ATTACHMENT E

Consideration of Roadside Features in the Highway Safety Manual

DEVELOPMENT OF EFCCRS FOR ROADSIDE HAZARDS

NCHRP 17-54

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INTRODUCTION

The roadside crash modification function, $CMF_{ROADSIDE}$, is assumed to have the following form:

$$CMF_{ROADSIDE} = \left[\beta_{SHLD} \cdot X_{SHLD} \cdot \prod_{j=1}^{m1} CMF_j\right] + \left[\beta_{UNSHLD} \cdot X_{UNSHLD} \cdot \prod_{k=1}^{m2} CMF_k\right]$$

Where:

X_{SHLD} = Proportion of the segment edge where longitudinal barriers are installed where $0 \leq X_{SHLD} \leq 1$.

X_{UNSHLD} = Proportion of the segment edge where there are unshielded ditches or roadside slopes and other unshielded fixed objects where $0 \leq X_{UNSHLD} \leq 1$.

Condition that: $1 = X_{SHLD} + X_{UNSHLD}$ (100% of the segment edge is accounted for).

β_{SHLD} = A regression coefficient associated with the segment edges where longitudinal barriers are installed.

β_{UNSHLD} = A regression coefficient associated with the segment edges where there are unshielded ditches, roadside slopes or fixed objects like trees, tree lines, utility poles, bridge piers, etc.

CMF_j = Crash modification factors associated with roadside feature j that modify the ROR crashes associated with longitudinal barriers. These CMFs would account for characteristics like barrier type, barrier terminals, barrier transitions, barrier offset, etc.

CMF_k = Crash modification factors associated with roadside feature k that modify the ROR crashes associated with unshielded roadsides. These CMFs would account for characteristics like the presence of ditches, the density of narrow fixed objects, and other unshielded objects.

The development of $CMF_{ROADSIDE}$ is presented in Attachment C16. The documentation of the roadside base conditions where CMF_j and CMF_k, are equal to unity is provided in Attachment D16. A simulated before/after study to develop of values for CMF_j and CMF_k outside of the base conditions will use RSAPv3, as originally presented and discussed in Attachment D12. The use of RSAPv3 for the simulated before/after study requires the development of Equivalent Fatal Crash Cost Ratios (EFCCRs) to represent the severity of a crash with each hazard category (i.e., Narrow Fixed Objects, Longitudinal Barriers, “Other” hazards). Documented herein is the development of the EFCCRs used in the simulated before/after study.

BACKGROUND

The analysis of alternative roadside designs have a rich history of using benefit-cost computer programs to implement the encroachment probability model explained in AASHTO’s Roadside Design Guide. [AASHTO89; AASHTO02; AASHTO06; AASHTO11] These models rely on understanding a series of conditional probabilities and crash outcomes. Namely, the probability of encroaching onto the roadside, the probability of experiencing a crash given an encroachment, the resulting severity of the crash and the cost of the crash. It is therefore necessary to estimate the likely average severity of the crash in order to appropriately apportion the crash risk and crash costs. Until recently, these programs calculated the crash risk to determine the crash cost, but did not capture the risk data. The advances made to the third version of the Roadside Safety Analysis Program (RSAPv3) under NCHRP 22-12(03) now allow for the review of the crash risk. [Ray13]

A new approach to modeling crash severity in roadside safety benefit-cost analysis programs was developed in NCHRP 22-27 [Ray12], the equivalent fatal crash cost ratio (EFCCR). This new approach for estimating crash severity was implemented into RSAPv3. The method is based on using observed crashes with particular roadside features to estimate the crash severity in RSAPv3, given an encroachment and a crash with the hazard. This attachment develops the EFCCRs for the hazard groups defined and discussed in Attachment D16 of this QPR. Namely, the categories are: narrow fixed object (NFO), longitudinal barriers (LB), and "other" hazards.

CRASH SEVERITY MODEL

Mak and Sicking in NCHRP Report 492 observed "all of the historical procedures for estimating crash severities have serious limitations and the resulting severity estimates that cannot be thoroughly validated." [Mak03] They went on to discuss the need to develop a new probability of injury method that would be based on observable crash data. Unfortunately, they were not able to pursue developing a new severity and retained the older subjective model in RSAP 2.0.3.

The new severity model used in RSAPv3 is based on observed police reported crashes which are then adjusted for unreported crashes and scaled to account for speed effects in order to develop a dimensionless severity measure that can be scaled according to the impact speed of each simulated collision. The new severity model used in RSAPv3 is called the equivalent crash cost ratio (EFCCR), it is described in the following sections. The data and resulting EFCCRs for this research are also discussed. Once EFCCRs are developed, the values will be added to RSAPv3 and used to perform the simulated before/after analysis.

