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James G. Strathman
Portland State University

Kenneth Dueker
Portland State University

Jihong Zhang
Portland State University

Timothy Williams
Portland State University

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James G. Strathman
Kenneth J. Dueker
Jihong Zhang
Timothy Williams

Center for Urban Studies
College of Urban and Public Affairs
Portland State University
Portland, OR 97207

for

Oregon Department of Transportation
Research Unit
Salem, OR 97310

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1.0 INTRODUCTION AND BACKGROUND

Since the passage of the Highway Safety Act of 1966, state departments of transportation have engaged in systematic safety improvement planning and programming. According to Davis (2000), the general approach to safety improvement planning employed by most states follows six principal steps:

1. Identification of hazardous roadway locations using crash records;
2. Detailed engineering study of selected hazardous locations to identify roadway design problems;
3. Identification of potential countermeasures;
4. Assessment of the costs and benefits of potential countermeasures;
5. Implementation of countermeasures with the highest net benefits;
6. Assessment of countermeasure effectiveness following implementation.

All planning processes are subject to uncertainty. In safety improvement planning, the determination of benefits from implementation of countermeasures depends greatly on projected crash reductions. Such projections are acknowledged to be the most uncertain element of the safety planning process (Pfefer et al., 1999). More than 25 years ago Laughland et al. (1975) identified the need for development of a national comprehensive set of crash reduction factors (CRFs) that states could employ in evaluating safety countermeasures. However, this need has not been addressed, and is not likely to be pursued (FHWA, 1991). As a result, states have been responsible for developing their own CRFs.

There is considerable variation among states in the number of CRFs used in evaluating safety improvement projects and in the sources of data employed in constructing CRFs (See Appendix A). In a few states, CRFs are based on extensive analysis of indigenous project and crash data, but the more common approach has been to draw CRFs from a variety of internal and external sources. Following the latter approach, a state's effort may become noteworthy for its thoroughness (e.g., Agent et al., 1996), with the result being that its CRFs are adopted, at least in part, by other states.

Although CRFs are derived from controlled analyses of countermeasure implementation, the extent to which their validity is maintained when transferred to other places where crash frequencies, roadway design, and other relevant circumstances differ is unknown. Clearly, while few states are able to invest in comprehensive validation of their CRFs, most realize that unrepresentative CRFs potentially undermine net benefit-based prioritization of safety projects and thereby reduce the returns to their limited resources.

In contrast to the site-specific orientation of studies analyzing changes in crash activity following countermeasure implementation, another approach focused at the system-level is emerging. In this approach, the highway system is decomposed into segments and crash frequencies are statistically related to roadway design and other attributes represented in each of the segments. An example is the research utilizing data from the

Federal Highway Administration's Highway Safety Information System (HSIS), a pilot project involving eight states (e.g., Council and Stewart, 1999; Miaou, 1994). The HSIS provides a consistent data base containing crash, roadway inventory and traffic volume data. Similar efforts have been undertaken in individual states where road inventory data is more extensive than that maintained by the HSIS (Carson and Mannering, 1999; Milton and Mannering, 1998).

At the present state of development, system-level analysis of the relationship between crash frequencies and road inventory attributes does not represent a direct substitute for traditional site-specific analysis. The number of road inventory attributes considered in system level analysis is very limited in comparison to the number of countermeasures for which CRFs have been estimated in site-specific studies. However, system-level studies frequently include analysis of the principal roadway cross-section features that represent the focus of a substantial amount of safety improvement investments. The system-level framework thus provides a means of assessing the external validity of an important subset of CRFs.

This report presents results from an analysis of crash frequencies on the Oregon state highway system. The analysis is differentiated according to functional classification (freeway v. non-freeway) and location (urban v. non-urban). Road inventory data are drawn from the Oregon Department of Transportation's (ODOT) Integrated Transportation Information System (ITIS). Estimates of the effects of countermeasures from statistical analysis of the state highway system are compared to their counterpart CRFs presently used in the evaluation of safety improvement projects. These CRFs were derived from a variety of sources and are differentiated by functional class, location, crash type, and severity.

2.0 METHODOLOGICAL ISSUES

2.1 RESEARCH DESIGN ISSUES

The traditional approach to estimating CRFs is to record crash frequency before and after the implementaion of a countermeasure at a given location. An alternative is to compare crash frequencies at sites where countermeasures have been implemented to comparable control sites that have not received treatment. The validity of either approach is subject to two problematic phenomena: regression-to-the-mean and crash migration. The regression-to-the-mean problem is a well-known problem in experimental research (Campbell and Stanley, 1963). Hauer (1980) was among the first to point out how regression-to-the-mean results from the selection of sites with frequent crashes for countermeasure treatment. He noted that because such sites exhibit high crash frequency, they are more likely to experience downward change over time irrespective of effects attributable to the implementation of a countermeasure. This problem is somewhat mitigated by comparable-site analysis, but the difficulty in this approach is in finding non-treatment sites that are truly comparable.

Assuming that regression-to-the-mean effects are minimized, CRFs derived from site-specific analysis tend to reflect the consequences of implementing countermeasures at the most hazardous locations. As the safety planning process progresses from more hazardous to less hazardous locations, it is likely that the changes in crash frequency from implementing countermeasures will also decline. In general, variations in the degree of hazard are not reflected in the development of CRFs or in the use of CRFs in safety project evaluation.

The crash migration problem occurs when countermeasure implementation shifts the location of crashes rather than reduces their frequency. Thus, while crashes may be observed to decline at treatment sites, they may increase elsewhere. A possible example of crash migration is the use of rumble strips on shoulders, which has been reported to reduce run-off-the-road crashes (Hanley et al., 2000). To the extent that rumble strips alert drivers that they are tired or otherwise impaired and lead to decisions to pull off the roadway, they provide an effective remedy. Alternatively, if drivers are only momentarily alerted and continue on, rumble strips are less effective in correcting the underlying hazard and may contribute to increases in other types of crashes at other locations.

In contrast to the traditional approach, cross sectional analysis seeks to estimate the systematic relationship between crash activity and highway design attributes. Cross sectional analysis employs regression methods to statistically estimate crash frequencies from a large sample of roadway segments whose design attributes vary systematically. Comprehensive representation of the highway system by the roadway segment sample makes the cross sectional approach less subject to regression-to-the-mean problems (Davis, 2000). The cross sectional approach also implies an underlying long run adjustment process, a desirable feature in relating highway design and crash activity. However, there are a variety of methodological issues that need to be recognized in applying cross sectional methods, which are discussed in the following subsections.

2.2 ESTIMATION ISSUES

A number of early cross sectional studies employed Ordinary Least Squares (OLS) regression to estimate the effects of highway design attributes on crash frequencies. An underlying assumption of OLS estimation is that crash frequency is normally distributed. Jovanis and Chang (1986), among others, pointed out that this assumption is rarely satisfied and that crash frequencies are skewed toward zero. They noted that crash frequencies typically corresponded to a Poisson distribution and thus recommended Poisson estimation over OLS.

Poisson estimation, however, requires the mean and variance of crash frequency to be equal. It is often the case that the variance will exceed the mean, which is characterized as "overdispersion." When crash frequencies are overdispersed, Poisson estimation is still unbiased, but the standard errors of the parameter estimates tend to be understated. The result is that selected parameters may be interpreted as statistically significant when, in fact, they are not. Alternatively, in Negative Binomial estimation the mean-variance equality restriction is relaxed. Econometric software packages usually report an overdispersion parameter estimate to provide a basis for choosing between Poisson and Negative Binomial estimation.

Another estimation issue is associated with the phenomenon of censoring. Cross sectional analysis usually includes crash frequency data over a several year time span, but a large share of sampled road segments are still likely to contain zero crashes. For some road segments, zero crashes reflect an inherently safe design. For other segments, however, the time span may be too short to capture the effects of underlying design-related hazards. One way of better distinguishing between these two states would be to expand the time frame, but doing so creates other problems. Driver behavior and factors relating to operating conditions can change, as can the roadway design itself. An alternative is to estimate a zero-inflated count model (either Poisson or Negative Binomial), which accounts for censoring effects. Vuong (1989) has developed a test based on the t-statistic to determine if censoring is a significant issue. However, Miaou (1994) points out that the interpretation of parameters from zero-inflated count models is more complex than the interpretation of parameters from standard Poisson and Negative Binomial models.

2.3 SPECIFICATION ISSUES

The specifications of cross sectional models vary considerably, based on data availability. Most include principal roadway cross section attributes such as number of lanes, lane width, shoulder width, and horizontal and vertical curve characteristics. Also, many applications include traffic volume and composition as covariates. The number of design-related factors in cross sectional models appears to be increasing over time, as state departments of transportation have moved to automate their roadway inventory data.

Given that specifications of cross sectional models consistently provide a less-than-complete representation of the full range of highway design attributes, they are subject to potential “omitted variable” specification bias. Attributes that are omitted from the specification are, by definition, represented in the error terms of these models. If the variables in the model are correlated with the omitted variables, it is possible that the estimated effects of the specified variables will be spurious. More generally, a maintained assumption in cross sectional models is that highway design attributes are separable from other crash determinants, such as driver characteristics and environmental conditions. There are reasons to believe that separability of design from these other factors is not achieved.

One possible manifestation of omitted variables is the violation of the requirement that the errors in estimating crash counts be serially independent. In general form, serial correlation is represented as follows:

$$e_i = \rho_1 e_{i-1} + \rho_2 e_{i-2} \ldots + \rho_n e_{i-n} + v_i \text{ , where}$$

e_i	=	the error term for the i TH road segment;
e_{i-1}	=	the error term for the first road segment preceding segment i;
ρ_1	=	the estimated correlation coefficient for the first preceding segment;
v_i	=	a random error term for e_i.

The equation above represents an n TH order serial correlation process. Serial correlation is defined to exist when non-zero ρ values are estimated. When serial correlation occurs, the parameter estimates associated with roadway design attributes may not be consistent and the standard errors of parameter estimates will be smaller than their true values. This results in erroneous interpretations of statistical significance. There is no discussion of serial correlation issues in the literature on cross sectional crash modeling. It is not clear what the appropriate test for serial correlation would be for Poisson, Negative Binomial, and zero-inflated count models, or what the appropriate correction would be if serial correlation were found to be present.

The lack of theory relating highway design and crash frequency means that decisions about the functional form of cross sectional models are largely ad hoc. In most instances it is assumed that the estimated marginal effects of design attributes are constant, but in reality these marginal effects could be increasing or decreasing over the range of observed attribute values. In addition, interaction effects between design attributes are rarely considered even though there is reason to believe they could be important. For example, the effect of narrow shoulders may be different on curves than on straight roadway sections, and lane width may be less important on low volume roads than it is on high volume roads.

It is assumed that design attributes are determinants of crash frequencies in cross sectional models, but sometimes the reverse can also be argued. Such occurrences reflect potential simultaneity bias. For example, crash frequency is commonly used as a basis for decisions on the location of warning signs, delineation of no-passing zones, and speed limitations. The solution for simultaneity bias is to estimate instrumental variables for the affected attributes (e.g., Carson and Mannering, 1999), but estimation error associated with this correction contributes to "errors-in-variables" problems.

