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Calibration of Predictive Models for Estimating the Safety of Ramp Design Configurations

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Abstract

The goal of the calibration process is to use predictive models developed with data collected from other jurisdictions and apply them to the jurisdiction of interest by adapting the models for local conditions and characteristics specific to this jurisdiction. Given the large costs associated with data collection, this process is often the only method available to transportation agencies for estimating the safety of different transportation facilities. Thus, recalibrating models produced from other jurisdictions allows agencies to produce their own models at relatively low costs.

The objective of the research was to recalibrate a set of crash prediction models for different ramp design configurations. The ramp design configurations addressed in this study included diagonal ramps, non-free-flow loop ramps, free-flow loop ramps, and outer connection ramps. A total of 44 ramps located in and around Austin, Texas were used in the calibration process. The results of the study have shown that more crashes occur on exit ramps than entrance ramps by a ratio of about 6 to 4. The results have also shown that the non-free-flow ramp experiences twice as many crashes as other types of ramp. Similarly, more crashes occur on rural than urban ramps.

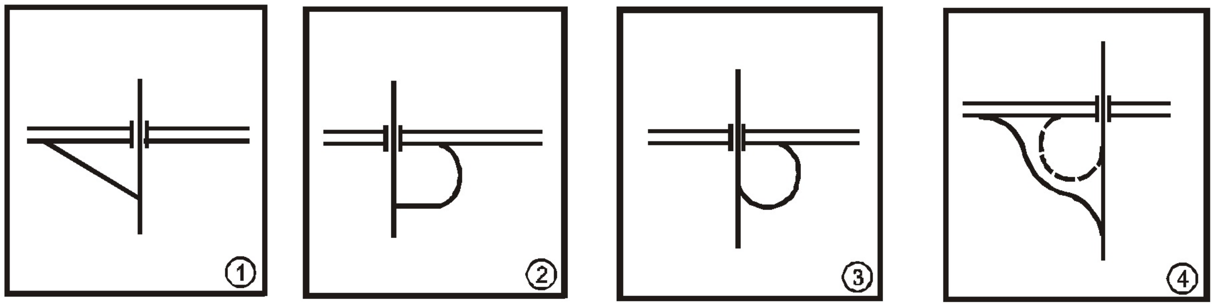
INTRODUCTION

The goal of the calibration process is to use predictive models developed with data collected from other jurisdictions and apply them to the jurisdiction of interest by adapting the models for local conditions and characteristics specific to this jurisdiction. Given the large costs associated with data collection, this process is often the only method available to transportation agencies for estimating the safety of different transportation facilities. Thus, recalibrating models produced from other jurisdictions allow agencies to produce their own models at a relatively low costs. The accuracy of the calibration process is obviously dependent on the accuracy of the prediction provided by these models.

The importance of predictive models in safety analysis makes it imperative that they be properly calibrated. Calibrating such models is however not an easy task. As reported by Persaud et al. (*1*), there are some important issues with calibrating predictive models. First, high quality data are required for large enough sample of entities and crashes, and there needs to be a method to easily link road characteristics, crashes and traffic flow databases together. Ramp-related crashes are relatively infrequent; thus, many years of data are required to build a database good enough for developing adequate statistical models. Hence, the only cost-effective solution is to recalibrate existing predictive models. Second, the actual process of model calibration is complicated by the fact that crash counts are integer and nonnegative, thus conventional regression based models using normal error distribution cannot be used.

This paper documents the steps taken to recalibrate safety prediction models for estimating the safety of four alternative ramp design configurations: diagonal ramps, non-free-flow loop ramps, free-flow loop ramps, and outer connection ramps (see Figure 1). The procedures presented in this work are consistent with those used by other researchers to calibrate safety prediction models for intersections (*1*, *2*). In general, a safety prediction model relates the annual crash experience of a facility to its traffic flow, traffic control, and design-related characteristics. It has several uses in safety analysis, including: (1) identifying facilities that may benefit from one or more safety improvements, and (2) providing numerical tools for evaluating alternative design configurations, especially when they are used to identify cost-effective interchange design alternatives

The paper is divided into five sections. The first section summarizes previous research performed on the transferability and calibration of predictive models. The second section describes the characteristics of existing predictive models used for estimating the safety of different ramp design configurations. The third section summarizes the steps taken for collecting the data and describes the results of the preliminary crash data analysis. The fourth section describes how the calibration process was carried out. The last section covers the results of the sensitivity analysis preformed on the recalibrated models.



a. Diagonal. b. Non-Free-Flow Loop. c. Free-Flow Loop. d. Outer Connection.