Measure of Crash Severity

The process for developing an EFCCR crash severity model for a particular roadside feature was originally described in the NCHRP 22-27 final report [Ray12] and involves the following steps:

1. Isolate a census of police-reported crashes with a particular type of roadside feature ideally over a range of posted speed limits
2. Determine the crash severity distribution for crashes that do not have events preceding the crashes with the hazard under evaluation and do not result in a penetration or rollover.
3. Determine or estimate the percentage of unreported crashes and add these crashes to the reported crash severity distribution.
4. Calculate the average crash cost of the severity distribution for each posted speed limit and determine the equivalent fatal crash cost ratio (EFCCR), and
5. Adjust for speed effects by determining the equivalent fatal crash cost ratio for a baseline impact speed of 65 mi/hr (i.e., $EFCCR_{65}$) for a particular hazard.

The five steps involved in developing the $EFCCR_{65}$ are discussed below. There is a significant difference between the crash data which has been used to develop the models to date and the data which will be used to develop the $EFCCR_{65}$ for NFOs, LBs, and "Other." Recall that all modeling done to date included any vehicle which left the road, regardless of the events that preceded or followed leaving the road. A subset of these crashes will be used to determine the severity of impacts with each hazard group. To determine the severity of impacts with each hazard group, the $EFCCR_{65}$ uses only single event crashes. Crashes which penetrate, rollover, or vault the hazard (PRV) or crashes that rollover after redirection (RSS) are excluded from this severity measure so the EFCCR only represents the severity of a single event in the overall crash sequence. When the $EFCCR_{65}$ is applied to the model, the severity of each hazard struck in the crash event is considered individually by RSAPv3. For example, the $EFCCR_{65}$ for NFOs is based on crashes where a NFO was the only object struck such that all of the harm resulting from the crash can be confidently associated with the collision with the NFO.

Severity Distribution

After removing the crashes from the dataset which included multiple events, the data were separated into the three hazard groups (i.e., NFO, Longitudinal Barriers, and "Other") and the severity distribution was determined for the divided and undivided roadways in both Ohio and Washington. The combined severity distributions were also determined. Each of these distributions were found across a range of posted speed limits. The results are shown in Table 1 through Table 6.

Speed and Crash Severity

The relationship between speed and crash severity in general has been established by many researchers in the past. [Nilsson81; Bowie94; Joksch93; ODay82] As stated in an FHWA synthesis on speed affects and crash severity:

> "*The relationship between vehicle speed and crash severity is unequivocal and based on the laws of physics. The kinetic energy of a moving vehicle is a function of its mass and velocity squared. .... Generally, the more kinetic energy to be dissipated in a collision the greater the potential for injury to vehicle occupants. Because kinetic energy is determined by the square of the vehicle's speed rather than by speed alone, the probability of injury and the severity of injuries that occur in a crash, increase exponentially with vehicle speed*." [FHWA88]

The linkage, therefore, between speed and severity has been made both statistically and based on the physics of vehicle crashes. Nilsson showed that for all types of crashes the number of injury crashes increases as a square of the ratio of velocities; to the third power for severe injury crashes and to the fourth power for fatal crashes. [Nilsson81] Similar results showing the importance of speed or change in speed have been obtained in the US by Bowie, Joksch and O'Day to name several. [Bowie94; Joksch93; ODay82] Nilsson has shown that the ratio of injury crashes prior to a change in average travel speed to those after is proportional to the ratio of speed squared:

$$\frac{P_{I2}}{P_{I1}} = \left[\frac{V_2}{V_1}\right]^2$$

Where P_{I1} and P_{I2} are the number of injury crashes before and after a change in average speed and V_1 and V_2 are the speeds before and after. For example, Nilsson's expression would indicate that a particular rural two lane road that experiences 10 injury crashes/mi/yr when the average travel speed is 55 mi/hr would experience on average 6.7 injury crashes/mi/yr if the average travel speed were reduced to 45 mi/hr. Since Nilsson has shown that injury crashes increase in severity as a function of the velocity to some power, it would appear to be a reasonable assumption that a crash severity model should be a function of some power of the posted speed limit. Posted Speed Limit, rather than impact speed is used simply because the posted speed data is generally available while impact speed data is generally not available.

Table 1. Police-Reported Severity of Narrow Fixed Objects (NFOs) on Undivided Roadways in Washington and Ohio.