Errors in variables problems are manifested in several ways in cross sectional models. The most common occurrence is associated with non-reporting of crashes. Non-reporting tends to vary by crash severity. Hauer and Hakkert (1988) found that nearly all crashes involving fatalities are reported, while less than half of the crashes limited to property damage are reported. They recommend that, at a minimum, models be disaggregated by crash severity. Even when disaggregated, consistent under-reporting implies that estimates of the marginal effects of design attributes will be biased downward. Hauer and Hakkert also concluded that the extent of under-reporting appears to vary from state to state, which led them to advise against multi-state cross sectional analysis. The existence of state-to-state differences in reporting levels also led them to advise against transferring CRFs from the states where they are estimated.

The consequences of errors-in-variables problems differ depending on whether they are confined to crash or design attribute and other causal variables. If crash frequencies are subject to measurement error, the consequence is a reduction in estimation efficiency of cross sectional models. If measurement error exists in causal variables the consequence is estimation bias. It has been shown that the direction of the estimation bias is downward (Maddala, 1977). Thus, it can be concluded that errors in independent variables will result in overly-conservative estimates of crash reductions. In addition to the crash frequency and instrumental variables examples discussed above, other data most prone to measurement error include traffic volume and composition.

There does not appear to be any direct evidence of errors-in-variables problems associated with highway design attribute data, but errors in coding crash locations produce the same effect. When crashes are geocoded to the "wrong" locations (based on inaccurate information in crash reports or actual geocoding errors), they are consequently linked to the "wrong" design attributes. The result is an error in specifying the design attributes of the true crash location. Austin (1995) compared locational information from crash records with known road feature locations using a geographic information system (GIS), and found selected mistakes in as many as 20% of crash records.

2.4 ROADWAY SEGMENTATION ISSUES

A roadway segment is the basic unit of observation in cross sectional crash frequency models. Generally, segments have been defined in two fundamentally alternative ways with respect to length and composition. The first defines a segment to be homogeneous with respect to road geometry, safety and traffic control devices, and traffic characteristics, resulting in variable lengths. The second defines segments by fixed length, which thus allows within-segment variation of road geometry and other features. Variable length homogeneous segments tend to be more frequently employed in cross sectional crash modeling studies.

A variety of alternative methodological approaches have been employed to construct roadway segments used in cross sectional crash frequency models. The simplest approach is to use segments that have already been defined for recovering Highway Performance Monitoring System (HPMS) data. HPMS segmentation is intended to yield variable length roadway sections that are relatively homogeneous with respect to highway geometrics, traffic volume, functional classification, and urban status. Forkenbrock and Foster (1997) used HPMS-defined segments in their cross sectional analysis of crash frequency on rural Iowa highways. It appears that HSIS data is also based on HPMS-defined segmentation.

Compared to the HPMS-based approach, a more extensive list of design criteria can be employed in defining roadway segments. For example, Mannering and his associates (Shankar et al., 1997; Milton and Mannering, 1998; Carson and Mannering, 1999; Lee and Mannering, 2000) have estimated a number of cross sectional models of the Washington state highway system in which segments were defined by changes in the following: district number, urban/rural status, state route number, roadway type, number of lanes, roadway width, shoulder width, presence of curbs/retaining walls, divided/undivided highway, speed, average annual daily traffic, truck percentage, peak hour factors, horizontal curve characteristics, and vertical curve characteristics.

Fixed length segments with variable design attributes have been used in a few studies. The choice of fixed over variable length appears to have been driven by an interest in analyzing the crash effects of point phenomena (signage, light fixtures, structures).

The more criteria that are employed in defining roadway segments, the greater is the control over extraneous factors that could potentially bias the estimated effects of design attributes on crash frequency. However, segment length is also inversely related to the number of segmentation criteria, which is potentially problematic. As segment length declines the share of segments containing zero crashes tends to increase, which is likely to contribute to censoring and the need to estimate zero-inflated crash count models. Thomas (1996) argues that overdispersion is more likely with smaller segments. Smaller segments also increase the likelihood that crash geocoding errors will occur. Council and Stewart (1999) deleted segments shorter than .10 mile in their cross sectional analysis based on concerns about illogical results obtained with short segments by Hauer in an unpublished study.

One way of avoiding the problems of short sections is discussed by Miaou and Lum (1993). They note that some analysts have chosen to define road segments to be non-homogeneous with respect to curve characteristics. This decision results in longer segments, with curve characteristics represented by surrogate measures such as number of curves, maximum curve length, and maximum curve angle.

2.5 INFERENCE ISSUES

The purpose of cross sectional models is to estimate the marginal effects of changes in highway design attributes on crash frequency. The segmentation process discussed above defines the geographic scale at which the estimated effects can be said to be valid. As Thomas (1996) notes, it is not advisable to apply results obtained at one scale to circumstances that occur at another scale. She emphasizes that this is particularly problematic in transferrals from a larger to a smaller scale, and results in what is known as "ecological fallacy." Geographers have generally recognized that the parameters defining spatial phenomena are frequently not invariant with respect to scale. Black (1991) confirmed the problem in his analysis of crashes at alternative scales in Indiana.

The main lesson suggested by the problems associated with the scale invariance issue is the need to anticipate how the estimates from cross sectional models will be applied. With respect to highway design attributes, the "appropriate" road segment scale should be that which is consistent with the scale of typical safety improvement projects. In reality, analysts must weigh trade-offs between estimation and application issues. For example, while Council and Stewart's (1999) decision to delete segments shorter than .10 mile may have been justified from a modeling standpoint, their decision also established a potentially troublesome lower bound on the scale at which their results could be considered valid.

1.1 SUMMARY

As is evident from the discussion above, there are advantages and disadvantages associated with both the before/after and the cross sectional approaches in estimating the effect of safety countermeasures on crash activity. The main advantage of the before/after approach is that it conforms to the ideal of a controlled experiment. Its main shortcomings (i.e., regression-to-the-mean, crash migration, transferability) are fairly well understood and are potentially resolvable. The main disadvantage of the before/after approach is that the cost of proper design and execution of such studies, particularly over the range of relevant safety countermeasures, is far beyond the means of state departments of transportation.

Alternatively, the main advantages of cross sectional models is that they draw on readily available data maintained by state transportation departments, reflect state-specific circumstances, and can be undertaken for a small fraction of the cost of comparable before/after studies. The main disadvantage of the cross sectional approach is that it requires an extensive amount of data to ensure proper specification, and it is subject to estimation problems related to data quality.

Gradual automation of roadway inventory data at the state level is increasingly mitigating specification-related problems and is broadening the range of countermeasures that can be addressed in cross sectional models. Recognizing that resource constraints will limit a state's ability to internally estimate CRFs from controlled experiments, cross sectional models should prove increasingly valuable in validating CRFs transferred from disparate settings.

3.0 EMPIRICAL APPROACH

3.1 DATA

To estimate the relationship between highway design attributes and crash frequency, data were drawn from the Oregon Department of Transportation's (ODOT) Integrated Transportation Information System (ITIS). Roadway inventory data from ITIS provided a relatively good representation of highway geometrics and traffic activity. Crash data for 1997 and 1998 were obtained from ODOT's Crash Analysis and Reporting Unit. The decision to focus on a two year period reflects the trade-offs discussed earlier. A multiple year time frame mitigates problems associated with data censoring and should thus provide more robust results. The time frame is limited to two years to minimize confounding effects associated with changes in roadway segment characteristics, driver behavior, and environmental conditions.

Given limited roadway inventory data on intersection characteristics, intersection-coded crashes were deleted. Crashes coded as work zone-related were also deleted. The coverage of roadway and crash data in the present analysis is confined to the state highway system, which consists of approximately 7,500 centerline miles.

The first step in organizing the data for analysis involved the creation of variable length homogeneous highway segments. This segmentation approach was chosen over the alternative of fixed length segments for data reasons. The ITIS contains almost no relevant point data (e.g., signage, roadside features), which would provide a rationale for segmenting the highway system into fixed lengths.

The ITIS roadway inventory variables used to define highway segments included the following: roadway ID, number of lanes, posted speed limit, surface width, right and left shoulder width, surface composition, right and left turn lanes, median type (six categories), urban/non-urban location and average daily traffic. A change in any of these variables defined a segment break. Following Miaou and Lum (1993), a decision was made not to include horizontal and vertical curve characteristics as segmentation criteria. Measures of curve characteristics within segments were subsequently developed, including the number of horizontal and vertical curves per segment, and the maximum central curve angle and vertical grade per segment. This approach results in relatively longer segments and should mitigate estimation problems. Also contributing to longer segments was the decision not to include intersections among the segmentation criteria, which was linked to the decision to delete intersection-coded crashes.

The segmentation process yielded an initial set of 12,400 roadway segments. Missing data, coding errors and milepoint anomalies reduced the total to 11,635 segments. Of this total, 1,118 segments were related to freeways (588 urban and 530 rural) and 10,517 segments were related to non-freeway roads (2,257 urban and 8,260 rural). Freeway segments included interstate highways as well as sections of US and Oregon state highways designed to interstate standards (i.e., OR 217, US 26 from the intersection of I-405 to the intersection of OR 6, and Or 126 from the intersection of I-5/I-105 to the intersection of OR 126 (Bus.)). Divided alignments were treated as independent road sections in the segmentation process. Overall, about 85% of the state highway system was successfully segmented.

Two key related factors to consider in evaluating the resulting sample of road segments are the number of very short segments and the number of segments containing zero crash counts. Figure 1 shows the frequency distribution of the sample with respect to segment length. While the mean segment length is .62 miles, there are a fairly large number of short segments in the sample. About 4,800 segments (40%) are shorter than .10 miles, despite the fact that curve characteristics and intersections were not included as segmentation criteria. At the other end of the distribution, about 1,400 segments (11%) are over one mile in length. The mean segment length compares to .44 miles reported by Miaou and Lum (1993), .42 miles in Forkenbrock and Foster (1997), and .06 miles reported by Shankar et al. (1997). The very short segment length mean obtained by Shankar et al. resulted from their use of a variety of curve characteristics as segmentation criteria.