Figure 1. Basic Ramp Configurations at Non-Frontage-Road Interchanges. (*3*)

PREVIOUS WORK

Ideally, robust safety prediction models (such as those developed by Bauer and Harwood (*3*) and Harwood *et al.* (*4*)) would be developed for every state and local jurisdiction responsible for the design and operation of highway facilities. Such models would accurately account for differences in crash causation among jurisdictions (e.g., due to differences in terrain, design practices, climate, trip purpose, or crash reporting threshold). However, the cost of developing these models would be prohibitive, primarily because of the effort required to assemble the database needed for model development. In recognition of this practical limitation, the robust models that have been developed through well-funded national research are typically extended to local conditions by carefully calibrating the model using local data.

The calibration process, as described by Harwood *et al.* (*4*), is based on the following three assumptions: (1) the functional form of the robust model accurately reflects local conditions; (2) the calibration coefficients in the robust model accurately reflect the trendwise relationships between model variables and crash frequency (although there may be some bias relative to local conditions); and (3) a single, multiplicative calibration factor can be used to eliminate the aforementioned bias by uniformly increasing (or decreasing) the crash frequency estimate obtained from the robust model.

Recent work on recalibrated predictive models has focused on the validation of the calibration process. As an example, Persaud et al. (*1*) noted that the calibration process should be evaluated using a combination of different statistical techniques. Among the suggested techniques, they proposed the Cumulative Residual (CURE) method, as initially developed by Hauer and Bamfo (*5*), the R_α^2 or the dispersion parameter-based R^2, the value of the overdispersion parameter α (or its inverse $1 / \phi$) for a Poisson-Gamma model, the t-test and the root-mean-square error (RMSE).

Oh et al. (*6*) proposed a dual validation approach which dictates that a model should be validated internally and externally. The tools used for validating the calibration process externally include the Pearson product moment of correlation, mean-prediction-bias (MPB), the mean-absolute-deviation (MAD), and the mean-squared-prediction error (MPSE). The internal validation consists of assessing potential biases introduced in the original predictive models used in the calibration process. The goal is to assess the quality of the data utilized in the original development of the models, potential omitted variables, and regression-to-the-mean bias. This work did not examine the internal validity of the predictive models, since the original data were not available to the research team.

SAFETY PREDICTION MODELS

The only safety prediction models specific to ramp type and configuration found in the literature are those developed by Bauer and Harwood (3). Bahar et al. (7) also proposed predictive models, but they aggregated ramp design configurations that were not suitable for this work. The models proposed by Bauer and Harwood (3) were developed with data collected from the State of Washington for the years 1993 to 1995. Two types of safety prediction model were developed. The first type predicts crashes of all severities (i.e., property damage only, injury, and fatality). The functional form of this model is:

$$N_t = 0.247\ C_t\, f_t \left(\frac{V_r}{1000}\right)^{0.76} \quad \textbf{(1)}$$

where:

N_t = predicted annual number of crashes (of all severities), crashes/yr;
f_t = crash adjustment factor for area type, ramp type, and ramp configuration (see Table 1);
C_t = calibration factor for local conditions; and
V_r = average daily traffic on the ramp, veh/d.

The subscript *t* associated with each model variable denotes that the variable represents crashes of all severities (including property-damage-only, injury, and fatal crashes). The standard deviation of the predicted annual number of crashes can be estimated using equation (2):

$$s_{Nt} = \frac{N_t}{\sqrt{\phi_t}} \quad \textbf{(2)}$$

where:

$s_{N\,t}$ = standard deviation of the predicted annual number of crashes (of all severities), crashes/yr;
ϕ_t = dispersion parameter for crashes of all severities (= 0.95).

The second model type predicts the number of fatal and injury crashes. The functional form of this model is:

$$N_{f+i} = 0.0957\ C_{f+i}\ f_{f+i} \left(\frac{V_r}{1000} \right)^{0.85} \quad \textbf{(3)}$$

where:

N_{f+i} = predicted annual number of fatal and injury crashes, crashes/yr;
f_{f+i} = crash adjustment factor for area type, ramp type, and ramp configuration (see Table 1);
C_{f+i} = calibration factor for local conditions; and
V_r = average daily traffic on the ramp, veh/d.

The subscript $f+i$ associated with each model variable denotes that the variable represents injury and fatal crashes (i.e., property-damage-only crashes are *not* included). The standard deviation of the predicted number of fatal and injury crashes can be estimated as:

$$s_{Nf+i} = \frac{N_{f+i}}{\sqrt{\phi_{f+i}}} \quad \textbf{(4)}$$

where:

s_{Nf+i} = standard deviation of the predicted annual number of fatal and injury crashes, crashes/yr;
ϕ_{f+i} = dispersion parameter for fatal and injury crashes (= 0.70).