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON													
<=25	0	0.00	5	2.18	41	4.78	24	3.82	84	3.96	17	4.43	171
30	0	0.00	2	0.87	11	1.28	7	1.11	34	1.60	12	3.13	66
35	9	8.04	18	7.86	94	10.96	58	9.22	187	8.82	46	11.98	412
40	10	8.93	10	4.37	54	6.29	34	5.41	93	4.39	31	8.07	232
45	2	1.79	8	3.49	45	5.24	38	6.04	135	6.37	20	5.21	248
50	28	25.00	58	25.33	220	25.64	169	26.87	658	31.05	87	22.66	1220
55	47	41.96	97	42.36	260	30.30	206	32.75	648	30.58	117	30.47	1375
60	15	13.39	31	13.54	130	15.15	89	14.15	275	12.98	52	13.54	592
65	1	0.89	0	0.00	3	0.35	4	0.64	5	0.24	2	0.52	15
70	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
OHIO													
<=25	5	1.81	16	1.06	66	1.27	35	1.62	412	2.43			534
30	0	0.00	0	0.00	0	0.00	0	0.00	1	0.01			1
35	16	5.78	85	5.65	276	5.32	159	7.37	1362	8.02			1898
40	8	2.89	27	1.79	104	2.00	54	2.50	343	2.02			536
45	19	6.86	108	7.18	378	7.28	143	6.63	1167	6.88			1815
50	0	0.00	39	2.59	98	1.89	42	1.95	336	1.98			515
55	228	82.31	1230	81.73	4265	82.15	1725	79.94	13326	78.52			20774
60	0	0.00	0	0.00	1	0.02	0	0.00	2	0.01			3
65	1	0.36	0	0.00	4	0.08	0	0.00	23	0.14			28

Table 1. Police-Reported Severity of Narrow Fixed Objects (NFOs) on Undivided Roadways in Washington and Ohio. CONT'D

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON and OHIO													
<=25	5	1.29	21	1.21	107	1.77	59	2.12	496	2.60	17	4.43	705
30	0	0.00	2	0.12	11	0.18	7	0.25	35	0.18	12	3.13	67
35	25	6.43	103	5.94	370	6.12	217	7.79	1549	8.11	46	11.98	2310
40	18	4.63	37	2.13	158	2.61	88	3.16	436	2.28	31	8.07	768
45	21	5.40	116	6.69	423	6.99	181	6.49	1302	6.82	20	5.21	2063
50	28	7.20	97	5.59	318	5.26	211	7.57	994	5.21	87	22.66	1735
55	275	70.69	1327	76.53	4525	74.79	1931	69.29	13974	73.20	117	30.47	22149
60	15	3.86	31	1.79	131	2.17	89	3.19	277	1.45	52	13.54	595
65	2	0.51	0	0.00	7	0.12	4	0.14	28	0.15	2	0.52	43
70	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0

Table 2. Police-Reported Severity of Longitudinal Barriers (LBs) on Undivided Roadways in the State of Washington and Ohio.

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON													
<=25	0	0.00	3	2.08	9	1.47	8	1.83	22	1.64	6	2.31	48
30	0	0.00	2	1.39	12	1.96	9	2.06	23	1.71	6	2.31	52
35	0	0.00	2	1.39	36	5.89	12	2.75	59	4.39	17	6.54	126
40	2	2.15	3	2.08	28	4.58	17	3.89	75	5.58	9	3.46	134
45	4	4.30	3	2.08	36	5.89	23	5.26	50	3.72	10	3.85	126
50	19	20.43	42	29.17	98	16.04	75	17.16	260	19.33	34	13.08	528
55	40	43.01	48	33.33	199	32.57	142	32.49	445	33.09	78	30.00	952
60	26	27.96	38	26.39	167	27.33	135	30.89	377	28.03	88	33.85	831
65	2	2.15	3	2.08	25	4.09	16	3.66	33	2.45	11	4.23	90
70	0	0.00	0	0.00	1	0.16	0	0.00	1	0.07	1	0.38	3
OHIO													
<=25	1	0.98	6	1.27	20	1.15	11	1.33	73	1.19			111
30	0	0.00	0	0.00	0	0.00	0	0.00	1	0.02			1
35	4	3.92	17	3.59	64	3.68	42	5.08	309	5.05			436
40	2	1.96	6	1.27	35	2.01	22	2.66	119	1.95			184
45	5	4.90	45	9.49	119	6.84	52	6.29	456	7.45			677
50	2	1.96	9	1.90	41	2.35	9	1.09	114	1.86			175
55	88	86.27	391	82.49	1462	83.97	691	83.56	5035	82.31			7667
60	0	0.00	0	0.00	0	0.00	0	0.00	5	0.08			5
65	0	0.00	0	0.00	0	0.00	0	0.00	5	0.08			5

Table 2. Police-Reported Severity of Longitudinal Barriers (LBs) on Undivided Roadways in the State of Washington and Ohio. **CONT'D**

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON and OHIO													
<=25	1	0.51	9	1.46	29	1.23	19	1.50	95	1.27	6	2.31	159
30	0	0.00	2	0.32	12	0.51	9	0.71	24	0.32	6	2.31	53
35	4	2.05	19	3.07	100	4.25	54	4.27	368	4.93	17	6.54	562
40	4	2.05	9	1.46	63	2.68	39	3.09	194	2.60	9	3.46	318
45	9	4.62	48	7.77	155	6.59	75	5.93	506	6.78	10	3.85	803
50	21	10.77	51	8.25	139	5.91	84	6.65	374	5.01	34	13.08	703
55	128	65.64	439	71.04	1661	70.62	833	65.90	5480	73.44	78	30.00	8619
60	26	13.33	38	6.15	167	7.10	135	10.68	382	5.12	88	33.85	836
65	2	1.03	3	0.49	25	1.06	16	1.27	38	0.51	11	4.23	95
70	0	0.00	0	0.00	1	0.04	0	0.00	1	0.01	1	0.38	3

Table 3. Police-Reported Severity of "Other" Hazards on Undivided Roadways in the State of Washington and Ohio.