Figure 1
Frequency Distribution of Highway Segment Lengths

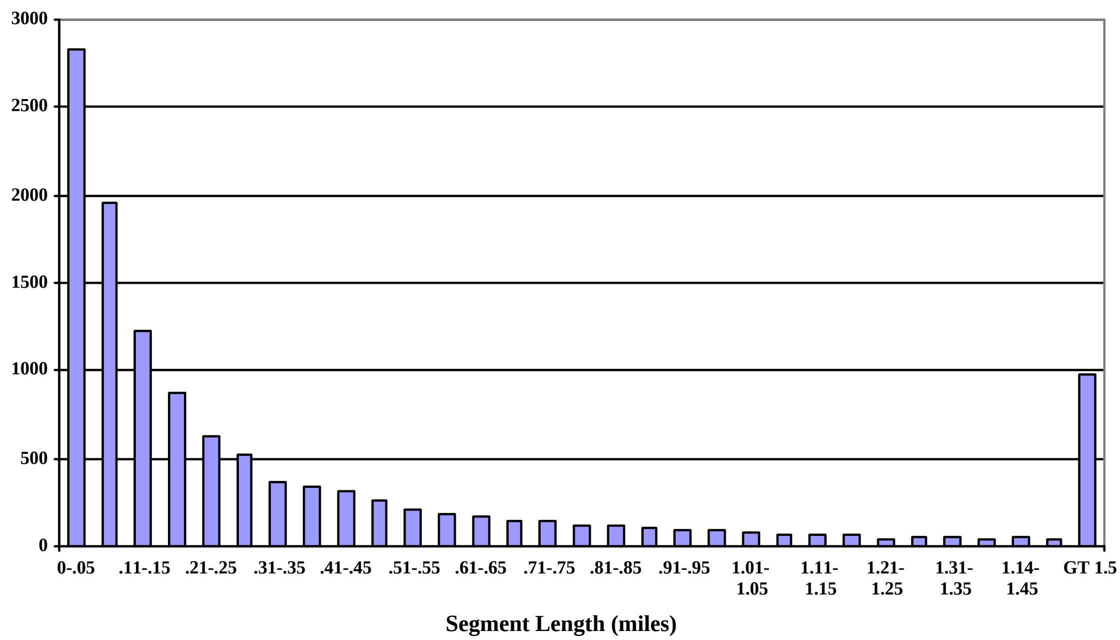

Figure 2 shows the frequency distribution of the number of crashes. The number of crashes in the sample segments totals 19,988, but over 7,300 segments (63%) contain no crashes for the two year period. The implications of these distributions are twofold. First, the large number of relatively short segments implies that overdispersion is more likely to exist. Second, the large number of zero crash segments implies that censoring is more likely to occur.

Figure 2
Frequency Distribution of Total Crashes
on Oregon State Highway Segments (1997-98)

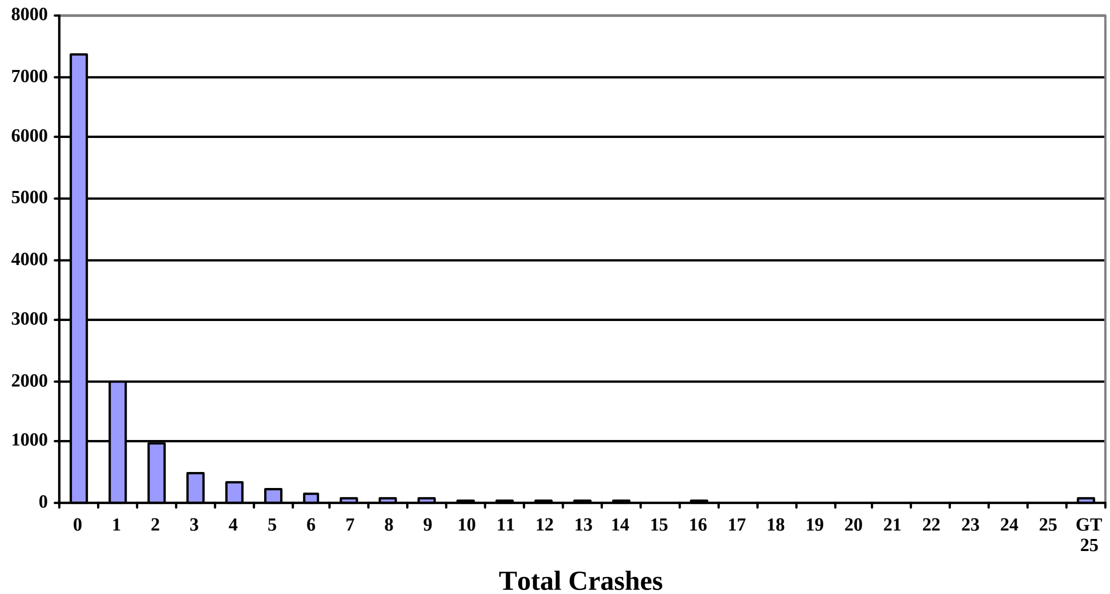

Table 1 provides a description of the variables in the data set and their summary statistics.[1] Mean total crash frequencies are about four times greater on freeway segments than non-freeway segments, and are also substantially greater for urban than rural segments. Segment lengths are typically much greater for freeways, while rural segments for both highway types are longer than their urban counterparts.[2] The mean number of lanes is roughly similar across all highway categories, which reflects the fact that the segments are alignment-specific. In almost all instances, freeways are defined by divided alignments, and in such cases the number of lanes in both directions would be twice the value reported. Multiple alignments also exist for non-freeway segments, but are much less common.

Posted speeds are higher for freeway segments, and for non-freeways the urban limit is substantially below the rural limit. Among non-freeway segments, turning lanes are more frequently observed in urban areas. Nineteen percent of urban non-freeway segments contain a left turn lane, while only nine percent of those segments contain a right turn lane. Maximum central curve angles are greater for rural segments, and the smallest mean central curve angle (6.09 degrees) is associated with urban non-freeway segments. Mean maximum curve length is greater for freeway segments, and among all categories tends to be greater in rural than in urban areas. Freeway segments tend to contain more curves than non-freeway segments, which is mainly due to their considerably greater lengths.

The mean maximum vertical grade is somewhat greater for freeway segments, and it is also greater in rural areas for both highway types. Freeway segments tend to contain more vertical grades, again due to their greater length, and their frequency is also greater in rural areas. Mean shoulder width tends to be about 80 percent greater for freeway segments. Regarding surface type, 40 percent of urban freeway segments and 20 percent of rural freeway segments are concrete-surfaced, while the counterpart values for non-freeway segments are four and two percent, respectively.

Four median treatments are included in the data set. Among freeway segments, median barriers are most commonly employed (33 percent of urban segments and 13 percent of rural segments). This is followed by vegetation medians (18 percent urban and 14 percent rural). Median guardrails are contained in four and six percent of urban and rural freeway segments, respectively. Among non-freeway segments, only curbed (6 percent in urban areas) and vegetation (1.5 percent in rural areas) medians are noticeably present. Two median types employed in the segmentation process – painted and jiggle bar (raised diagonal multiple speed bumps) – were dropped from further analysis when it was found that the former was present in only .3% of the sample road segments and the latter was present in none.

Average lane width among freeway segments is just over 12 feet, and does not exhibit much variation. Lane width of non-freeway segments is slightly greater and also tends to vary more. Average daily traffic on freeway segments is about double that of non-freeway segments, while the volume on urban segments is about twice that of non-urban segments.

3.2 RELATED CROSS SECTIONAL STUDIES

A review of literature on the effects of highway design attributes on crash frequency shows consideration of nearly all of the variables included in the present analysis. Table 2 summarizes the main features of the most relevant studies, including a description of the sample and context, the estimation process, the highway design attributes analyzed, and miscellaneous comments.

Fourteen of the seventeen studies listed in Table 2 employ cross sectional models to estimate the effect of selected highway design attributes on crash frequency. Two of the remaining studies (Hanley et al., 2000; and Ogden, 1997) are included as examples of traditional before/after analysis. The remaining study by Elvik (1995) does not involve cross sectional or before/after analysis. Rather, it is a meta-analysis of the results of 32 studies estimating crash reductions associated with median barriers, guardrails and crash cushions. The relevance of Elvik's analysis is its ability to assess whether "publication bias" exists in the reporting of crash frequency study findings. Meta-analysis is useful in determining whether there is a tendency toward publication of only statistically significant results clustered around given benchmark values. If publication bias were present in the crash modeling literature, this would imply a tendency to overstate the effects of design attributes on crash frequencies. Elvik found no evidence of publication bias with respect to the three subject countermeasures.

Table 2 lists only the highway design attributes which were analyzed in the studies. In addition to these attributes, the model specifications typically included a number of co-variates as statistical controls. Common co-variates included segment length and average daily traffic. Although posted speeds are not a design attribute, they are included in the table. Where the effect of an attribute is estimated to be statistically significant, the direction of that effect is shown in parentheses. A negative sign indicates that the analysis found a significant reduction in crash frequency associated with the attribute, while a positive sign indicates a significant increase.

Six of the studies in Table 2 are most comparable to the present analysis in terms of addressing a similar range of roadway cross section features. These include the studies by Carson and Mannering (1999), Hadi et al. (1995), Lee and Mannering (2000), Miaou and Lum (1993), Milton and Mannering (1998), and Shankar et al. (1997). The findings from these studies are discussed below.

The estimated effect of posted speeds is consistently negative, which is counter-intuitive. This result has been interpreted in several ways. First, it is argued that roads with higher posted speeds are designed to be inherently safer. However, given that these models already control for a number of safety-related design attributes, such an interpretation implies an omitted variable problem in the models' specifications. A second interpretation is that the speed limit variable is subject to simultaneous equations bias. This would be the case if decisions on posted speeds reflect consideration of crash frequency. If simultaneity is an issue, it is more likely to be relevant for non-freeway road segments.

The number of travel lanes is usually positively associated with crash frequency. Given that the models control for the effects of traffic volume, this result highlights the increased hazard associated with lane changes.

Travel lane and shoulder width are treated as either continuous or dummy variables in the cross sectional models. When defined as a continuous variable, lane width has a significant negative effect on crash frequency in some of the studies, but no significant effect in the others. Alternatively, Shankar et al. (1997) define dummy variables for narrow lanes (less than 3.46m) and narrow shoulders (less than 1.51m) and in both cases estimated a positive effect on crash frequency.

All of the studies that address vertical grade estimate that increasing steepness is positively associated with crash frequency. The same outcome pertains to curve sharpness. Curve length usually has a positive effect on crash frequency. The number of curves per segment is assessed in one study (Shankar et al., 1995) and found to be positively related to crash frequency. Shankar et al. (1997) also estimate greater crash frequency associated with adjacent curves.

Although roadside features are the focus of much attention in safety improvement planning, they are mostly absent from the cross sectional models. This most likely reflects a lack of data. Two of the studies in Table 2 include roadside features. Lee and Mannering (2000) assess distance from shoulders to guardrails and light poles, the number of isolated trees, and cut-slopes (dummy variable) and find only the latter to have a positive effect on crash frequency. Shankar et al. (1997) estimate significant increases in crash frequency for segments with roadside walls.

Crash frequencies are generally estimated to be lower for divided highways and wider medians. With respect to median treatments, raised curbs, grass medians, guard rails, and crash cushions have been estimated to reduce crash frequency. The presence of two-way left turn lanes was estimated to reduce crash frequency compared to undivided roadways (Brown and Tarko, 1999), but to result in higher crash frequencies in comparison to various types of controlled-access medians (Hadi et al., 1995). It was also found that median barriers contributed to an increase in crash frequency, but a decline in severity (Elvik, 1995).