The adjustment factors f_t and f_{f+i} in equations (1) and (3), respectively, are used to adapt the model to alternative combinations of area type, ramp type, and ramp configuration. The regression analysis reported by Bauer and Harwood (3) indicate that the factors listed in Table 1 are appropriate for this purpose. For crashes of all severities, the factors vary from 0.38 to 2.48, depending on the combination of attributes associated with a specific ramp. The range is slightly larger for the fatal-plus-injury crashes. Both ranges are relatively wide and suggest that ramp configuration design decisions can have a significant impact on safety.

Table 1. Crash Adjustment Factors.

Area Type: Rural				Area Type: Urban			
Ramp Type	Ramp Configuration	Adjustment Factor		Ramp Type	Ramp Configuration	Adjustment Factor	
		f_t	f_{f+i}			f_t	f_{f+i}
Exit	Diagonal	1.00	1.00	Exit	Diagonal	1.42	1.40
	Non-free-flow loop	1.75	1.97		Non-free-flow loop	2.48	2.77
	Free-flow loop	0.63	0.59		Free-flow loop	0.89	0.83
	Outer connection	1.31	1.30		Outer connection	1.86	1.82
Entrance	Diagonal	0.61	0.58	Entrance	Diagonal	0.86	0.81
	Non-free-flow loop	1.06	1.14		Non-free-flow loop	1.51	1.60
	Free-flow loop	0.38	0.34		Free-flow loop	0.54	0.48
	Outer connection	0.79	0.75		Outer connection	1.13	1.05

The adjustment factors C_t and C_{f+i} in equations (1) and (3), respectively, are used to adapt the model to local conditions. The procedure used to determine their value for use in Texas is described in subsequent sections of this document.

DATA COLLECTION AND EXPLORATORY ANALYSIS

The composition of the database in this work was dictated by the variables included in the safety prediction models to be calibrated (i.e., equations 1 and 3). Collectively, these variables describe the crash characteristics of each ramp as well as its geometric, environmental, and traffic characteristics. The variables collected to calibrate equations (1) and (3) are listed in Table 2.

Table 2. Safety Database Composition.

Category	Variable	Variable Values	Source
Crash	Severity	Property damage only, injury, fatality	DPS[1]
	Crash type	Ran-off-road, rear-end, sideswipe	
	Relationship	Associated with ramp (excl. speed-change lanes and ramp terminal)	
Ramp Geometry	Type	Exit, entrance	Aerial photos
	Configuration	Diagonal, non-free-flow loop, free-flow loop, outer connection	
Environment	Area type	Rural, urban	
Traffic	Ramp AADT	Vehicles	Field survey

Notes:
1 - DPS = Department of Public Safety (in Texas)

Data representing each variable were collected for 44 ramps at 10 interchanges in Travis County near Austin, Texas. Each ramp had to be located at an interchange without frontage roads. Aerial photographs of each interchange were obtained and used to identify the ramp configuration and area type. Table 3 summarizes the characteristics of the selected ramp design configurations. Note that a "site" in this work is defined as one interchange ramp.

Table 3. Candidate Study Sites.

No.	Location	Terminal Control	Area Type	No. of Sites for Each Ramp Configuration[1]			
				Diagonal	NFF Loop	FF Loop	Outer
1	US 290 & SH 21	TWSC	Rural	4	0	0	0
2	US 183 & SH 21	TWSC	Rural	4	0	0	0
3	SH 21 & US 77	TWSC	Rural	4	0	0	0
4	US 183 & SH 71	Free	Rural	0	0	3	4
5	US 79 & B79	TWSC	Rural	0	0	2	2
6	LP 360 & RM 2222	Signal	Urban	4	0	0	0
7	US 183 & FM 969	Signal	Urban	4	0	0	0
8	SH 1 & Windsor	Signal	Urban	1	2	0	0
9	SH 1 & 35th Street	Sig./TWSC	Urban	1	1	2	2
10	LP 360 & RM 2244	Signal	Urban	4	0	0	0
				26	3	7	8

Notes:
1 - NFF Loop: non-free-flow loop; FF Loop: free-flow loop.
2 - A "site" is one interchange ramp.

Crash data were extracted from printed peace officer crash reports that occurred in the vicinity of the interchange. A crash was defined to be in the "vicinity" of the interchange when it occurred on the major road within at least ±1000 ft of the interchange center or when it occurred on the minor road within at least ±500 ft of the interchange center; the interchange center is located where the minor road crosses the major road. Given some issues related to the accuracy of the crash location, a "box" had to be created to capture all potential crashes occurring within the vicinity of the interchange. The reports were obtained from the Texas Department of Public Safety (DPS). Crashes for three years (1998 to 2000) were obtained to ensure an adequate sample size. Once the reports were obtain, each report was verified manually to determine whether crash occurred on a ramp. Crashes occurring on the speed-change lane or at the intersection located at the end of the ramp were not included in this analysis; note that Bauer and Harwood (*3*) have models that include crashes occurring on speed-lane changes and ramp terminals. In the end, from 586 crashes that initially were found in the vicinity of the 10 interchanges, 62 crashes were officially assigned to an entrance or exit ramp. These excluded crashes that occurred at the ramp terminal junction.