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON													
<=25	0	0.00	1	0.93	20	4.22	13	4.23	30	2.64	7	3.40	71
30	0	0.00	2	1.87	7	1.48	3	0.98	12	1.06	5	2.43	29
35	3	7.32	4	3.74	34	7.17	18	5.86	63	5.54	16	7.77	138
40	1	2.44	0	0.00	24	5.06	10	3.26	43	3.78	9	4.37	87
45	1	2.44	5	4.67	20	4.22	11	3.58	58	5.10	10	4.85	105
50	8	19.51	23	21.50	110	23.21	71	23.13	287	25.24	32	15.53	531
55	16	39.02	37	34.58	130	27.43	88	28.66	356	31.31	49	23.79	676
60	9	21.95	26	24.30	106	22.36	82	26.71	254	22.34	69	33.50	546
65	2	4.88	9	8.41	23	4.85	11	3.58	34	2.99	9	4.37	88
70	1	2.44	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1
OHIO													
<=25	1	1.00	8	1.37	27	1.45	26	3.47	244	3.70			306
30	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00			0
35	4	4.00	28	4.81	115	6.16	62	8.27	632	9.58			841
40	2	2.00	12	2.06	40	2.14	14	1.87	178	2.70			246
45	11	11.00	41	7.04	138	7.40	53	7.07	449	6.80			692
50	1	1.00	9	1.55	29	1.55	19	2.53	132	2.00			190
55	81	81.00	484	83.16	1516	81.24	573	76.40	4959	75.14			7613
60	0	0.00	0	0.00	1	0.05	1	0.13	1	0.02			3
65	0	0.00	0	0.00	0	0.00	2	0.27	5	0.08			7

Table 3. Police-Reported Severity of "Other" Hazards on Undivided Roadways in the State of Washington and Ohio.
CONT'D

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON and OHIO													
<=25	1	0.71	9	1.31	47	2.01	39	3.69	274	3.54	7	3.40	377
30	0	0.00	2	0.29	7	0.30	3	0.28	12	0.16	5	2.43	29
35	7	4.96	32	4.64	149	6.37	80	7.57	695	8.98	16	7.77	979
40	3	2.13	12	1.74	64	2.74	24	2.27	221	2.86	9	4.37	333
45	12	8.51	46	6.68	158	6.75	64	6.05	507	6.55	10	4.85	797
50	9	6.38	32	4.64	139	5.94	90	8.51	419	5.42	32	15.53	721
55	97	68.79	521	75.62	1646	70.34	661	62.54	5315	68.70	49	23.79	8289
60	9	6.38	26	3.77	107	4.57	83	7.85	255	3.30	69	33.50	549
65	2	1.42	9	1.31	23	0.98	13	1.23	39	0.50	9	4.37	95
70	1	0.71	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1

Table 4. Police-Reported Severity of Narrow Fixed Objects (NFOs) on Divided Roadways in Washington and Ohio.

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON													
<=25	0	0.00	0	0.00	3	1.47	0	0.00	4	1.07	0	0.00	7
30	0	0.00	1	2.70	0	0.00	1	0.71	0	0.00	0	0.00	2
35	0	0.00	0	0.00	2	0.98	0	0.00	5	1.34	1	1.03	8
40	0	0.00	0	0.00	1	0.49	0	0.00	1	0.27	0	0.00	2
45	0	0.00	0	0.00	0	0.00	2	1.42	4	1.07	1	1.03	7
50	0	0.00	0	0.00	4	1.96	3	2.13	4	1.07	1	1.03	12
55	2	13.33	2	5.41	9	4.41	9	6.38	33	8.85	2	2.06	57
60	3	20.00	16	43.24	65	31.86	43	30.50	103	27.61	30	30.93	260
65	1	6.67	2	5.41	5	2.45	2	1.42	7	1.88	3	3.09	20
70	9	60.00	16	43.24	115	56.37	81	57.45	212	56.84	59	60.82	492
OHIO													
<=25	0	0	0	0.00	0	0.00	0	0.00	1	0.03			1
30	0	0	0	0.00	0	0.00	0	0.00	0	0.00			0
35	0	0	0	0.00	3	0.55	1	0.36	8	0.25			12
40	0	0	0	0.00	0	0.00	0	0.00	2	0.06			2
45	0	0	0	0.00	0	0.00	0	0.00	6	0.19			6
50	0	0	1	0.79	11	2.02	1	0.36	49	1.55			62
55	2	7	30	23.62	109	20.04	46	16.37	569	17.96			756
60	0	0	15	11.81	64	11.76	37	13.17	321	10.13			437
65	26	93	81	63.78	357	65.63	196	69.75	2212	69.82			2872