Pavement type is addressed in only one of the studies (Hanley et al., 2000), which found that an open-graded asphalt overlay contributed to lower crash frequencies. Pavement condition was considered in two of the studies. Tarko et al. (1998) estimated lower crash frequencies as pavement serviceability improved on Indiana highways, while Forkenbrock and Foster (1997) estimated a weakly significant inverse relationship between serviceability ratings and crash frequencies in Iowa.

4.0 DATA ANALYSIS

4.1 ESTIMATION

Crash frequency models were estimated from the Oregon road segment data using LIMDEP 7.0 (Greene, 1998). The choice of estimator was made on the basis of tests for overdispersion and censoring, which are represented by the overdispersion parameter and Vuong statistic, respectively. Overdispersion was present in all cases. With respect to censoring, the Vuong statistic indicates that Zero-inflated Negative Binomial estimation should be employed for rural freeway and non-freeway segments (see Table 3)[3]. Negative Binomial estimation is indicated by the test result for urban non-freeway segments. The Vuong statistic for urban freeway segments is indeterminant, and the Negative Binomial estimator was chosen in this case. When no locational distinction is made, the test results indicate the need for Zero-inflated Negative Binomial estimation for both freeways and non-freeways.

Table 3
Test Results for Censoring Effects

Model	Vuong Statistic	Estimator Selected
Freeway		
All Segments	3.59	Zero-Inflated Negative Binomial
Urban Segments	.99	Negative Binomial
Non-Urban Segments	2.72	Zero-Inflated Negative Binomial
Non-Freeway		
All Segments	5.28	Zero-Inflated Negative Binomial
Urban Segments	-16.91	Negative Binomial
Non-Urban Segments	7.48	Zero-Inflated Negative Binomial

In addition, it is possible to test for the significance of locational distinctions in the accident frequency models. Such distinctions can be addressed by estimating separate models for urban and non-urban segments for both freeways and non-freeways. In this case, the appropriate test employs the likelihood ratio statistic (Judge et al., 1980) to determine whether a significant improvement in the likelihood function occurs as a result of estimating the crash frequency models from separate sub-samples rather than a joint sample. The likelihood ratio statistic is defined as follows:

$$LR = -2[\ L_t(ß) - L_u(ß) - L_r(ß)\ ], \text{ where}$$

$L_t(ß)$ = the value of the log-likelihood function at convergence for the joint sample;

$L_u(ß)$	=	the value of the log-likelihood function at convergence for the urban sample;
$L_r(ß)$	=	the value of the log-likelihood function at convergence for the non-urban sample.

The likelihood ratio statistic is distributed as Chi-Square, with degrees of freedom equal to the number of estimated coefficients.

With respect to freeways, the likelihood ratio statistic from estimation of separate urban and non-urban models is 454 with 16 degrees of freedom, which exceeds the critical Chi-Square value of 26.3 (.05 level). For non-freeways, the value of the likelihood ratio statistic is 240 with 15 degrees of freedom, which exceeds the critical Chi-Square value of 25.0. Thus it is concluded that performance is significantly improved in both instances from estimation of separate urban and non-urban models.

4.2 ESTIMATION RESULTS

The estimated parameters for the crash frequency models for freeway and non-freeway segments are presented in Tables 4 and 5.[4] It should be noted that the estimated coefficient are not directly interpretable and that elasticities will be derived in the following section.

Focusing first on the covariates included in the models, crash frequencies are estimated to increase with segment length and traffic volume, with greater marginal effects occuring in urban areas and, overall, on non-freeway segments in both cases. As has often been the case in previous studies, crash frequencies were also estimated to be inversely related to posted speeds. Several interpretations have been offered for this counter-intuitive result. The first is that segments with higher speed limits have been designed to be inherently safer. The second is that this result could reflect the effects of simultaneous equations bias, discussed earlier, if posted speeds are lowered in response to crash activity.

4.2.1 Horizontal and Vertical Curves

The horizontal curve attributes included in the models were estimated to have very limited effects on crash frequencies. The maximum curve angle in a segment was not found to be related to crash activity in any of the models, while the maximum curve length and the number of curves were estimated to have a positive effect on crash frequencies for rural non-freeway and urban freeway segments, respectively. In contrast, the maximum vertical grade was estimated to be positively related to crash frequencies for all types of roadway segments. The number of vertical grades per segment was not estimated to be significantly related to crash frequency in any of the highway categories.

Table 4

Crash Frequency Model Parameter Estimates: Non-Freeway Segments*

Variable	Unit of Measurement	All Segments	Urban Segments	Non-Urban Segments
Segment Length	miles	.410 (24.18)**	2.484 (90.84)**	.336 (23.45)**
No. of Lanes	integer	.011 (1.04)	.099 (2.20)**	-.008 (-.84)
Posted Speed	miles per hour	-.005 (-7.99)**	-.042 (-10.93)**	-.003 (-4.74)**
Right Turn Lane	1, 0	.028 (.81)	.311 (2.85)**	.010 (.30)
Left Turn Lane	1, 0	-.116 (-5.04)**	.163 (1.90)	-.111 (-5.01)**
Max. Curve Angle	degrees	.0004 (.99)	-.0004 (-.16)	.0002 (.53)
Max. Curve Length	feet	.00006 (2.94)**	.00003 (.18)	.00006 (3.23)**
No. of Curves	integer	-.004 (-1.88)	-.041 (-1.86)	.0005 (.26)
Max. Vertical Grade	absolute degrees	.024 (5.45)**	.056 (2.10)**	.019 (5.04)**
No. of Vertical Grades	integer	.003 (.92)	-.010 (-.72)	-.004 (-1.39)
Right Shoulder Width	feet	-.008 (-3.77)**	-.011 (-1.38)	-.004 (-1.90)
Av. Lane Width	feet	-.010 (-4.02)**	.016 (1.53)	-.014 (-5.56)**
Concrete Surface	1, 0	.038 (.81)	-.155 (-.86)	.038 (.83)
Vegetation Median	1, 0	-.618 (-9.84)**	-.762 (-.01)	-.449 (-8.86)**
Curbed Median	1, 0	-.397 (-6.98)**	-.822 (-4.78)**	-.235 (-2.90)**
ADT	vehicles	.00005 (33.88)**	.00006 (11.41)**	.00004 (23.10)**

* t-values are reported in parentheses. T-values denoted by ** are significant at the .05 level critical value of 1.96.

Table 5

Crash Frequency Model Parameter Estimates: Freeway Segments*

Variable	Unit of Measurement	All Segments	Urban Segments	Non-Urban Segments
Segment Length	miles	.160 (7.38)**	.178 (4.63)**	.178 (10.48)**
No. of Lanes	integer	.652 (11.97)**	.458 (6.09)**	.216 (3.59)**
Posted Speed	miles per hour	-.046 (-7.96)**	-.091 (-7.60)**	-.012 (-2.60)
Max. Curve Angle	degrees	.005 (1.80)	.001 (.36)	.005 (1.72)
Max. Curve Length	feet	.00005 (1.09)	.00006 (.97)	.00008 (1.87)
No. of Curves	integer	.026 (1.90)	.058 (3.11)**	.009 (.66)
Max. Vertical Grade	absolute degrees	.095 (4.33)**	.081 (2.33)**	.079 (3.57)**
No. of Vertical Grades	integer	.017 (1.23)	.018 (.75)	.006 (.47)
Right Shoulder Width	feet	.023 (2.60)**	.013 (.97)	.029 (2.53)**
Av. Lane Width	feet	.100 (3.48)**	.421 (7.82)**	-.015 (-.60)
Concrete Surface	1, 0	.167 (2.44)**	-.713 (-.62)	.041 (.42)
Vegetation Median	1, 0	-.106 (-.99)	-.369 (-2.10)**	-.105 (-.90)
Median Guardrail	1, 0	-.040 (-.28)	-.084 (-.32)	.064 (.42)
Median Barrier	1, 0	.359 (4.17)**	.159 (1.30)	.147 (1.20)
ADT	vehicles	.00001 (9.42)**	.000005 (2.83)**	.00001 (3.71)**

* t-values are reported in parentheses. T-values denoted by ** are significant at the .05 level critical value of 1.96.

4.2.2 Travel Lanes and Shoulders

Holding traffic volume constant, crash frequencies were estimated to increase with the number of lanes. This finding has been observed in a number of the studies reviewed earlier, and most likely highlights the hazards associated with lane changing maneuvers. Shoulder width was estimated to have a counterintuitive positive effect for rural freeway segments and a negative effect for all non-freeway segments. These mixed results reflect the findings in other studies. Of the eleven studies reviewed earlier that included variables for shoulder width, three (Lee and Mannering, 2000; Miaou, 1994; Miaou and Lum, 1993) found no relationship between shoulder width and crash frequency, and one (Carson and Mannering, 1999) estimated that crash frequencies were lower on road segments with narrow shoulders. Similarly, average lane width was estimated to be positively related to crash frequency for urban freeway segments, and negatively related for rural non-freeway segments. Only three of the previous studies addressed lane width, with two (Hadi et al., 1995); Shankar et al., 1997) estimating an inverse relationship and one (Milton and Mannering, 1998) estimating that crash frequencies were lower on road segments with narrow travel lanes.

On interpretation of the mixed results obtained for travel lanes and shoulders is offered by risk homeostasis theory, which posits that behavior adapts to changes in perceived hazards (Wilde, 1989). For example, wider shoulders and travel lanes ought to increase safety by providing more room for recovery and crash avoidance. However, motorists might compensate in situations that they perceive to be safer by driving faster, reducing following distance, and paying less attention. These adaptations can diminish or even off-set the expected improvement in safety from countermeasure implementation. On the basis of risk homeostasis theory one may contend that the estimated positive relationship between crash frequency and shoulder width for rural interstate segments in Oregon reflects an adjustment in driver behavior corresponding to perceptions of reduced risk.

4.2.3 Medians
The types of median treatments specified in the models generally differed for freeway and non-freeway segments, with only vegetation medians being common to both. This treatment was estimated to have a negative effect on crash frequencies for urban freeway and rural non-freeway segments. Median guardrails and barriers were included for freeway segments, and only barriers were estimated to have an effect (positive for all highway types). Curbed medians were specified for non-freeway segments, and were estimated to have a negative effect on crash frequencies in all cases.

4.2.4 Turning Lanes
Right and left turn lanes were also specified for non-freeway segments. Right turn lanes were estimated to be positively related to crash activity for urban segments, and there are several possible interpretations for this result. First, the presence of a turning lane indicates the possible presence of an intersection. Even though intersection-coded crashes have been deleted from the data, the approaches may still include lane changing, slowing, and queues that can contribute to crash activity that is not coded as intersection-related. Second, right turn lanes in urban areas are more likely to involve conflicts with pedestrians and cyclists. Also, a simultaneity problem may be present if frequent accidents near intersections lead to decisions to add turning lanes. The situation for left turn lanes is more clear, with an estimated negative effect on crash frequency as a result of vehicles being removed from travel lanes. This is particularly relevant for segments containing continuous two-way left turn lanes.