As indicated in Table 2, the AADT for each ramp was included in the database. The ramp AADT was estimated using a one-day (i.e., 24-hour) count taken in January or February 2004. The AADT was estimated from the one-day count by adjusting it for day-of-week and month-of-year variations. The day-of-week and month-of-year adjustment factors were obtained from

TxDOT's Transportation Planning and Programming (TPP) Division and were used to adjust the ramp AADT for the year 1999.

Table 4 summarizes the data collected for the calibration process. As indicated in the first row of data, only 43 sites are represented in the database. One site (i.e., the northbound exit ramp at LP 360 and RM 2222) was found to have unusual crash patterns. In particular, this ramp was found to have experienced 24 crashes during the three-year study period. This frequency was about 27 times larger than the average crash frequency of the other 43 sites. Closer examination indicated that the ramp had the following attributes: (1) relatively sharp crest curve, (2) high volume, and (3) a public street intersection just downstream of the crest curve. It is believed that these attributes combine to explain many of the crashes that occurred. This ramp was removed from the database because driveways and intersections are rarely provided on ramps in Texas (in part, because they tend to create safety problems). This was the only ramp study site with an intersection on it.

Table 4. Summary of Crash and Traffic Volume Database.

Category	Statistic [1]	Ramp Type [2]		Ramp Configuration [3]				Area Type		Overall
		Exit	Entrance	Diagonal	NFF Loop	FF Loop	Outer	Rural	Urban	
Total Sites		21	22	25	3	7	8	23	20	43
All Crashes	Min. crashes/3 yr	0	0	0	1	0	0	0	0	0
	Max. crashes/3 yr	5	3	5	3	4	2	4	5	5
	Average crashes/3 yr	1.14	0.64	0.64	2.33	1.29	0.75	0.74	1.05	0.88
	Total crashes/3 yr	24	14	16	7	9	6	17	21	38
	Crash Rate [4], cmv	**0.26**	**0.16**	**0.15**	**0.26**	**0.45**	**0.20**	**0.45**	**0.15**	**0.21**
Fatal & Injury Crashes	Min. crashes/3 yr	0	0	0	1	0	0	0	0	0
	Max. crashes/3 yr	3	2	3	3	1	1	1	3	3
	Average crashes/3 yr	0.67	0.32	0.40	2.00	0.29	0.38	0.30	0.70	0.49
	Total crashes/3 yr	14	7	10	6	2	3	7	14	21
	Crash Rate [4], cmv	**0.15**	**0.08**	**0.10**	**0.22**	**0.10**	**0.10**	**0.18**	**0.10**	**0.12**
1999 Ramp Volume	Minimum, veh/day	250	100	250	5450	100	300	100	2200	100
	Maximum, veh/day	10500	10000	9600	10500	7450	10000	10000	10500	10500
	Average, veh/day	4000	3700	3800	8200	2600	3400	1500	6500	3850

Notes:
1 - Crash data represent site crash history for years 1998, 1999, and 2000.
2 - The length of the ramp is not available.
3 - NFF Loop: non-free-flow loop; FF Loop: free-flow loop.
4 - cmv: crashes per million vehicles.

The crash data in Table 4 indicates that 38 crashes occurred on the set of 43 ramp study sites during the three-year study period. Of these crashes, 21 were associated with a fatality or injury to one or more persons. In other words, 55 percent of the crashes were fatal or injury-related and 45 percent were property-damage-only (PDO) crashes. The latter percentage is smaller than the nationwide average of 58 percent PDO crashes, as derived from Table 28 of *Traffic Safety Facts 2000* (8), and is likely due to the use of a higher crash reporting threshold in the various Texas jurisdictions. A crash in Texas is classified as reportable if the costs are higher than $1,000 or the crash caused an occupant injury. However, depending on resources, local jurisdictions may use a higher threshold. For instance, some jurisdictions require that a vehicle be towed away to be categorized as a reportable crash.

The crash rates shown in Table 4 were computed to determine general trends in the data and to facilitate comparison with previous research. With regard to ramp type, exit ramps are found to have about 62 percent more crashes (= 0.26/0.16 − 1) than entrance ramps, given the same ramp traffic volume. This trend is consistent with that found by Bauer and Harwood (3) and Twomey *et al.* (9). The former researchers reported that exit ramps have 65 percent more crashes whereas the latter group reported 35 percent more crashes.