Table 4. Police-Reported Severity of Narrow Fixed Objects (NFOs) on Divided Roadways in Washington and Ohio.
CONT'D

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON and OHIO													
<=25	0	0.00	0	0.00	3	0.40	0	0.00	5	0.14	0	0.00	8
30	0	0.00	1	0.61	0	0.00	1	0.24	0	0.00	0	0.00	2
35	0	0.00	0	0.00	5	0.67	1	0.24	13	0.37	1	1.03	20
40	0	0.00	0	0.00	1	0.13	0	0.00	3	0.08	0	0.00	4
45	0	0.00	0	0.00	0	0.00	2	0.47	10	0.28	1	1.03	13
50	0	0.00	1	0.61	15	2.01	4	0.95	53	1.50	1	1.03	74
55	4	9.30	32	19.51	118	15.78	55	13.03	602	17.00	2	2.06	813
60	3	6.98	31	18.90	129	17.25	80	18.96	424	11.97	30	30.93	697
65	27	62.79	83	50.61	362	48.40	198	46.92	2219	62.67	3	3.09	2892
70	9	20.93	16	9.76	115	15.37	81	19.19	212	5.99	59	60.82	492

Table 5. Police-Reported Severity of Longitudinal Barriers (LBs) on Divided Roadways in the State of Washington and Ohio.

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON													
<=25	0	0.00	1	1.25	0	0.00	1	0.16	3	0.17	2	0.45	7
30	0	0.00	0	0.00	2	0.25	0	0.00	0	0.00	0	0.00	2
35	0	0.00	0	0.00	4	0.49	3	0.47	9	0.51	2	0.45	18
40	0	0.00	0	0.00	1	0.12	0	0.00	2	0.11	0	0.00	3
45	0	0.00	0	0.00	38	4.67	14	2.20	42	2.39	14	3.15	108
50	0	0.00	1	1.25	2	0.25	6	0.94	17	0.97	5	1.12	31
55	1	3.57	8	10.00	75	9.21	62	9.73	182	10.35	28	6.29	356
60	5	17.86	25	31.25	181	22.24	148	23.23	385	21.89	119	26.74	863
65	3	10.71	3	3.75	92	11.30	57	8.95	175	9.95	38	8.54	368
70	19	67.86	42	52.50	419	51.47	346	54.32	944	53.67	237	53.26	2007
OHIO													
<=25	0	0.00	0	0.00	1	0.05	0	0.00	1	0.01			2
30	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00			0
35	0	0.00	0	0.00	1	0.05	0	0.00	7	0.07			8
40	0	0.00	0	0.00	0	0.00	1	0.08	8	0.08			9
45	0	0.00	0	0.00	3	0.14	2	0.15	24	0.24			29
50	0	0.00	2	0.55	4	0.19	4	0.31	21	0.21			31
55	8	13.33	55	15.15	209	9.96	124	9.60	925	9.20			1321
60	1	1.67	20	5.51	145	6.91	64	4.95	515	5.12			745
65	51	85.00	286	78.79	1735	82.70	1097	84.91	8552	85.07			11721

Table 5. Police-Reported Severity of Longitudinal Barriers (LBs) on Divided Roadways in the State of Washington and Ohio.
CONT'D

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON and OHIO													
<=25	0	0.00	1	0.23	1	0.03	1	0.05	4	0.03	2	0.45	9
30	0	0.00	0	0.00	2	0.07	0	0.00	0	0.00	0	0.00	2
35	0	0.00	0	0.00	5	0.17	3	0.16	16	0.14	2	0.45	26
40	0	0.00	0	0.00	1	0.03	1	0.05	10	0.08	0	0.00	12
45	0	0.00	0	0.00	41	1.41	16	0.83	66	0.56	14	3.15	137
50	0	0.00	3	0.68	6	0.21	10	0.52	38	0.32	5	1.12	62
55	9	10.23	63	14.22	284	9.75	186	9.64	1107	9.37	28	6.29	1677
60	6	6.82	45	10.16	326	11.20	212	10.99	900	7.62	119	26.74	1608
65	54	61.36	289	65.24	1827	62.74	1154	59.82	8727	73.88	38	8.54	12089
70	19	21.59	42	9.48	419	14.39	346	17.94	944	7.99	237	53.26	2007

Table 6. Police-Reported Severity of "Other" Hazards on Divided Roadways in the State of Washington and Ohio.