4.2.5 Roadway Surface
Roadway surface material was represented by a concrete surface dummy variable, which was found to be positively related to crash frequency for freeway segments. However, this finding did not hold up for the submodels covering urban and rural segments. The logic for a positive relationship is based on the argument that asphalt overlays tend to

drain better and pose less spray hazard than concrete surfaces. However, given that concrete surfaces are twice as likely to be found on urban freeways than they are on rural freeways, the estimation results may reflect a confounding of surface type and location.

4.3 ANALYSIS OF MARGINAL EFFECTS

The parameter estimates from Poisson and Negative Binomial estimation are not as directly interpretable as those from Ordinary Least Squares estimation. Liao (1994) and Milton and Mannering (1998) recommend that elasticities be calculated from these parameter estimates. An elasticity is defined as the proportionate change in crash frequency resulting from a proportionate change in a given attribute. Absolute values approaching or exceeding one are generally interpreted to be "elastic," while values approaching zero are interpreted as "inelastic." The elasticity for a continuously measured attribute is calculated as follows:

$$E_{xj} = ß_j x_j ,$$

where E_{xj} is the elasticity associated with attribute *j*, $ß_j$ is the estimated parameter for attribute *j* and x_j is the mean value of attribute *j*. In the case of binary variables, a "pseudo-elasticity" can be calculated as follows:

$$E_{xj} = (\exp(ß_j)-1)/(\exp(ß_j)).$$

Elasticities calculated from the significant parameter estimates in Tables 4 and 5 are reported in Table 6. The counterintuitive coefficients that were hypothesized to be the result of simultaneous equations bias were not included in these calculations.

The calculated average daily traffic elasticity in Table 6 for all freeway segments is .26, which means that a one percent increase in ADT is estimated to yield a .26 percent increase in crash frequency. The relative crash elasticities for ADT are generally greater for urban segments and for non-freeway segments, with the value exceeding one in the case of urban non-freeway segments. The elasticity values for the number of lanes are also fairly large, exceeding one for urban freeway segments. Only one elasticity was recovered for the number of curves per segment (urban freeways), and its value is fairly small. The elasticites for maximum vertical grade are also generally small, but the values for freeway segments tend to be four to five times larger than the values for non-freeway segments. Elasticities related to medians are generally substantial, with the value for curbed medians on urban non-freeway segments being the largest of those reported in the table. The remaining values for lane width, shoulder width, and surface type tend to be fairly inelastic.

Table 6
Selected Elasticity Estimates

	Freeways		
Variable	**All Segments**	**Urban**	**Non-Urban**
ADT	.26	.19	.13
No. of Lanes	1.56	1.17	.48
No. of Curves	--	.16	--
Max. Vertical Grade	.18	.14	.16
Concrete Surface	.15	--	--
Vegetation Median	--	-.45	--
	Non-Freeways		
ADT	.47	1.13	.27
No. of Lanes	--	.27	--
Left Turn Lane	-.12	--	-.12
Max. Curve Length	.02	--	.02
Max. Vertical Grade	.04	.05	.03
Right Shoulder Width	-.04	--	--
Av. Lane Width	-.13	--	-.17
Vegetation Median	-.86	--	-.57
Curbed Median	-.49	-1.28	-.26

4.4 COMPARISON TO CAT CRFs

Safety improvement projects in Oregon are presently evaluated using a Countermeasure Analaysis Tool (CAT) software that relates CRFs to a variety of countermeasures. The CAT distinguishes between urban and rural areas, identifying 60 urban countermeasures and 71 rural countermeasures. For any countermeasure, CRFs may distinguish between crash severity level (fatality, injury, property damage, overall), and potentially between 11 types of accidents (e.g., head-on, rear-end, angle, pedestrian, turning, side-swipe, etc.). Overall, the CAT includes 677 CRFs (333 urban and 344 rural) drawn from a variety of published sources, with TRB *Special Report 214* (TRB, 1987) serving as principal reference.

There are four countermeasure CRFs in the CAT that correspond to the statistically significant parameters estimated in the various crash models. These include curbed and vegetation medians, left turn lanes, and shoulder widening. For these countermeasures it is possible to compare the CAT CRFs with those derived from crash model parameter estimates. To facilitate comparison, crash model CRFs were calculated at the upper and lower 95th percentile range values of the estimated parameters. From Liao (1994), the calculated marginal upper bound CRF for a given countermeasure is defined as follows:

$$CRF_i = (\beta_{.975} * \Delta X_i) * 100, \text{ where}$$

CRF_i	=	Estimated CRF for countermeasure i;
$\beta_{.975}$	=	The upper bound parameter estimate for countermeasure i;
	=	β_i - 1.96 x Standard Error of β_i[5];
ΔX_i	=	The change in roadway attribute i associated with countermeasure implementation.

Table 7
Comparison of CAT and Crash Model CRFs

Countermeasure	Crash Models		CAT CRF
	Lower Bound	Upper Bound	
Curbed Median (Urban Non-Freeway)	48.5%	115.9%	30%
Vegetation Median (Urban Freeway)	2.4%	71.4%	30%
Left Turn Lane, Unsignalized Intersect. (Rural Non-Freeway)	6.8%	15.4%	25%
Widen Shoulder From 0-8 ft. (Urban/Rural Non-Freeway)	1.6%	3.2%	43%

The CRF values are presented in Table 7[6]. Regarding median countermeasures, the CAT includes one CRF for both curbed and vegetation medians in urban areas and does not distinguish between freeway and non-freeway road types. The crash model CRF range for curbed medians on urban non-freeways exceeds the CAT CRF value, while the calculated 95th percentile range for vegetation medians on urban freeways includes the CAT CRF value. In the case of the shoulder widening and left turn lane countermeasures, the calculated CRF ranges from the crash models fall below the CAT CRF values.

Considering the basis from which the crash model and CAT CRFs are derived, one would not expect very close conformance. The CAT CRFs are mainly drawn from before/after studies of countermeasure implementation. As discussed earlier, such studies tend to focus on more hazardous sites, thereby yielding relatively larger CRFs. Alternatively, the crash model parameters are estimated at the means of the roadway design attributes, and their associated CRFs reflect expected changes in what can be characterized as a more typical environment. However, the evidence in Table 7 does not support the expectation that CRFs derived from crash models would be consistently smaller than those obtained from before/after studies.

The CAT includes many countermeasures that are not presently represented in the ODOT ITIS data, including signage, signalization, roadside design characteristics and features, and access control measures. In time, ITIS will likely become populated with data on these countermeasures, and it will be possible to extend the present analysis to validate the CRFs used in countermeasure evaluation. In the meantime, the CRF validation and updating process will continue to depend on evidence drawn from multiple studies conducted in a variety of settings. For some countermeasures there are a sufficient number of studies to undertake a meta-analysis, which can help in synthesizing the findings and in identifying the best CRF estimate. Elvik (1995) provides a good example of how this approach is applied in the case of guardrails and barriers. It should be noted, however, that the variation in study results identified through meta-analysis can be attributed to differences in locational context and in research design. Given the objective of transferring findings from one setting to another, it would be desirable to carefully account for both contextual and design effects in the meta-analysis. Our review of the literature did not uncover evidence of such accounting. Smith and Huang (1995) provide an illustration of how such controls can be applied in their meta-analysis of hedonic air quality studies.

5.0 CONCLUSIONS

This report has investigated the statistical relationship between crash activity and roadway design attributes on the Oregon state highway system. Crash models were estimated from highway segments distinguished by facility type and urban status. A number of design attributes were found to be statistically related to crash activity in the various models, including the number of lanes, curve characteristics, vertical grade, surface type, median type, turning lanes, shoulder width, and lane width. In selected instances, CRFs calculated from crash model results were compared to those presently used to evaluate projects in ODOT's Safety Improvement Program.

The range of design attributes addressed in this study is similar to what has been covered by other studies reported in the crash modeling literature, and the results obtained for Oregon are generally consistent with those obtained from other study areas. Although relatively few at present, the number of design attributes included in crash models will likely grow over time as automated roadway inventory data become increasingly available. Nevertheless, it is doubtful that the coverage of crash models will ever be sufficiently comprehensive to effectively substitute for the present system, which encompasses hundreds of countermeasures in differing contexts.

While the number of highway design attributes specified in crash models is limited, it is worth recognizing that they represent a relatively large share of the capital invested in safety improvements. Safety-related outlays for lane and shoulder widening, altering horizontal and vertical curves, introducing median treatments, and for resurfacing have very large cost implications compared to outlays for signage and markings. Cross sectional crash models usually specify variables that represent countermeasures associated with the more costly outlays. Thus, the models provide states with an opportunity to validate the CRFs that are most important economically.

6.0 ENDNOTES

1. The variables selected from ITIS for the analysis are those which were posited to represent possible countermeasures or potential covariates. For some potentially relevant variables, missing data in ITIS precluded selection (e.g., median width). In other cases (e.g., rumble strips), a treatment had been applied to segments after the study period. To date, ITIS has not been populated with data on roadside features (e.g., signage,lighting, sideslopes) that would have been potentially relevant for crash modeling. There were also instances in which choices were made between variables that reflect similar phenomena (e.g., vertical and horizontal curve characteristics were selected, while variables for no pass zones and sight distance were not). Vehicle classification data were considered, but it was found that the reported traffic volumes across all classes did not match the reported total traffic volume data for highway segments.

2. Given the differences in segment length and traffic volumes among the various highway classes, it is difficult to interpret the mean crash frequencies in Table 1. To facilitate interpretation, the table below reports mean crash frequencies per mile by highway class and traffic volume. Given that intersection-coded crashes have been deleted from the data, the reader is still cautioned against comparing crash frequencies between highway classes and locations. For example, had intersection crashes been included, the mean frequencies for non-freeways would have been substantially greater, as would the frequencies for urban segments. Nevertheless, the table does show how crash frequencies increase with traffic volume within each of the categories.

Mean Crash Frequencies Per Mile, 1997-98*

	Freeways		**Non-Freeways**	
Average Daily Traffic	**Urban**	**Rural**	**Urban**	**Rural**
L.T. 1,000	--	--	--	0.3
1,000-5,000	--	1.6	2.3	2.4
5,000-10,000	11.2	2.4	5.2	3.0
G.T. 10,000	26.3	3.4	23.5	12.6

* Crash frequencies are not reported for categories with fewer than 50 observations.

3. When overdispersion exists, the Vuong statistic test provides a basis for selecting between a Negative Binomial (NB) and Zero-inflated Negative Binomial (ZINB) estimator. If the Vuong statistic exceeds the critical t value of 1.96, it can be concluded that censoring exists and that a ZINB estimator should be used. Alternatively, when the Vuong statistic falls below –1.96, it can be concluded that censoring does not exist and that a NB estimator should be used. When the Vuong statistic falls between 1.96 and –1.96 the test is inconclusive.