With regard to ramp configuration, the crash rates indicate that free-flow loop ramps are associated with about twice as many crashes as other ramps. This finding is contrary to that found in the safety relationships reported by Bauer and Harwood (3) and by Twomey *et al.* (9). Both of these groups of researchers found that free-flow loop ramps were associated with the *fewest* crashes. This trend is not apparent in the crash rates for the "fatal and injury" crashes. For this crash category, the *non*-free-flow loop is associated with the highest rate of severe crashes; a trend that is consistent with Bauer and Harwood (3).

Setting aside the free-flow loop ramp, the remaining three ramp categories can be listed in order of decreasing crash rate as: non-free-flow loop, outer connection, and diagonal ramp. This order is consistent with that found in the safety relationships reported by Bauer and Harwood (3) and by Twomey et al. (9). Therefore, while the crash rate for free-flow loops in Texas is higher than expected, the other trends related to ramp configuration are consistent with reported trends. It is possible that the high crash rate for free-flow loops in Texas is related to driver familiarity. These loops are not used as often in Texas as in the states included in the data examined by Bauer and Harwood or by Twomey et al.

With regard to area type, the crash rates in Table 4 indicate that rural ramps have more crashes than urban ramps, given the same traffic volume. This finding is contrary to that found from an examination of the safety relationship reported by Bauer and Harwood (3). They found that rural ramps were associated with *fewer* crashes. However, the crash rate for rural ramps is very consistent with the rural ramp crash rates reported by Twomey *et al.* (9). Thus, it is possible that the urban ramps included in this study have an exceptionally low crash risk, relative to the urban ramps in Washington (as studied by Bauer and Harwood), or that many of the PDO crashes on urban ramps are not being reported to the DPS.

Closer examination of the distribution of crash severity indicates that the PDO percentage varies between rural and urban crashes. For rural crashes, it is 59 percent which is consistent with the nationwide average. For urban ramps, it is only 33 percent. This finding suggests that only about 36 percent of the PDO crashes occurring on the urban ramps are being reported.

Alternatively, it suggests that the urban crashes listed in the "all crashes" category in Table 4 should be inflated by 1.60 (= {1−0.33}/{1−0.59}) to better reflect the distribution of fatal, injury, and PDO crashes that likely occurred on these ramps. In other words, this value is used to adjust the number of crashes in this study with what would be expected from the national average for ramps located in urban areas.

CALIBRATION PROCESS

The methods proposed by Persaud *et al.* (1) and others (5, 10) were used for the calibration process. However, instead of one calibration factor for all combinations of area type, ramp type, and ramp configuration, separate calibration factors were considered for each attribute combination. This disaggregate approach would allow for a better fit to the data if the effect of an attribute differed between Washington and Texas. Separate analyses were conducted for the "all crash" and the "fatal and injury crash" models.

Several statistical tests were used to determine which attribute combination offered the best fit between the calibrated model and the crash data. They included the RMSE, MPSE and the variance of the estimated calibration factors (see equation 7), as described above. Calibration factors were evaluated, using the statistical tools above, for several different types of group (e.g., rural-exit, rural-entrance, etc.). Based on this analysis, it was determined that separate calibration factors for urban and rural ramps (entrances and exits combined) would provide the most accurate safety prediction model.

The calibration factor for rural ramps $C_{t,\,rural}$ was estimated with the following equation (1, 5, 10):

$$C_{t,rural} = \frac{\sum_i O_{t,rural,i}}{n \sum_i N_{t,rural,i}} \left(1 + \frac{Var[N_{t,rural}]}{\left(\sum_i N_{t,rural,i} \right)^2} \right)^{-1} \quad \mathbf{(5)}$$

where,

$C_{t,rural}$ = calibration factor for all crashes on rural ramps;
$O_{t,rural,i}$ = observed crashes (of all severities) on rural ramp *i* during *n* years, crashes;
$N_{t,rural,i}$ = predicted annual number of crashes (of all severities) on rural ramp *i*; crashes/yr;
n = number of years crashes were observed (*n* = 3 for the ramp database); and
$Var[x]$ = variance of random variable *x*.

The variance of the predicted annual number of crashes $Var[N_{t,rural}]$ was estimated using the following equation:

$$Var[N_{t,rural}] = \sum_i \frac{(N_{t,rural,i})^2}{\phi_t} \quad \mathbf{(6)}$$

Equations (5) and (6) were also used to compute $C_{t,urban}$ for the urban ramps. In this instance, the observed and predicted crashes corresponded to urban ramps. These equations were also used to compute $C_{f+i,rural}$ and $C_{f+i,urban}$. However, only the fatal and injury crashes at the rural and urban ramps were used for this computation, as was the dispersion factor k_{f+i} of 4.0 (see Table 5: 1 / 0.25).