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON													
<=25	0	0.00	0	0.00	1	0.77	1	0.94	3	0.94	0	0.00	5
30	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
35	0	0.00	0	0.00	0	0.00	0	0.00	1	0.31	4	5.06	5
40	0	0.00	0	0.00	0	0.00	0	0.00	2	0.63	0	0.00	2
45	0	0.00	0	0.00	1	0.77	2	1.89	4	1.25	1	1.27	8
50	2	16.67	0	0.00	0	0.00	0	0.00	1	0.31	2	2.53	5
55	0	0.00	1	4.17	8	6.15	3	2.83	17	5.31	4	5.06	33
60	2	16.67	4	16.67	25	19.23	12	11.32	56	17.50	12	15.19	111
65	1	8.33	0	0.00	2	1.54	0	0.00	3	0.94	2	2.53	8
70	7	58.33	19	79.17	93	71.54	88	83.02	233	72.81	54	68.35	494
OHIO													
<=25	0	0.00	0	0.00	0	0.00	0	0.00	1	0.05			1
30	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00			0
35	1	4.17	1	0.99	1	0.27	1	0.53	5	0.27			9
40	0	0.00	0	0.00	0	0.00	0	0.00	1	0.05			1
45	1	4.17	1	0.99	0	0.00	0	0.00	4	0.21			6
50	4	16.67	3	2.97	7	1.88	1	0.53	24	1.29			39
55	4	16.67	13	12.87	68	18.28	24	12.70	230	12.36			339
60	1	4.17	18	17.82	31	8.33	18	9.52	102	5.48			170
65	13	54.17	65	64.36	265	71.24	145	76.72	1494	80.28			1982

Table 6. Police-Reported Severity of “Other” Hazards on Divided Roadways in the State of Washington and Ohio. **CONT’D**

PSL (mi/hr)	K		A		B		C		O		Unk		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
WASHINGTON and OHIO													
<=25	0	0.00	0	0.00	1	0.20	1	0.34	4	0.18	0	0.00	6
30	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
35	1	2.78	1	0.80	1	0.20	1	0.34	6	0.28	4	5.06	14
40	0	0.00	0	0.00	0	0.00	0	0.00	3	0.14	0	0.00	3
45	1	2.78	1	0.80	1	0.20	2	0.68	8	0.37	1	1.27	14
50	6	16.67	3	2.40	7	1.39	1	0.34	25	1.15	2	2.53	44
55	4	11.11	14	11.20	76	15.14	27	9.15	247	11.33	4	5.06	372
60	3	8.33	22	17.60	56	11.16	30	10.17	158	7.24	12	15.19	281
65	14	38.89	65	52.00	267	53.19	145	49.15	1497	68.64	2	2.53	1990
70	7	19.44	19	15.20	93	18.53	88	29.83	233	10.68	54	68.35	494

Unreported Crashes

It has long been recognized that police-reported crash data underreport lower severity crashes. The state of Washington used a $500 reporting threshold during the data collection period; that is, crashes with damage less than $500 need not be reported. These low-severity crashes represent roadside safety and roadside design successes since the vehicle was able to encroach onto the roadside or median without causing an injury. Before using a crash severity distribution, an appropriate adjustment to account for underreported lower severity crashes must be made. Conversely, Ohio requires that all crashes be reported regardless of the severity.

RSAPv3 predicts the total number of encroachments – those that produce reportable crashes as well as those that result in unreported or no crashes. These successes must be accounted for in the EFCCR approach by adjusting for the unreported crashes. Properly adjusting for underreported crashes will allow for more correct crash cost estimates, otherwise, RSAPv3 would overestimate crash costs by inappropriately modeling these successes as more severe crashes.

Several research studies have estimated the size of the unreported crash problem including NCHRP Report 490, the FHWA Pole Study and NCHRP Report 638. [Ray03; Mak80; Fitzpatrick99] Blincoe estimated for all types of highway crashes that nearly half (i.e., 48 percent) of all PDO crashes and a little over 20 percent (i.e., 21.42 percent) of injury crashes are not reported. [Blincoe02] Unfortunately, estimating the percentage of unreported collisions is extremely difficult. Mak and Mason examined collisions with breakaway and non-breakaway poles and signs in the 1970's. [Mak80] One of the many aspects of pole collisions they attempted to address was the issue of unreported crashes. Mak and Mason found that in addition to the 1,637 police reported pole crashes there were another 761 pole collisions that were not reported to the police (i.e., 32 percent). Even this estimate is probably too low since it was based on damage to poles that required repair or maintenance that could not be attributed to a police-reported crash. Crashes where there was no serious damage to the pole would not be reported to the maintenance authorities resulting in an even higher percentage than that shown. Not surprisingly, there was a wide variation in the unreported rates based on the types of poles and the functional classification of the roadway.

As discussed earlier, Nilsson has shown that the probability of injury crashes increases with the square of the average travel speed. If the probability of injury crashes increases with the square of velocity then the probability of non-injury crashes must decrease with the square of velocity. These non-injury crashes would include both reported property damage only crashes as well as unreported crashes. Assuming the total number of encroachments is the same before and after the speed change (i.e., P_{I1} and P_{I2}), the percent of injury crashes (P_{IC}) can be written in Nilsson's form. Further, the percent of non-injury crashes by definition would be P_{NIC}=1-P_{IC}: which results in the following:

$$\frac{P_{I2}}{P_{I1}} = \left[\frac{V_2}{V_1}\right]^2$$

Rearranging and solving for the percent of injury crashes in the after (P_{I2}) period yields:

$$P_{I2} = P_{I1}\left[\frac{V_2}{V_1}\right]^2$$

If the percent of injury crashes is known or estimated at one speed, it can be used to estimate the percentage of injury crashes at some other speed. The highest percentage of injury crashes should occur at higher speeds according to the Nilsen model and the level of unreported crashes should likewise be at its smallest at the higher posted speeds.