4. The estimation results are for crash frequencies over all levels of severity. Models were also estimated for varying levels of severity (i.e., fatality, serious injury, minor injury, and property damage), but the fatality/injury-related results were not interpretable. This may be due to the exclusion of intersection-coded crashes, which usually have more serious consequences.

   Analysis was also done to assess the consequences of very short segments. Crash frequencies were estimated from a sample containing segments shorter than .10 mile. For these segments, crash frequencies were estimated to increase significantly with increases in segment length, thus mitigating Hauer's concerns about analyses employing very short segments.

   A variety of variable transformations and interaction effects were also explored.

5. This confidence interval defines the 95th percentile range of the distribution of the estimated coefficient around the true underlying parameter value. Although the expected value of the estimated coefficient and the true parameter are equal, the two values can differ in a given instance as a result of sampling error. This confidence interval defines the range of 95 percent estimated coefficient values that would be obtained from many replications of the sample. See Wonnacott and Wonnacott (1972: 270-275) for a discussion of the derivation.

6. Note that while the confidence interval limit may exceed 100 percent, this is the maximum potential value of the CRF.

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8.0 GLOSSARY OF TERMS

Censoring In reference to crash data on roadway segments, a situation in which the data is not observable over its entire range, due to temporal abbreviation. In the instance of zero reported crash activity on a given segment over a stated time period, censoring occurs when an expansion of the time frame results in crash activity shifting from a zero to a positive state. Alternatively, if crash activity remains in a zero state with expansion of the time frame, the data is considered uncensored.

Chi-square Statistic A test statistic used to determine goodness-of-fit, or whether a phenomenon is randomly distributed.

Countermeasure A corrective action taken to improve safety and reduce crash activity. General examples include installation of barriers, channelization, changing horizontal and vertical alignment, signage, illumination and signalization, median treatments, lane and shoulder widening, altering sideslopes and removal of roadside obstructions, and intersection improvements.

Crash Reduction Factor The projected percentage change in crashes resulting from implementation of a countermeasure.

Cross-Sectional Models Statistical estimation employing data sampled from a population at a given point in time.

Likelihood Ratio Statistic A test statistic used in to determine whether a set of constraints imposed on parameter estimates results in a significant reduction in the likelihood statistic.

Negative Binomial Distribution A probability distribution for rare discrete events, characterized by the condition that the variance of the distribution exceed the expected value.

Ordinary Least Squares An estimation procedure which is based on the objective of mimimizing the squared errors between the observed and predicted values of a variable.

Overdispersion A condition in which the variance of a variable exceeds its mean value.

Poisson Distribution A probability distribution for rare discrete events, characterized by the condition that the expected value and variance of the distribution be equal.

Regression-to-the-Mean A phenomenon in experimental and quasi-experimental research in which changes from extreme initial values are erroneously attributed to a treatment effect.

Segments Roadway sections, typically defined by one of two alternative criteria: 1) constant length, in which the principal design characteristics can vary within sections; 2) variable length, in which the principal design characteristics remain unchanged within sections.

Site Specific Analysis In evaluation of the effect of countermeasures, a comparison of crash activity before and after countermeasure implementation at specific locations relative to crash activity at similar locations where countermeasures were not implemented.

System-level Analysis (See Cross Sectional Models) An evaluation of the effect of countermeasures based on statistical analysis of crash activity on a highway network decomposed into segments in which given countermeasures are present in some segments and absent in the others.

Vuong Statistic A test statistic used to determine whether zero-valued counts are over-represented in the dependent variable.

Zero-Inflated Count Model A modification of a Poisson or Negative Binomial count estimator which corrects for the over-representation of zero-valued counts in the dependent variable.

9.0 APPENDIX A: CRF SURVEY RESULTS

Presently, there is a fair amount of uncertainty about the practices employed by state departments of transportation in evaluating safety improvement projects. States are responsible for developing evaluation procedures. These procedures may include use of crash reduction factors (CRFs) and, to varying extent, cost-benefit analysis (CBA). For states that employ CRFs, it is unclear what range of countermeasures and crash types are covered. The source(s) of the CRFs is also unknown. For those states that employ CBA, the extent to which it is applied to projects is unclear, as is information about key parameters such as the discount rate, the monetary values assumed with respect to crash types and severity levels, and the discounting period.

To provide background information for the present project, a survey of state departments of transportation was undertaken to obtain information on the use of CRFs and CBA in safety project evaluation. The instrument for this survey (See Appendix B) was web-based, residing on the Oregon DOT server. Research unit directors were contacted by email and asked to forward the request for information and the web link to the appropriate safety program person. The initial request for information was distributed in the Fall of 1999, with several follow-ups occurring through the end of the calendar year. Respondents had the option of completing the survey online or downloading the instrument and returning it in hard copy form.

Survey Results

Thirty-five states responded to the CRF survey. Among the respondents only four states (North Dakota, Arkansas, Mississippi and Massachusetts) reported that they did not employ reduction factors in evaluating safety projects (See Figure A1). Notably all the responding western states reported that they used crash reduction factors, including Alaska. There was no response from Hawaii. As well, most upper mid west states responded that they employed crash reduction factors. The extent of non-response tended to be greater among eastern states.

Sources of Crash Reduction Factors

State DOT's typically drew on a number of sources for their crash reduction factors. Most drew from a combination of sources, and of the twenty-three responses to this question sixteen states had developed their CRFs in house. Fourteen states used other published literature as one source of their CRFs and five used the reports developed by other states.

Specific details from the state responses are as follows:

Other Published Literature Used:

- **Kentucky**, **Louisiana**, **Maine** and **South Carolina** derive 100% of their CRFs from published studies and reports; **Nevada** derives 95%; **Oklahoma** derives 62%; and **Minnesota** derives 25% of their CRFs from the University of Kentucky's Transportation Center "Development of Accident Reduction Factors."

- **California** uses a report entitled "Evaluation of Minor Improvements" (Part 1 thru 8).

- **Connecticut** uses NCHRPR 162 to develop their CRFs.

- **Florida**: In addition to developing their own CRFs, Florida uses "Development of Accident Reduction Factors," T. Creasey and K.R. Agent, UKTRP-85-6, March 1985.

- **Georgia** uses the FHWA Annual Report on Highway Safety Improvements.

- **Oklahoma** derives an additional 6% from "FHWA Highway System Needs Study Report to Congress (1976)."

States Who Use Other State's Sources:

- **Oklahoma** uses the "Iowa State Spot Location benefit Cost Determination Report" for 2% of their CRFs.

Other Sources Listed in Surveys Include:

- **Arizona** used FHWA-SA-96-040 as a source for 50% of their CRFs

- **Oklahoma** responded that 29% of their CRFs are interpolated from the three following sources:
  - Kentucky State Accident Reduction Plan
  - Iowa State Spot Location Benefit Cost Determination Report
  - FHWA Highway System Needs Study Report to Congress (1976)

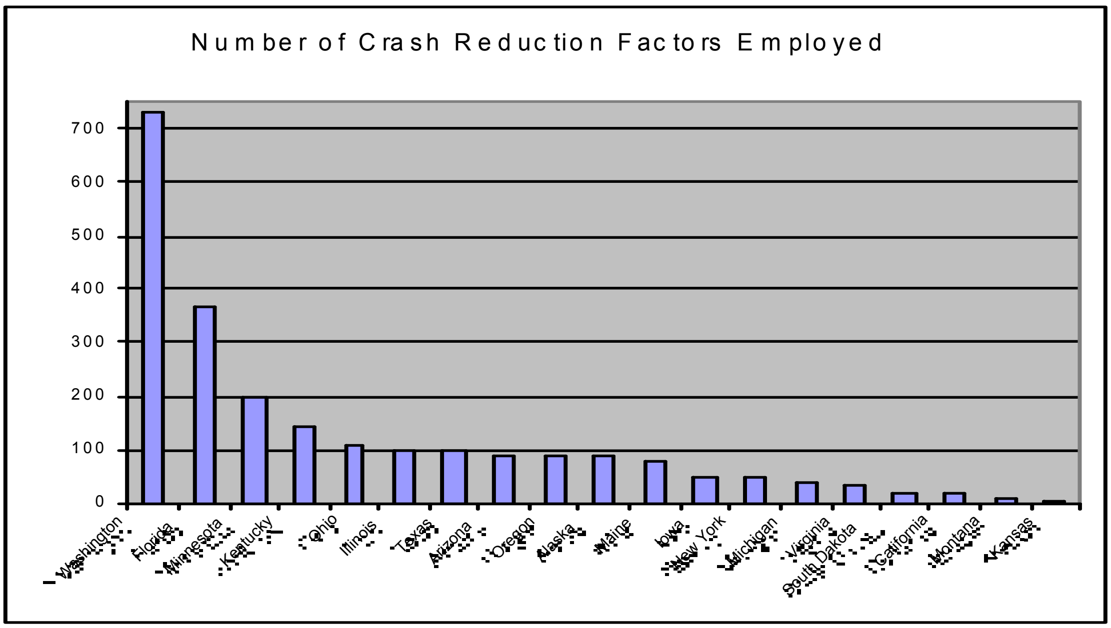
- **Virginia** noted that 44% of their CRFs are simply a default value. No other explanation was offered.

- **Texas** used various research in the establishment of their reduction factors.

- **Washington** DOT has compiled a list of research called the Countermeasurers Reference Summary. This refers to various research done. A new list of CRFs is being developed by the Highways and Local Programs Division.

Number of CRFs Employed

There was a great deal of variation in the number of CRFs employed by individual states. Of the eighteen states who responded to this question, Washington used the greatest number of factors at 732, Florida was second with 367, and Kansas used the fewest with 5. Most responses were around 100, with the median calculated at 88.



Severity Coverage

From the thirty responses, the fourteen states that cover fatalities cover injury and property as well. There were diverse approaches reported on the breakdown of accident severity covered by CRFs.

Comments from individual states are as follows:

- **California** does not specifically breakdown each type of the severity that will be reduced. The CRF is applied to the whole crash experience. They do a statistical test on the severity of crashes to determine if higher crash cost should be applied in the Traffic Safety Index calculation. If it is within the "normal" range of crash severity then the average cost/crash is used for that type of roadway.

- **Illinois**: Accident severity is included indirectly by an annual procedure that tabulates crash severity by type of collision for three types of state-marked highway: Urban, Rural, and Chicago.

- **Iowa** stated that CRFs are an estimate of reduction in overall crash related costs with crashes of all types/severities aggregated.

- **Kansas** responded that they consider Injury/Fatality combined and PDO.

- **Kentucky** noted most of their reduction factors are for the type of improvement. However, there are some CRFs that are distinguished by severity.

- **Louisiana** stated that they use a percentage reduction in total crashes.

- **Maine** noted that they use overall crash reduction and apply to each severity level for any given site.

- **Montana** uses CRFs for correctable crashes (no differentiation between fatalities, injuries, PDO). They account for severity in benefit/cost analysis.