The methods proposed by Persaud *et al.* (1) and others (5, 10) only employs the first term in equation (5) for the calibration process. The second term (i.e., the term raised to the power -1) was added for this calibration because of the relatively small number of crashes in the ramp database. Hauer (10) recommends using this term to remove the bias associated with the first term when the database includes fewer than 500 crashes. For the ramp database, this bias adjustment term reduced the quantity obtained from the first term by about 10 percent.

The variance of $C_{t,rural}$ is given by:

$$Var[C_{t,rural}] = C_{t,rural}^2 \left(\frac{Var[O_{t,rural}]}{\left(\sum_i O_{t,rural,i}\right)^2} + \frac{Var[N_{t,rural}]}{\left(\sum_i N_{t,rural,i}\right)^2} \right) \left(1 + \frac{Var[N_{t,rural}]}{\left(\sum_i N_{t,rural,i}\right)^2} \right)^{-2} \quad \textbf{(7)}$$

The variance of the observed number of crashes $Var[O_{t,rural}]$, as needed for equation (7), was estimated using the following equation:

$$Var[O_{t,rural}] = \sum_i O_{t,rural,i} \quad \textbf{(8)}$$

This equation is based on the assumption that the observed crash counts follow a Poisson distribution. Equations (5), (6), and (8) were used to compute the variance of $C_{t,rural}$, $C_{t,urban}$, $C_{f+i,rural}$, and $C_{f+i,urban}$, with proper substitution of the applicable observed and predicted crash data.

The overdispersion parameter ($\alpha_t = 1 / \phi_t$) for the recalibrated models was estimated using the weighted regression analysis (without an intercept term) proposed by Cameron and Trivedi (11). The parameter α_t was estimated using equation (9):

$$Y_t = \alpha_t P_t \quad \textbf{(9)}$$

where,

$Y_t = [(O_t - P_t)^2 - O_t] / P_t$;
O_t = observed crash counts on ramps (rural or urban); and,
P_t = predicted crash counts on ramps (rural or urban) from recalibrated models (eqs. 10 and 13).

The calibration factors obtained from equations (5) through (8) are shown in Table 5. This table also shows the standard error for each factor. The standard error is an indicator of the level of uncertainty associated with each calibration factor.

Table 5. Calibration Factors.

Statistic	Area Type: Rural		Area Type: Urban	
	All Crashes	Fatal & Injury	All Crashes	Fatal & Injury
ΣO	17	7	21	14
$n\ \Sigma N$	18.8	7.6	78	36.3
Original ϕ	0.95	0.7	0.95	0.7
Var[N]	3.9	1	47.4	15.3
Calibration Factor, *C*	**0.83**	**0.8**	**0.25**	**0.35**
Standard Error of *C*	0.3	0.38	0.08	0.13
Overdispersion Parameter (α)†	0.47	0.03	1.57	0.48
Standard Error of α†	0.18	0.41	0.47	0.12
Recalibrated ϕ $(1 / \alpha)$	2.12	32.7‡	0.63	2.08

† Estimated from the output of the weighted regression analysis (equation 9)
‡ Poisson approximation

CALIBRATED SAFETY PREDICTION MODELS

The calibration factors in Table 5 were combined with the adjustment factors in Table 1 to produce a single calibration constant for use in simplified versions of equations (1) and (3). The resulting constants for the "all crash" category for urban ramps were also inflated by a factor of 1.60 to account for the apparent under-reporting of urban ramp crashes in Texas. The resulting calibration coefficients are listed in Table 6.

Table 6. Calibrated Model Coefficients.

Area Type: Rural				Area Type: Urban			
Ramp Type	Ramp Configuration	Model Coefficient		Ramp Type	Ramp Configuration	Model Coefficient	
		a_t	a_{f+i}			a_t	a_{f+i}
Exit	Diagonal	0.83	0.80	Exit	Diagonal	0.57	0.49
	Non-free-flow loop	1.45	1.58		Non-free-flow loop	0.99	0.97
	Free-flow loop	0.52	0.47		Free-flow loop	0.35	0.29
	Outer connection	1.09	1.04		Outer connection	0.74	0.64
Entrance	Diagonal	0.50	0.46	Entrance	Diagonal	0.34	0.28
	Non-free-flow loop	0.88	0.91		Non-free-flow loop	0.6	0.56
	Free-flow loop	0.31	0.27		Free-flow loop	0.22	0.17
	Outer connection	0.66	0.60		Outer connection	0.45	0.37

The simplified safety prediction model for all crashes is:

$$N_t = 0.247\ a_t \left(\frac{V_r}{1000} \right)^{0.76} \qquad \textbf{(10)}$$

where:

N_t = predicted annual number of crashes (of all severities), crashes/yr;
a_t = model calibration coefficient for area type, ramp type, and ramp configuration; and,
V_r = average daily traffic on the ramp, veh/day.