The reported crash severity values shown previously, for example in Table 1 for NFOs, indicate that the speed limit category with the most data are the 55 mi/hr roadways where there were 1,375 crashes in Washington, 610 of which were injury crashes. The percent of reported injury crashes was, therefore, 610/1375 = 44 percent. This could serve as a good first approximation of the true percent of injury crashes under the assumption that few cases go unreported on higher speed roadways. With this first approximation, we can estimate the percent of injury crashes at, say, 35 mi/hr as:

$$P_{I2} = P_{I1}\left[\frac{V_2}{V_1}\right]^2 = 0.44 \cdot \left[\frac{35}{55}\right]^2 = 0.18 = 18\%$$

The percent of NFO injury crashes on roadways in Washington State with 35 mi/hr posted speed limits, therefore, is estimated to be 18 percent. As shown in Table 1, 179 injury crashes and 233 non-injury crashes were actually observed on 35 mi/hr for a total of 412 NFO crashes. Knowing that 179 injury crashes occurred and the estimated percent of injury crashes is 18 percent, the total number of crashes would be expected to be 179/0.18=994. Since the estimate is that there were 994 total crashes (i.e., reported and unreported) and there were fewer than that number actually reported (i.e.,412), the model results are plausible. This would indicate that (994-412)/994 = 59 percent of NFO crashes on 35 mi/hr roadway go unreported. This is reasonable since even the airbag and other protective systems on most modern passenger vehicles are designed to minimize injuries at 30 mi/hr and below.

This process suggests a more general method of estimating the variation in the percent of injury crashes and unreported collisions. If all the injury crashes over all PSLs are tabulated and the injury percentage at the highest speed, P_{I1}, is assumed, then the percent of injury crashes and total number of crashes at each speed limit can be estimated as shown in the following equations where:

N_{I2} = the number of injury crashes predicted for that PSL,
N_{T2} = the total number of crashes at the that PSL and
N_{OBS2} = the number of crashes observed for that PSL.

$$P_{I2} = P_{I1}\left[\frac{V_2^2}{V_1^2}\right]$$

$$P_{I2} = \left[\frac{N_{I2}}{N_{T2}}\right]$$

$$N_{OBS2} \leq N_{T2} = \left[\frac{N_{I2}}{P_{I2}}\right]\left[\frac{V_1^2}{V_2^2}\right]$$

As shown above, the total number of predicted crashes must be greater than or equal to the number observed crashes. The difference between the number of total predicted crashes and the total number of observed crashes are the expected number of unreported and unobservable crashes. The value of P_{I1} at the highest PSL is then varied in a trial-and-error manner until the number of observed crashes is less than or equal to the total number of predicted crashes. This process produces the most likely percentage of injury crashes distribution that is consistent with both the observed data and the assumption that crash severity increases with the square of speed.

A trial value for the percent injury of about 44 percent would appear to be a good starting point based on the observations at 55 mi/hr. This calculation is repeated for each speed within each hazard group individually, assuming the number of predicted unreported crashes increases until at some point every speed category has an estimated total number of crashes that is equal to or greater than the observed number of crashes.

Equivalent Fatal Crash Cost Ratio

Now that the number of unreported crashes has been estimated, the true severity distribution of crashes is found by adding the unreported cases to the severity distributions of Table 1 through Table 6.

The FHWA uses the willingness-to-pay approach or comprehensive costs approach which has been documented by economists who observed that people “express how much well-being they get out of something by demonstrating *willingness-to-pay* for it.” [AASHTO03] Miller *et al* conducted a study in 1988 which determined the comprehensive costs of crashes related to the KABCO scale and Blincoe did a similar study relating comprehensive costs to the MAIS scale. [Miller88; FHWA09] Each letter of the KABCO scale corresponds to a different comprehensive cost. The authors noted that “these costs should be updated annually using the GDP implicit price deflator.” [Miller88] FHWA subsequently updated this study in 1994 and 2009. In 2009, FHWA moved away from using the GDP to update the costs and began updating the values each year. [FHWA09] These comprehensive cost values can be used to calculate the average expected crash cost given a severity distribution like the distributions shown for NFOs, LBs and “Other” hazards in Table 1 through Table 6.

Crash costs, like any economic indicator, change continuously so it is desirable to represent crash severity in a non-dimensional way. Similarly, it is also useful to represent average crash severity as a single number rather than a distribution of five values (i.e., KABCO). A single, dimensionless value allows for direct comparison of hazard severity between roadside hazards. The equivalent fatal crash cost ratio (EFCCR) accomplishes this by dividing the average crash cost calculated in any particular year by the cost of a fatal crash in that same year.