- **New York** has CRFs by severity (total, and fatal/injury). They also have CRFs for appropriate accident types as they relate to particular accident countermeasures.

- **Oklahoma's** CRFs are for total number of collisions. However, Annual Average Benefit is based upon an average cost by type of road using the following values:

• $2,600,000 = $180,000 - Incapacitating Injury;
• $36,000 Evident Injury; $19,000 Possible Injury;
• Property Damage = Cost of property damage as reported by investigating officer.
• Values assembled from FHWA Technical Advisory, "Motor Vehicle Accident Costs," October 31, 1994.

- **South Dakota's** injury accidents are broken down into "Incapacitating Injury", "Non-incapacitating Injury", and "Possible Injury".

- **Texas** uses the severity of the crash in their cost/benefit formula, not the severity of the persons injured. Crash severity is assigned based on the most severe injury sustained in the crash.

- **Washington** noted that sometimes the CRFs separate out crash severity

States Whose CRF's Distinguish Types of Crashes and the Frequency of CRF Types

Of the twenty-five responses to whether CRF's were distinguish among types of crashes, twenty-one states (60 percent) replied that they did and fourteen (40 percent) said they did not. The distribution of types of CRF's included in the survey was flat, ranging from 7 percent for non-collisions to 12 percent for head on collisions. Other types of CRF's mentioned by states included:

- **Alaska**: Wet-nighttime, dry-nighttime, wet pavement, nighttime, train, animal, drift off road.

- **Florida**: Run off road, wet pavement, night, urban, and rural.

- **Oklahoma**: Parked vehicles, trains, overturned in road, run off road, animals.

- **Virginia**: Train, deer, other animal, bicyclist, motorcyclist.

- **Wyoming** commented that although they work heavily with traffic and urban areas on intersections, they focus mainly in the rural areas for hazard identification and elimination. In addition to the above choices, they are very concerned about run-off-roadway overturn crashes (Wyoming's typical fatal crash).

States with Empirically Validated CRFs and Methods of Validation

Approximately two-thirds of the thirty-five responses indicated that they used empirically validated CRFs. Of those responses, fifteen states use longitudinal analysis (i.e. before and after) of crashes at specific locations.

None of the responding states used cross-sectional statistical analysis in relation to highway geometry.

States Using Benefit Cost Methods

Of twenty-eight responses, twenty-four (86 percent) use CBA. Of the twenty-four, eighteen evaluate all projects using CBA. Of those states that do not have 100 percent coverage:

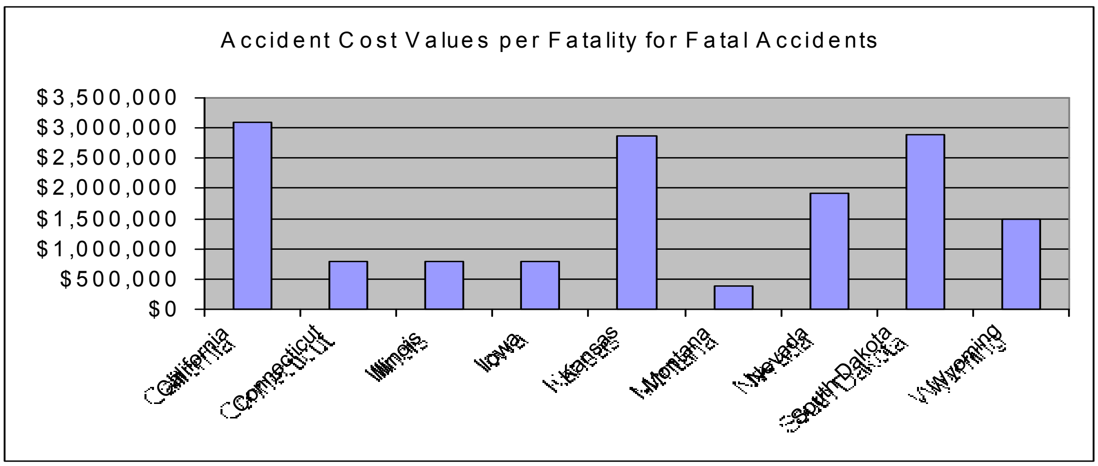
- **Florida** and **Louisiana** cover ninety-five percent and **Montana** ninety-eight percent of projects;

- **Washington** and **Oklahoma** cover seventy-five percent of projects;

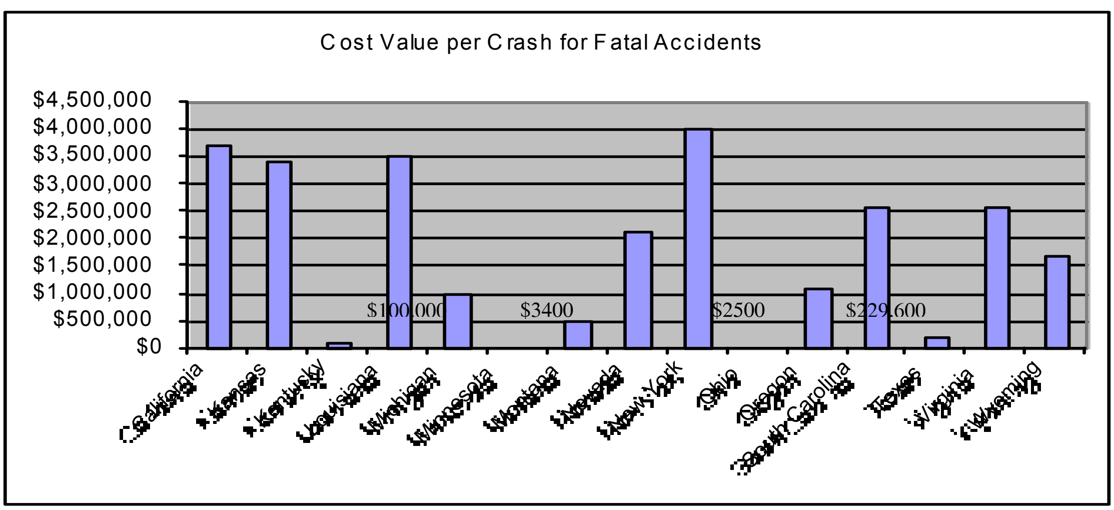
- **California** covers forty-five percent.

Accident Cost Values

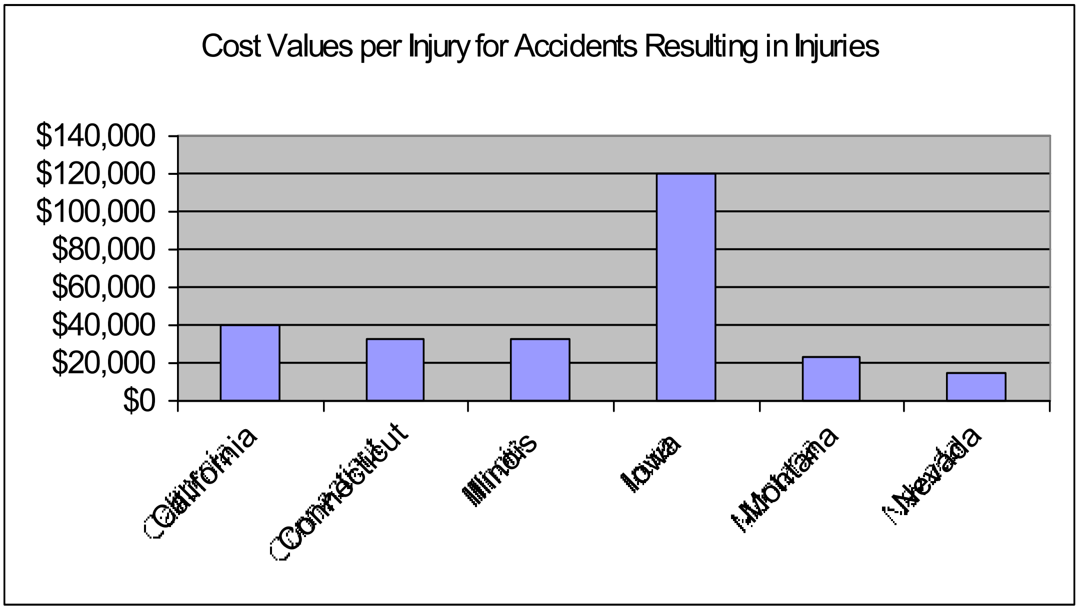
The reports of cost values used by accident type and severity were scattered. Several states only filled out categories of cost per accident, injury and property damage as they related to their own system of classification. In many cases, the classification of cost values differed among states. In terms of cost values per fatality for fatal accidents five states reported values in the $1.5-3 million range while four states were below $800,000.



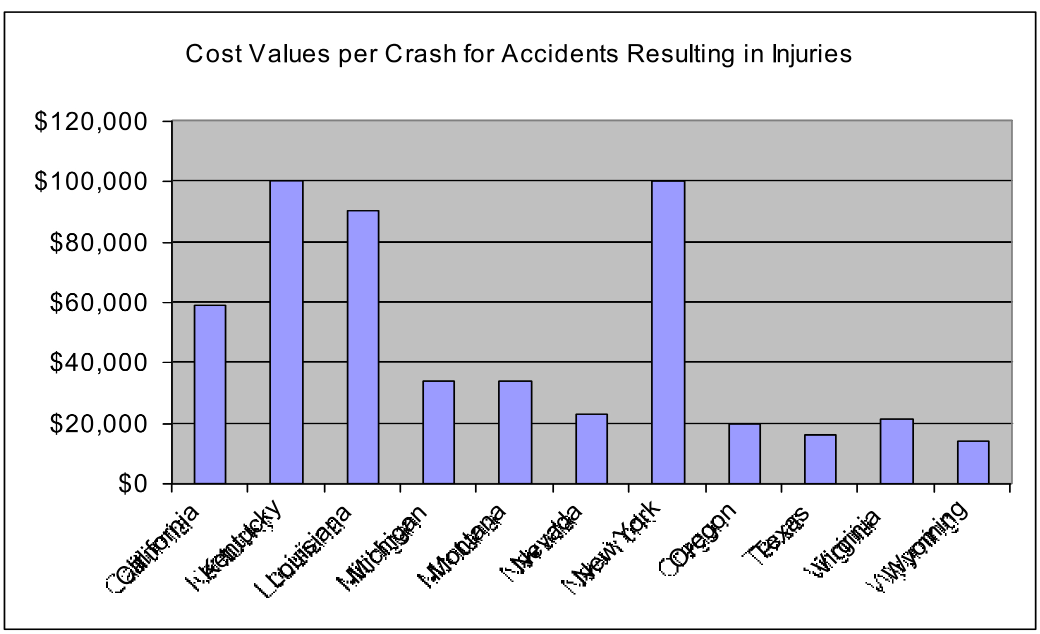
Responses for cost value per crash also varied widely, with a grouping of six states above $2 million and wide dispersion below $2 million.. Minnesota and Ohio reported remarkably low values of $3400 and $2500 respectively.