The subscript *t* associated with each model variable denotes that the variable represents crashes of all severities (including property-damage-only, injury, and fatal crashes). The standard deviation of the predicted annual number of crashes for rural and urban areas are:

$$s_{Nt_{rural}} = 0.68\ N_t \qquad \textbf{(11)}$$

$$s_{Nt_{urban}} = 1.25\ N_t \qquad \textbf{(12)}$$

The simplified safety prediction model for fatal and injury crashes is:

$$N_{f+i} = 0.0957\ a_{f+i} \left(\frac{V_r}{1000} \right)^{0.85} \qquad \textbf{(13)}$$

where:

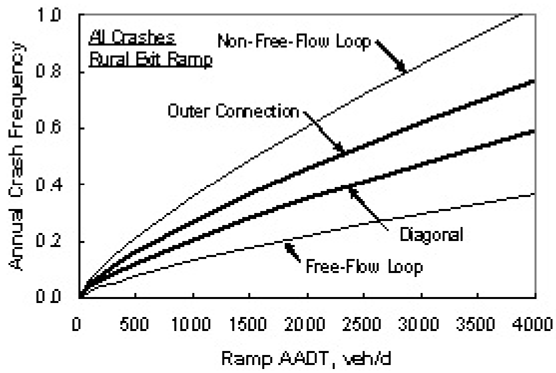
N_{f+i} = predicted annual number of fatal and injury crashes, crashes/yr;

The subscript $f+i$ associated with each model variable denotes that the variable represents injury and fatal crashes (i.e., property-damage-only crashes are *not* included). The standard deviation of the predicted annual number of fatal and injury crashes for rural and urban areas are:

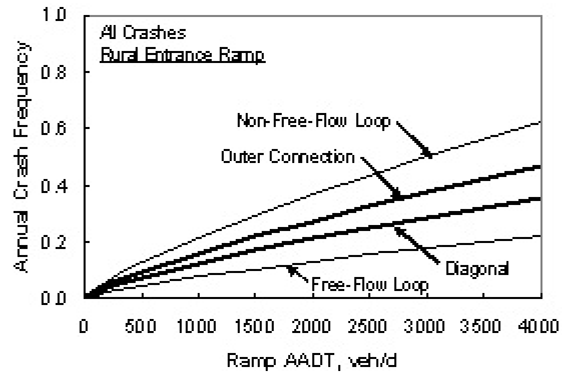
$$s_{Nf+i_{rural}} = 0.17\ N_{f+i} \qquad \textbf{(14)}$$

$$s_{Nf+i_{urban}} = 0.69\ N_{f+i} \qquad \textbf{(15)}$$

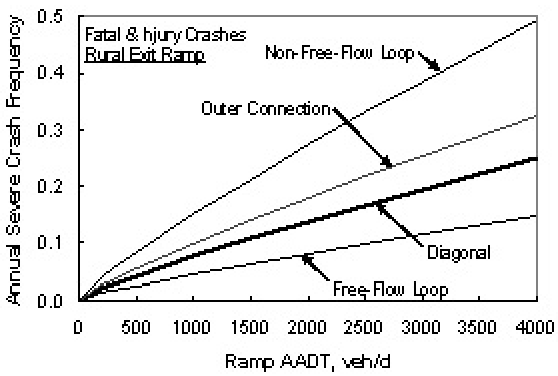
The relationship between daily ramp volume and crash frequency is shown in Figures 2 and 3 for rural and urban ramps respectively. They were developed using equations (10) and (13), and the factors shown in Table 6, for a reasonable range of AADTs.



