390	283	109	10	58	15	0	895
10	0	16	0	2	2	307	192	74	7	46	12	0	659
11	0	11	0	1	2	244	131	50	5	36	9	0	490
12	0	11	0	2	2	278	128	49	5	42	11	0	527
1 PM	0	73	1	0	15	435	214	23	28	28	7	0	825
2	0	83	2	0	15	431	246	27	33	27	7	0	871
3	0	90	22	0	14	399	266	29	35	25	7	0	886
4	0	118	2	0	16	451	348	37	46	29	7	0	1054
5	0	152	3	0	17	498	448	48	59	32	7	0	1265
6	0	195	4	0	19	551	576	62	76	35	8	0	1528
7	0	138	3	0	16	455	409	44	54	29	9	0	1154
8	0	79	2	0	10	303	234	25	31	19	7	0	709
9	0	47	1	1	7	209	139	15	18	13	5	0	454
10	0	34	0	0	6	176	101	11	13	11	3	0	356
11	0	20	0	0	4	118	58	6	8	8	3	0	224
12	0	10	0	0	2	68	29	3	4	4	2	0	121
Totals	**0**	**1171**	**21**	**13**	**185**	**8388**	**4590**	**912**	**459**	**600**	**156**	**0**	**14,476**

The geometric condition for proposed Two-way and All-way stop and signal control on all approaches included a single protected left turn bay, a single through lane and a single protected right turn bay with protected/permitted left turn phasing for signal control and timing calculated with Hcm/ICU procedures. Approach speeds were assumed as 35 mph for signal control and 25 mph for Two and All-way stop control. Using appropriate input data to the conflict opportunity algorithm, Table 3 presents a comparison of estimated Am and Pm delays with a comparison to another HCM-based software.

Table 3 Comparison of Alternative Delay Estimators

	Traditional HCM-based Delay Estimates					**Conflict Opportunity Software Delay Estimates**				
Control Type / Time	EB	NB	WB	SB	**Total Delay**	EB	NB	WB	SB	**Total Delay**
TWSC AM	1.5	9.7	3.1	39.3	**8.1**	10.0	0.0 [1]	7.1	50.9	**6.3**
TWSC PM	1.9	27.4	5.8	82.8	**14.9**	10.0	0.0 [1]	7.8	116	**6.7**
AWSC AM	8.8	7.4	8.2	8.1	**7.8**	6.3	600 [2]	16.6	6.9	**254**
AWSC PM	8.1	10.6	13.0	6.4	**11.2**	8.0	600 [2]	19.5	6.4	**234**
Signal AM	10.4	5.7	7.4	28.7	**8.9**	17.6 [3]	14.4	9.1	11.9	**11.9**
Signal PM	11.3	7.2	5.6	50.9	**8.8**	20.9 [3]	21.1	8.2	12.5	**15.0**
Roundabout AM	12.3 [4]	7.3	10.2	14.9	**9.5**	11.9 [5]	20.0	22.8	13.3	**20.6**
Roundabout PM	14.3 [4]	8.4	10.3	15.3	**10.3**	16.4 [5]	32.8	39.8	12.8	**33.4**

1. Delay does not accumulate to a free flow right turn bay
2. Excessive Right turn delay requires an automatic maximum of 10 minutes delay assigned each vehicle.
3. Uses conservative cycle selection/timing from NCHRP and ITE recommendations compared to HCM.
4. From a commercially available Roundabout Software
5. HCM 2000 Roundabout procedures with conservative assumption of lower bound gap.

When comparing the approach results of Table 3, it may be seen that each of traditional HCM delay-based algorithm responses (at the approach level) are within a reasonable range of the delay responses of the Conflict Opportunity software and certainly within the ± 30 percent error range of any HCM delay based estimate when comparing HCM estimates to actual field collected delay data. Thus it appears that the delay-based estimates of the conflict opportunity software (which are also used to predict accident probabilities) are as reasonable as any of the other commercially available delay estimators.