Returning to the Washington State Undivided example of NFOs, using the severity distribution with includes the estimated unreported crashes shown in Table 7, the distribution can be transformed into an average expected crash cost for a NFO collision by multiplying the crash cost of each severity level times its percentage and summing. As shown in Table 7, the expected average NFO crash in the State of Washington on 55 mi/hr roadways was $93,959.70 and only $6,041.84 on 30 mi/hr roadways using the 2009 FHWA crash costs. It makes sense that the crash cost should be much higher on higher speed roadways since the expected crash severity should be higher. The observed EFCCR on 55 mi/hr highways in Washington State was, therefore, $93,959.70/$2,600,000=0.0361 as shown in Table 7.

Table 7. 2009 Crash Costs and EFCCRs of NFO Crashes on Undivided Roadways in Washington.

Posted Speed Limit (mi/hr)	No. Cases	Police Reported Severity						Unrep	Total Crash Cost k$	EFCCR
		K	A	B	C	PDO	Unk			
		2,600 k$	180 k$	36 k$	19 k$	2 k$	2 k$	1 k$		
		%	%	%	%	%	%	%		
<=25	0	0.00	0.55	4.48	2.62	9.18	1.86	81.30	4130.10	0.0016
30	15	0.00	1.10	6.06	3.86	18.73	6.61	63.63	6041.84	0.0023
35	601	0.75	1.51	7.88	4.86	15.67	3.85	65.47	27128.49	0.0104
40	1647	1.81	1.81	9.80	6.17	16.87	5.62	57.91	56158.28	0.0216
45	1552	0.53	2.13	12.00	10.13	35.99	5.33	33.88	25113.36	0.0097
50	375	1.80	3.74	14.18	10.89	42.41	5.61	21.37	61993.13	0.0238
55	551	2.85	5.89	15.79	12.51	39.35	7.10	16.51	93959.70	0.0361
60	1193	2.50	5.16	21.62	14.80	45.75	8.65	1.52	85857.97	0.0330
65	181	6.47	0.00	19.40	25.87	32.33	12.93	3.00	180972.07	0.0696
70	915	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0000

It is convenient to reformulate the EFCCR in terms of a single baseline speed since the average EFCCR and PSL will be different for each crash estimated. RSAPv3 uses 65 mi/hr as a baseline speed for the $EFCCR_{65}$ (i.e., the EFCCR at a PSL of 65 mi/hr). $\overline{EFCCR}$ is the case weighted average EFCCR and $\overline{PSL}$ is the case weighted average speed limit, the bridge pier $EFCCR_{65}$ can be calculated as follows:

$$EFCCR_{65\ Undiv\_NFO\_Washington} = \frac{\overline{EFCCR} \cdot 65^3}{(\overline{PSL})^3} = \frac{0.025745 \cdot 65^3}{\left(\overline{50.2782}\right)^3} = 0.0535$$

The $EFCCR_{65}$ for NFO crashes on undivided roadways in Washington State is, therefore, 0.0535. This means that on average when a NFO crash occurs on a road with a posted speed limit of 65 mi/hr the average crash cost is 5.35 percent of the fatal crash cost or $139,100 using the 2009 fatal crash cost of $2.6 million. The EFCCR for any other arbitrary speed can now be calculated based on the tabulated values for the $EFCCR_{65}$ using:

$$EFCCR = \left[\frac{EFCCR_{65}}{65^3}\right] V_i^3$$

This same methodology was applied to each hazard group for both divided and undivided roadways in Washington and Ohio. The results of the analysis are shown in Table 8.

Table 8. Summary of $EFCCR_{65}$ Values for Washington and Ohio Roadsides.

Highway Type	State	NFO $EFCCR_{65}$	Other $EFCCR_{65}$	LB $EFCCR_{65}$
Undivided	OH	0.0116	0.0191	0.0311
Undivided	WA	0.0535	0.0368	0.0318
Undivided	WA & OH	0.0215	0.0325	0.0226
Divided	OH	0.0121	0.0128	0.0092
Divided	WA	0.0210	0.0198	0.0100
Divided	WA & OH	0.0125	0.0131	0.0093

Summary

The $EFCCR_{65}$ is a single, dimensionless measure of crash severity with a particular roadside feature at a baseline speed of 65 mi/hr. This value allows for direct comparison of hazard severity between roadside hazards and the use of data gathered for a specific hazard at one speed to be used to evaluate the same hazard for situations were data is not available. The values for the $EFCCR_{65}$ are based on observable police-reported crashes and adjusted to account for unreported crashes based on the model of crash severity discussed above.

Using the $EFCCR_{65}$ to estimate crash severity in a conditional probability model like RSAPv3 provides a systematic methodology based on observed data and established crash severity relationships. The EFCCR can be considered the conditional probability of a severe injury crash given that an impact has occurred. The probability is always zero at a speed of zero and increases to unity at some speed.

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