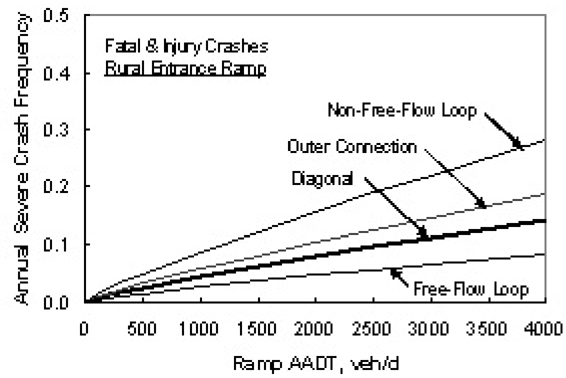
a. All Crashes on Exit Ramps



b. All Crashes on Entrance Ramps

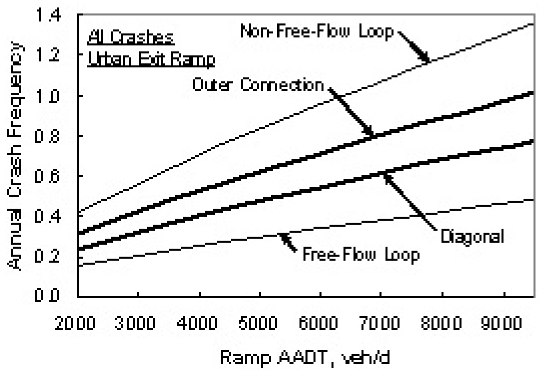


c. Severe Crashes on Exit Ramps

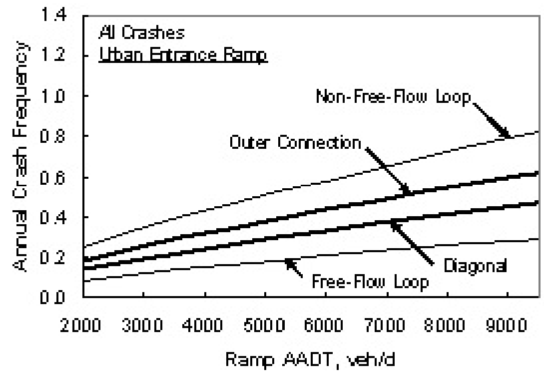


d. Severe Crashes on Entrance Ramps

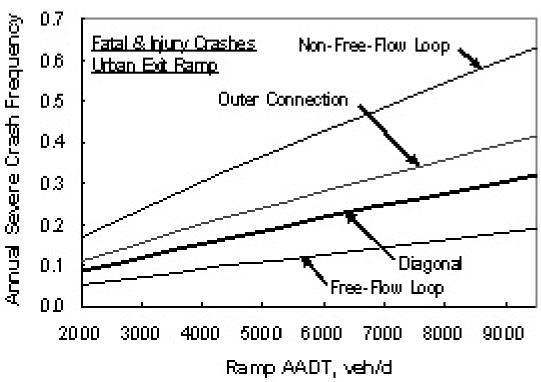
Figure 2. Effect of Ramp Volume on Crash Frequency on Rural Ramps.



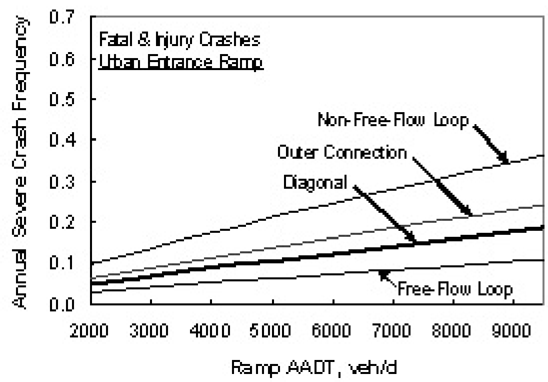
a. All Crashes on Exit Ramps



b. All Crashes on Entrance Ramps



c. Severe Crashes on Exit Ramps



d. Severe Crashes on Entrance Ramps

Figure 3. Effect of Ramp Volume on Crash Frequency on Urban Ramps.

It should be pointed out that equations (10) and (13) are calibrated for use in computing the crash frequency for interchange ramps constructed in Texas. They are applicable to interchanges in non-frontage-road settings. They can be used to evaluate the safety of alternative ramp configurations at an interchange proposed for construction or at an interchange undergoing major reconstruction. The methodology proposed in this paper should be used whenever models need to be recalibrated for other jurisdictions.

In this application, the expected frequency of total crashes and injury+fatal crashes would be computed for each year of the interchange design life and summed. These totals would be used to justify the selection of the "best" ramp based on the consideration of safety, operations, and cost' as determined by the designer. Benefit-cost analysis is one method for comparing the benefits of alternative ramp configurations, based on the societal cost of crashes and delays, with the costs associated with ramp design and maintenance. It is recommended to recalibrate equations (10) and (13) every three years to insure they continue to reflect current driver behavior and design practices.

SUMMARY AND CONCLUSIONS

This paper has described the calibration process for recalibrating crash prediction models for estimating the safety of different ramp design configurations. Four design ramp design configurations were evaluated in this study: 1) diagonal ramp, 2) non-free-flow loop ramp, 3) free-flow loop ramp, and 4) outer connection ramp. The calibration process was conducted using crash data on 44 ramps located in Texas.

The outcome of the calibration process has shown that more crashes occur on exit ramps than entrance ramps by a ratio of about 60/40. The results have also shown that non-free-flow ramps experience twice as many crashes than other types of ramps. Similarly, more crashes occur on rural than urban ramps. Given the outcome of the calibration process, ramp-related crashes occur less frequently in Texas than in Washington state. The magnitude of the difference is greater for urban areas. This outcome may suggest that many PDO crashes occurring on urban ramps are under-reported. Finally, it is recommended to recalibrate the predictive models every three years to insure they continue to reflect current driver behavior and design practices.

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