Recognizing the annual accident estimation validation provided above for TWSC, AWSC, signalized intersections and roundabouts and conformance of the above delay estimators, Table 4 presents a summary of annual accident and injury estimates along with a safety+delay value estimate (the Performance Index) for each of the potential traffic control types, as well as a Safety Level of Service indicator for the respective traffic control type based upon the research of Ossenbruggen.(27,28)

In summary, a review of the AM and PM delay estimates from Table 3 indicate that with exception to All-way Stop control (which must accommodate over 400 and 575 vph respectively turning left and which a common software doubtfully indicates can be accommodated at LOS “A”), all of the remaining signal, TWSC and roundabout options appear acceptable in both AM and PM peak periods from a delay perspective. Given this acceptability, the safety performance of the remaining alternates from Table 4 indicates that while a two-way stop control may provide the “safest” performance, that performance is within an acceptable margin of lifetime injury-based safety performance and thus any of the remaining options (signal, two-way stop or single lane roundabout) are acceptable options and are expected to provide acceptable service during their 20 year lifetime of performance. However, given the total entering volume, it may be questionable whether a traffic signal and the ancillary annual maintenance and operations cost will be warranted, thus the options of practical significance appear as a two-way stop or a roundabout and in this particular instance, the developer elected to use a roundabout to also help control the amount of residential cut-through traffic in the proposed development.

Table 4 Comparison of Alternative Safety Traffic Control Strategies using Conflict Opportunities

Traffic Control Type (14,475 ADT/2026)	**TWSC**	**AWSC**	**Signal**	**Single Lane Roundabout**
Approach Speeds (mph)	25/25	25/25	35/35	20/20
Laneage (Historic Sully)	1L+1TH+1R	1L+1TH+1R	1&1L(Prot)+1TH+1R	100InsD/70CiD
Laneage (Turley Hall)	1L+1TH+1R	1L+1TH+1R	1&1L(Prot)+1TH+1R	35 Entry/Exit Radii
			May not Warrant	
Total Accidents/yr	0.5	1.5	1.4	2.4
Total Injury Accidents/yr	0.12	0.15	0.42	0.65
Lifetime Serious Injury Risk Based Safety Level of Service (SLOS)[1]	Acceptable Safety **SLOS=B**	Acceptable Safety **SLOS=B**	Acceptable Safety **SLOS=A**	Acceptable Safety **SLOS=B**
Serious Injury Accidents/5-yrs[1]	0.01	0.0.01	0.04	0.03
Safety+Delay Performance Index[2]	**58**	**741**	**94**	**133**

1. See Reference 24
2. Values are stable over all scenarios at $3.75/hr for delay, $6400 property damage accident and $50,000/ injury or fatal accident.

Conclusions

Using a disaggregate or finite-element, microscopic conflict-opportunity analysis to define the accident potential of an existing or proposed intersection, the application of theoretical angle, rear-end and sideswipe conflict opportunity statistical models and an exposure-based fixed object/single vehicle model offers a unique algorithm and approach to the identification of relative effectiveness between alternative safety treatments. Validation of software developed to replicate this algorithm indicate that for a random sample of 100 signalized intersections, total annual accidents can be predicted within approximately 20 percent of the 3-year historical average (an accuracy of approximately 80 percent). More importantly and unlike any prior accident prediction model, this accuracy is developed from internal validations that predict the most common angle and rear-end events with over 70 percent accuracy compared to the 3-year historical record. And while the signalized data is from only one state, the significance of this accuracy lends credibility that this approach may be easily transferred across jurisdictions and state boundaries with little need for correction. And while total accident predictions at unsignalized two-way stop control intersections and roundabout are more complex rare-events and thus expected to be less accurate, validation to 100 two-way stop intersections provided an almost 70 percent accuracy while roundabout accident comparison to Maryland DOT accident histories also indicated accuracies in excess of 70 percent for single lane roundabouts.

A real-world example of optimal traffic control selection was also performed to compare the delay, safety and delay+safety value of Two-way stop and All-way stop control, protected/permissive signal control, and roundabout control. This analysis found that All-way stop control would generate excessive delay but that all of the remaining alternatives (signal, Two-way stop and roundabout) would provide acceptable safety performance although there were differences in estimated annual accidents, injury accidents and their safety+delay annual performance. And given that a signal may not warrant due to the low ADT and the annual maintenance and operations costs, the developer elected to use a single lane roundabout to minimize cut-through arterial traffic in the development. .

As a decision support tool, the conflict opportunity algorithms and software require little additional data beyond that already required for Am and Pm HCM analysis (speeds and ADT), and given the very strong 70-80 percent validations to existing accident data regardless of the traffic control type, it appears clear that this technology can generate realistic estimates of safety and delay and provide for both planners and engineers the ability to document their proposed planning and design treatments and weigh them appropriately against delay and safety elements to aid in their judgments of how to protect both the safety, economy, and overall welfare.

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