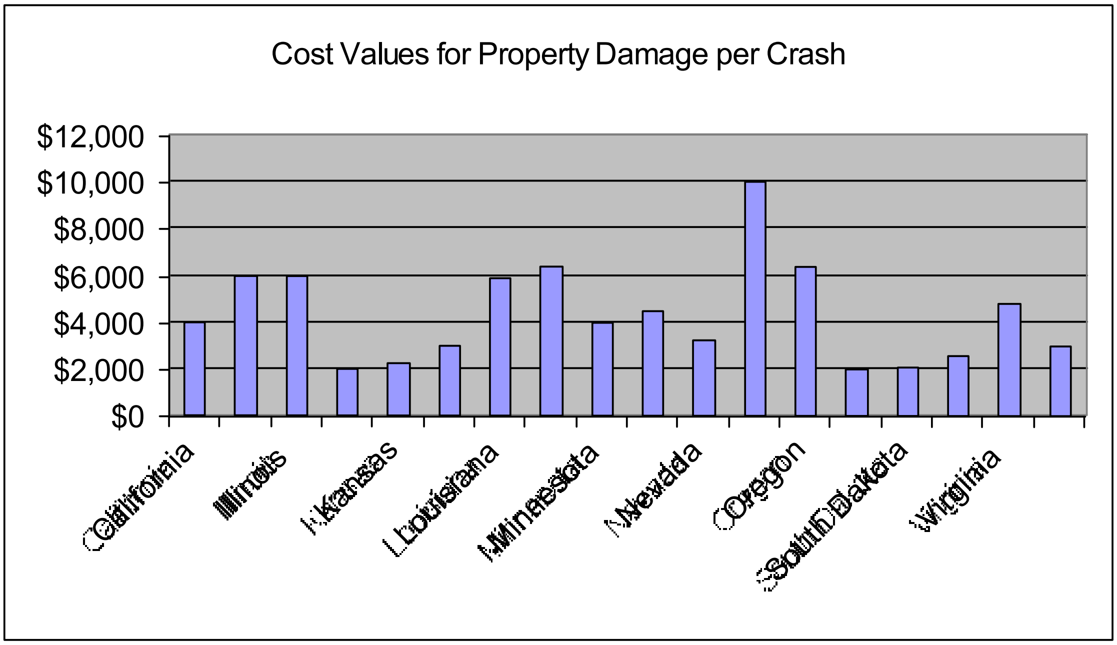
Reponses for cost per injury were generally between $14,000 and $40,000, with Iowa being the outlier at $120,000.



Cost values per crash for accidents resulting in injuries showed a clustering between $14,000 and $58,000, with Kentucky, Louisiana and New York reporting over $90,000.



Finally, costs for property damage per crash generated a much higher response rate, with responses ranging from $2,000 to $10,000. The median is $4000.



There were a variety of sources of cost values and comments on how states determine these values:

- **Connecticut, Illinois, Michigan and Georgia**: National Safety Council
- **Alaska**: Monetary values are dependent on road type classification, and are based on empirical data in combination with FHWA fatality, injury, and property damage average costs.
- **Arizona:** Fatal accidents $ 2,600,000; Incapacitating $ 180,000; Evident Injury $ 36,000; Possible Injury $19,000; PDO $ 2,000 . Costs estimated using FHWA'S comprehensive costs in 1994 dollars. New dollar values have been received but not implemented as of yet
- **California**: Dr. Ted R. Miller's "Highway Crash Costs in the United States by Driver Age, Blood Alcohol level, Victim Age and Restrain Use."(1998)
- **Florida**: Cost varies by facility type. All state roads average cost/crash is $83,070. The monetary value is derived from 1994-1996 traffic crash and injury severity data for crashes on state roads in Florida, using the formulation described in FHWA Technical Advisory "Motor Vehicle Accident Costs", T 7570.1, dated June 30, 1988 and updated injury costs provided in the companion FHWA Technical Advisory, T 7570.2, dated October 31, 1994.

- **Iowa**: $2000 minimum per crash for property damage; $8000 for minor injury; Developed internally.
- **Kansas**: FHWA Technical Advisory dated 10/31/94 adjusted for inflation. B/C is used for site specific evaluation of roadside improvements. It is considered to be one factor to consider, but is not the sole basis for decisions.
- **Kentucky:** A combination of National Safety Council, FHWA, and Transportation Cabinet decisions.
- **Louisiana:** Federal Highway Administration
- **Maine**: FHWA Technical Advisory T 7570.2 Motor Vehicle Accident Costs, 10/31/94.
- **Minnesota**: Crash injuries are broken down to A ($260,000), B ($56,000), and C ($27,000). They use US/DOT's 1997 Comprehensive Costs (as per Technical Advisory T 7570.2) along with a 3 year weighted average of Minnesota's number of injuries per crashes and came up with costs per crash.
- **Montana:** FHWA June 1991 transmittal.
- **Nevada:** Developed costs using the "Willingness to Pay Approach" from FHWA and have adjusted them annually by applying the consumer price index.
- **New York**: Willingness to pay. Average accident cost: $50,000. Unique costs based on facility types.
- **Oklahoma:** $2,600,000 - $180,000 Incapacitating Injury; $36,000 Evident Injury; $19,000 Possible Injury; Property Damage = Cost of property damage as reported by investigating officer. FHWA Technical Advisory, "Motor Vehicle Accident Costs," October 31, 1994.
- **South Carolina**: Injury crashes based on type 1,2,3; Injuries * $ per crash = 19,000, 36, 000, 180,000. FHWA Technical Advisory dated 10/31/94, Subject: Motor Vehicle Accident Cost
- **South Dakota**: FHWA Technical Advisory T7580.2 10-31-94, updated annually. Injuries/$ per fatality or injury - $198000/39000/21000
- **Texas**: Costs are computed annually based on the National Safety Council report "Estimating the Costs Unintentional Injuries, 1998" (the most current report is used each year). The above cost are assigned as follows:$229,600 = Fatal & Incapacitating Injury Crashes; $16,300 = Non-Incapacitating & Possible Injury Crashes; $2,600 = Property Damage Only Crashes
- **Virginia**: The figures were for base period 1982-84=100 and the Annual CPI factors were used to calculate the percent of change compared to the Annual CPI of the previous year. The base numbers were from the National Safety Council.
- **Wyoming**: Injuries are separated by injury severity: Incapacitating injury = $180,000 (in dollars - not thousands of dollars); Non-incapacitating injury = $36,000; Possible Injury = $19,000

Discount Rates

Eleven of the twenty-five respondents stated that they use discount rates. The range of discount rates was between four and eight percent.

10.0 APPENDIX B: CRF SURVEY INSTRUMENT

Use of Crash Reduction Factors in Evaluating Safety-Related Projects

State of the Practice Survey

QUESTIONNAIRE

The Oregon Department of Transportation (ODOT), in conjunction with Portland State University, is conducting a research study to evaluate the use of crash reduction factors (CRFs) in evaluating safety improvement projects. The study will statistically relate roadway features and crash activity on Oregon's state highway system, in an effort to validate the CRFs that ODOT uses in project evaluation.

As a part of the study, we would like to learn how other states evaluate safety related roadway improvements. When completed, this information will be shared with all interested agencies and listed in the Transportation Research Information System (TRIS).

Please forward this questionnaire to the appropriate person for completion.

Return the completed questionnaire and any supporting documents to:

Rob Edgar

Research Unit
Oregon DOT
200 Hawthorne SE, Suite B-240
Salem, OR 97301-5192
Phone: (503) 986-2844
Fax: (503) 986-2844
Email: robert.a.edgar@odot.state.or.us.

We would appreciate your response by **October 29, 1999.**

If you have any questions about this survey or our research study, please contact Jim Strathman at Portland State University (503-725-4069, jims@upa.pdx.edu) or Rob Edgar.

Use of Crash Reduction Factors in Evaluating Safety-Related Projects

State of the Practice Survey

General Information

Name of respondent	
Title:	
Organization	
Address	
Phone	
Email address	

Crash Reduction Factors (CRF) are estimates of how much each roadway safety improvement reduces crashes. Generally, CRFs are given for different crash severities (fatal, injury and property damage) and roadway safety countermeasures (such as roadway re-alignments, intersection reconstruction, traffic signals, illumination, warning signs, guardrails, etc).

CRFs are used with injury/property damage cost estimates to determine the benefit-to-cost ratio (B/C) for various roadway safety improvements. The B/C compares the project cost with the estimated crash reduction cost savings. The B/C helps to determine the best roadway improvement solution for a hazardous road segment.

Please answer the following:

1. **Do you use crash reduction factors in evaluating crash countermeasures in safety-related projects?**

(X)	
	Yes
	No

If "no", how are safety-related projects evaluated?

The next set of questions deals with crash reduction factors. If you do not use crash reduction factors, skip to question 7.

2. Is there a manual, handbook, report, or memorandum that presents your crash reduction factors and/or explains how safety-related projects are evaluated?

(X)	
	Yes
	No

If yes, please send us the document and any supporting information.

3. What percentage of your crash reduction factors come from the following sources?

(%)	Source
	TRB Special Report 214
	Other published literature reports (please give name of document below)
	Developed internally by your DOT (please give name of document below)
	From another state DOT (please give state and name of document below)
	Other (explain below)

	What is the approximate number of crash reduction factors used

Explain if needed

4. What levels of severity are covered by your crash reduction factors?

(X)	
	Fatalities
	Injuries
	Property Damage
	Other (please explain below)

Explain if needed

5. What types of crashes do your crash reduction factors cover?

(X)		(X)		(X)	
	Head on		Non-Collision		Parking
	Rear End		Fixed Object		Backing
	Turning		Pedestrian		
	Angle		Sideswipe		

Other (please list):

6. **Have your crash reduction factors been empirically validated in your state by any of the means identified below?**

Method	**Select one**		
	Yes	**No**	**Don't Know**
Longitudinal (i.e., before and after countermeasure implementation) analysis of crash activity at specific locations.			
Aggregate statistical analysis of cross sectional or pooled cross section-time series crash data in relation to highway geometry and characteristics.			
Other means (explain below)			

Explain if needed

7. Do you use Benefit-Cost methods in evaluating safety-related projects?

(X)			
	Yes, for all safety-related projects		
	Yes, for approximately	%	of safety-related projects
	No		

8. If/when Benefit-Cost is used, what monetary values do you assign the following:

	$ per fatality or injury	$ per crash
Fatalities		
Injuries		
Property Damage		

9. What is (are) the source(s) of these monetary values?

10. When computing Benefit-Cost analysis of safety-related projects, are discount rates used?

(X)			
	Yes	If yes, what is the discount rate (% per year)	
	No		
	Don't know		

11. When computing present values in Benefit-Cost analysis of safety-related projects, what value is used to represent the expected life of the safety countermeasure?

Expected life ranges from		to		years, depending on the countermeasure

12. Please give us any other comments you would like to make:

13. Check below if you would like a report describing the results of this survey?

	Yes, send me a report to the address shown above

THANK YOU FOR COMPLETING THIS SURVEY